External Research Report

ER66 [2021]

Removing the barriers to the use of significant levels of SCMs in concrete production in New Zealand

James Mackechnie

Project LR12312

Concrete NZ, funded by the Building Research Levy

Funded from the Building Research Levy

1222 Moonshine Rd, RD1, Porirua 5381
Private Bag 50 908, Porirua 5240
New Zealand
branz.nz

ISSN: 2423-0839

Removing the barriers to the use of significant levels of SCMs in concrete production in New Zealand as a major step towards decarbonising concrete construction

James Mackechnie – September 2021

EXECUTIVE SUMMARY

The New Zealand cement industry has been able to reduce carbon emissions associated with Portland cement production, primarily by process efficiencies. Further reductions will require significant use of supplementary cementitious materials (SCMs) in concrete to reduce clinker factor. Predicting the performance of concrete made with SCMs is required for designers and contractors to have confidence with these materials. An experimental research programme was therefore initiated in early 2020 to investigate local materials and test methods and compare performance with international norms and standards.

Experimental work was undertaken using cement paste, mortar and concrete mixes containing a wide range of Portland cement and industrial and natural SCMs from local and overseas sources. Three grades of concrete were designed with water/binder ratios of 0.65, 0.45 and 0.35 that were used to provide a comparative assessment of fresh and hardened concrete properties. Laboratory testing at the University of Canterbury was undertaken between May 2020 and August 2021. Fresh concrete properties assessed were slump, bleed, setting and workability assessment while hardened concrete properties were density, compressive strength, porosity, oxygen permeability, accelerated carbonation, chloride resistance and expansion induced by alkali silica reaction. Test methods used were New Zealand standards for the primary control tests and overseas standards for specialist and durability techniques.

Findings from this research showed that predictions of strength performance of SCM concrete could be significantly improved using either modified strength activity testing, isothermal calorimetry or bound water from thermo-gravimetric analysis. Compressive strength development of SCM concrete was generally slower compared with control concrete containing 100% Portland cement as binder. Durability performance of concrete made with these SCMs is also presented including properties such as chloride resistance, carbonation, alkali silica reaction, permeability, electrical resistivity and porosity. Concrete containing natural pozzolans or calcined clay showed reasonable strength performance and good durability potential comparable with established SCMs such as fly ash and slag.

This research showed promising durability performance such that concrete made with more reactive SCMs (e.g. fly ash, pozzolana, calcined clay and silica fume) had consistently lower porosity and permeability and improved resistivity and chloride resistance. All SCMs showed a beneficial effect in reducing expansion associated with alkali silica reaction although some materials were more effective than others in the longer-term. SCM concretes did however have poorer carbonation resistance when compared with control concrete particularly when wet curing was limited to three days.

Findings from this SCM research show that replacement of 30% Portland cement with SCMs was able to achieve reasonable strengths and superior durability properties in some cases. Finer SCMs such as calcined clay and silica fume were found to be most effective in concrete with lower water/binder ratios that achieve higher compressive strength. Fly ash in concrete was more effective in lower strength grades since workability was not negatively affected by water demand issues. The use of SCMs in concrete at 30% replacement of Portland cement was calculated to have the potential of reducing embodied carbon by as much as 20% in several cases.

TABLE OF CONTENTS

1.0 INTRODUCTION

This research was undertaken to identify ways of reducing barriers and risks in using significant levels of supplementary cementitious materials (SCMs) in concrete production within New Zealand. Use of these binders is seen as a medium-term solution for reducing carbon emissions associated with Portland cement. SCMs included in this investigation are industrial and natural pozzolans and latent hydraulic binders.

New Zealand has seen a 15% reduction in carbon emissions associated with Portland cement production and consumption since 2005 despite concrete production increasing by 13% during the same period. This has been achieved by better process efficiencies during cement production and replacing less efficient cement operations. Further reductions in carbon emissions are required by 2030 and this will need to be driven by more widespread use on SCMs in concrete. The clinker factor in New Zealand is still relatively high compared with OECD countries partly due to the limited availability of industrial wastes such as fly ash, slag or silica fume.

Identifying barriers to higher utilisation of SCMs in concrete needs to consider economic, logistic, regulatory and technical factors. This research focuses on technical barriers, which can be significant given the conservative nature of design and construction. Three main technical issues need to be addressed; classification of SCM reactivity, structural and durability performance.

The value of this research is that it allows performance and comparison to be made of concrete mixes made using local materials and testing standards. The research programme also needs to be sufficiently broad that potential SCMs can be compared with traditional materials such as fly ash, slag or silica fume. Additionally, comparative testing across different methodologies can allow the reliability of different test methods to be assessed.

1.1 Research relevance

A general hypothesis for this research was that it should be possible to identify or develop a classification system that is able to predict the hardened performance of concrete containing SCMs. Optimum use of SCMs in concrete will encourage greater utilisation of these materials in concrete and help in lowering carbon emissions.

2.0 LITERATURE REVIEW

2.1 Background and motivation

Literature reviewed was limited to blended cements with Portland cement (PC) and alternative binder technology such as calcium sulphate or magnesium cements were not considered. These alternative binders have the potential to significantly lower carbon emissions but are many years away from commercialisation and therefore cannot provide a solution in the short to medium-term. Focusing of SCMs that can reduce PC consumption represents a pragmatic approach to addressing the sustainability of concrete. Adoption of significant levels of SCMs in concrete has been achieved in some countries but guidance based on conservative principles is required to achieve similar benefits in New Zealand.

2.2 Potential for sustainability of concrete in New Zealand

Cement-based materials are important for the built environment, especially for infrastructure and development. While the world's population has almost tripled in the last 75 years, PC production has increased 35 times to almost 4000 Mt/year [1]. Concrete has low embodied energy, but the massive scale of production means the sector is a large consumer of natural resources and has the second largest share of global industrial CO_2 emissions after the energy industry [2,3]. Relative global CO_2 emissions from concrete have risen from 2% in 1930 to 8% in 2014, although this does include emissions from reinforcing steel, aggregates and transport [4]. Emissions directly from PC production are projected to increase by 17% by 2050 if current trends continue whereas a reduction of 24% is required to meet the United Nations target of limiting the rise in global temperatures to below 1.5 ^{0}C [5].

In New Zealand, an independent analysis by Thinkstep-ANZ showed there has been a 15% reduction in carbon emissions associated with PC production since 2005 despite concrete production increasing by 13% during the same period [6]. This has been achieved by better process efficiencies at existing cement factories and by replacing older and less efficient production facilities. Kiln burning efficiency at local cement factories has been achieved by utilising waste materials such as biomass and tyres that reduce coal consumption and by adopting advanced process control measures. Increased utilisation of SCMs in concrete has only resulted in a comparatively low reduction in carbon emissions with current replacement levels being below 10%. The relatively high clinker factor (percentage of clinker in cement) in New Zealand is primarily due to the relatively low industrial base of the country, with SCMs from waste materials such as fly ash, slag or silica fume being either limited or not locally available due to an absence of associated industrial production [7].

Combining current good practices in cement kiln efficiency and process control with increased use of SCMs could reduce NZ carbon emission by a further 15% by 2030. Achieving this target will require a better understanding of how industrial and natural SCMs can be best utilised in concrete construction. Carbon emissions are relatively simple to measure given the manner of production of cement so can be tracked reliably [8].

2.3 Supplementary Cementitious Materials (SCMs)

SCMs are either sourced from industrial wastes such as pulverised fuel (PFA) or called fly ash, ground granulated blast-furnace slag (GGBS) and silica fume or from natural materials that are beneficiated into pozzolans such as pumicite, micro-silica, diatomite and calcined clays such as metakaolin [9,10]. SCMs have diverse chemical and physical properties that affects their reactivity and interaction with PC [11]. This means that these SCMs have differing optimum replacement levels such that GGBS may replace up to 70% of PC while fly ash is commonly used at 30% replacement. Silica fume/microsilica has high reactivity but due to its negative effect on workability of fresh concrete is rarely used at more than 10% replacement [12].

2.3.1 Industrial SCMs

SCMs made from industrial waste such as fly ash, GGBS or silica fume are widely used in countries with a strong industrial base where these waste materials are generated [9]. These materials have been used in concrete for more than 50 years and performance of blended cements in concrete is well understood although characterisation techniques are still improving as discussed in Section 4 of this report. A summary of the main types of industrial SCMs is given in Table 1 below.

Table 1: Main industrial SCMs used in concrete construction internationally

SCM name/s	Source of waste	Processing	Typical replacement level
Blast-furnace slag (GGBS)	Steel making	Ground	50-75%
Fly ash (PFA)	Coal fired power stations	Electrostatically sorted	20-35%
Silica fume (micro-silica)	Ferrosilicon industry	Sorted and densified	7-10%
Rice husk ash	Rice processing	Ground	20-30%

High quality wastes such as GGBS have 90% utilisation in concrete with associated global consumption of 330 Mt/y, which represents 7% of PC production internationally [1,13]. The quality of fly ash is more variable with currently only 30% being utilised in concrete at 300 Mt/y [1,14]. Higher levels of consumption are possible with older coal fired power stations being replaced with more modern plants burning cleaner and producing fly ash with more consistent quality. The availability of fly ash is likely to diminish in the longer-term as energy production moves to renewable sources. Silica fume is a by-product of the ferrosilicon industry with 65% utilisation of the 1.5 Mt/y produced annually [1]. This material is mostly used in niche applications where high strength and/or durability is essential for concrete structures [15].

These three industrial SCMs represent the bulk of cement replacement but are quite diverse in chemical and physical properties. These differences in reactivity mean that replacement levels and their effect on the fresh and hardened properties of concrete vary quite significantly. New Zealand sources of industrial SCMs are limited due to the low industrial base of the country with only one coal fired power station (Huntly) that produces a limited amount of fly ash and one steel manufacturing plant (Glenbrook) whose slag is unsuitable for use as GGBS. No silica fume is produced locally at present but a high quality amorphous silica was previously supplied by Microsilica NZ [17].

2.3.2 Calcined clays

Recently, it has been shown that by making a coupled substitution of clinker with calcined clay and limestone (LC^3) at a ratio of 2:1, mechanical performance similar to that with PC concrete is obtained at a clinker factor of 0.4 to 0.6 [18]. This is because the aluminate of the calcined clay reacts with the carbonate present in the limestone to form carboaluminate phases, which produces a hardened microstructure similar with that of calcium silicate hydrate. Promising research from Europe shows that even at a 50% replacement level, strength equivalent to PC is obtained at 28 days [19]. As opposed to fly ash concrete, the compressive strength of LC^3 concrete is similar to that of PC concrete at all the ages, implying faster rate of strength development. Considerable research has been reported for LC^3 cement using low purity clays, which makes the material cost-effective [20].

Alongside the mechanical and fresh properties, the durability of LC^3 systems has also been investigated. LC^3 concrete has shown to have exceptionally high surface resistivity, which reduces corrosion rates in reinforced concrete [19]. Moreover, the alumina present in the clay helps in binding more chloride as compared to PC, which could further assist in improving overall durability of the concrete. The oxygen permeability index, which is a measure of pore connectivity and tortuosity, shows values similar with PC and fly ash mixes, implying it will provide similar resistance to ion ingress at a much lower clinker factor [19].

2.3.3 Natural pozzolans

Natural pozzolans are primarily alumino-silicates or amorphous silica that react with hydroxyl ions in concrete to produce secondary pozzolanic reactions. These are generally mildly reactive amorphous materials associated with volcanic regions of the world. International utilisation is only 75 Mt/y and applications are mostly limited to used in Southern Europe, South America and East Africa [9,21]. The reactive phases are volcanic glasses and zeolites and suitable deposits need to have low contamination of unreactive materials such as clay, feldspar and quartz. Moreover many volcanic glasses are associated with relatively high water contents, which needs to be removed during processing [22].

Four main types of natural pozzolan may be classified when considering their application in concrete [23]:

- Volcanic glass deposits of pyroclastic origin that includes non-consolidated volcanic ash and pumice with variable pozzolanic activity depending on their siliceous content and fineness (e.g. pumice and volcanic ash)
- Amorphous silica from either biogenic or hydrothermal activity that form relatively soft clastic rock types such as diatomite or amorphous silica deposits (e.g. diatomaceous earth and amorphous silica)
- Zeolites produced by lithification of volcanic glass deposits that are partially transformed from amorphous to crystalline but still retains pozzolanic activity due to their microporous nature (e.g. tuffs and ignimbrite)
- Clay minerals such as bentonite or kaolinite that are very mildly reactive but can be made significantly more reactive when calcined at 700-800 ^{0}C (e.g. metakaolin)

As with industrial SCMs, the reactivity of natural pozzolans is primarily dependent on the mineralogy and physical properties of these materials [23]. Some natural pozzolans are more reactive when finely ground such as amorphous silica and metakaolin and are used at low replacement levels of 10% or less whereas moderately reactive pozzolans such as volcanic glasses are used at higher replacement levels of 20-30%. Predicting the reactivity of pozzolanic materials is more complicated than with industrial SCMs such as fly ash or silica fume, which are relatively pure and have low porosity. This means that industrial pozzolans, in contrast with industrial pozzolans, are characterised by low absorption of water, which makes water requirements easy to control in pastes and mortars used to measure pozzolanic reactivity.

The geology of New Zealand provides significant resources of natural pozzolans and clay minerals, including [24]:

- Pumice deposits that can be ground to form pumicite that has been shown to have similar reactivity to that of fly ash
- Amorphous silica in the Rotorua region that have in the past been able to provide very high reactivity similar to that of silica fume
- Tuff and ignimbrite resources that are widespread and have reasonable reactivity as SCMs by being partially amorphous and microporous
- Kaolin deposits that when contaminated with iron and/or magnesium cannot be used as pigments and fillers but could theoretically be activated at moderate temperatures (e.g. 700 ^{0}C) to form metakaolin
- Other reactive silica sources such as diatomaceous earth that have shown promise when tested in the 1980's and 1990's but may be difficult to extract due to concerns about silica dust

The geological resources of New Zealand were well documented 60 years ago by DSIR, in university theses and other geological reports. Kennerley and Clelland from NZ DSIR investigated a wide range of natural pozzolans including rhyolite, pumicite, ignimbrite, andesite tuff and basaltic tuff in the 1950's [25]. Testing included petrographic examination, chemical analysis, and mortar and concrete tests of blends of cement and pozzolan. Findings from the PC-pozzolan blends showed several trends that are consistent with modern understanding of pozzolanic materials. Reactivity of pozzolans was found to increase with increasing fineness, glass content and thermal activation.

Pumicite was found to produce relatively promising results in terms of strength development when ground to a high surface area of above 4000 cm^2/g, which is shown in Figure 1. Similar findings were reported by South and Mason who investigated pumicites made from New Zealand pumic deposits and found equivalent strength to PC concrete after 90 days but early-age strength development was slower than PC concrete [21,26].

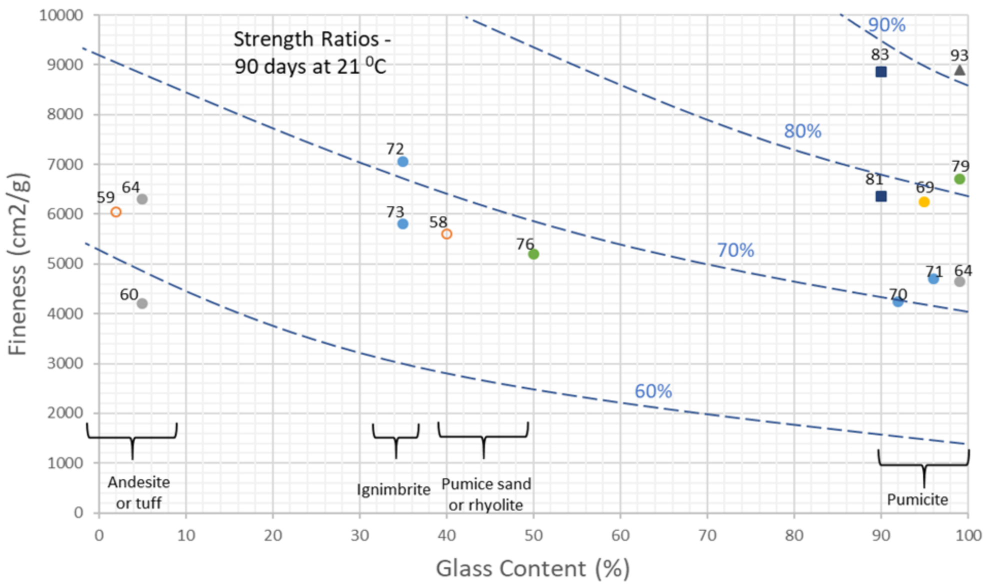

Figure 1: Strength ratio of mortar samples made with 35% replacement of natural pozzolans [25,27]

2.3.4 SCM research trends

The development of industrial SCMs has been achieved over the last 50 years with ground-granulated slag (GGBS) first developed followed by fly ash and then silica fume. Knowledge of these materials is now fairly mature and this has led to increased utilisation in locations where these SCMs are available. Many textbooks and state of the art reports provide excellent resources on these materials [11,23,28]. Significant ongoing research is being undertaken on these SCMs that includes:

- Special applications using these SCMs such as self-compacting, tremie and high strength concrete [29,30]
- Activation of less reactive SCMs such as fly ash using chemical activators or by physical adjustment [31,32,33]
- Durability and sustainability advantages using different combinations of SCMs [34,35]
- Review of the current classification methodology used to assess the reactivity of industrial pozzolans
- Performance of ternary blends containing PC with two SCMs to improve sustainability and properties

Natural pozzolans have be researched over as long a period as industrial SCMs and have been utilised for thousands of years. Early research interest in natural pozzolans waned with the advent and widespread use of industrial SCMs but there has been renewed interest in recent years, most notably in Europe. A motivation for the renewed interest in natural pozzolans has been the concerns about the long-term sense of relying on industrial SCMs, which are likely to reduce in the future. Recent research on natural pozzolans has focused on the following aspects:

- Investigations of alternative natural pozzolans that have until now not received much research attention such as perlite and calcined clays [36,37]
- Experimental investigation of alternative processing such better mechanical milling of raw materials used as natural pozzolans [38]
- Criticism of current classification techniques used to predict SCM reactivity that are seen to discriminate against natural pozzolans and may also not accurately predict concrete performance [39,40,41]

2.4 Characterisation of SCMs

The quality of PC is typically characterised primarily by the strength performance of mortar or concrete samples made from the material. The chemical and physical properties of PC have a significant bearing on this hardened performance. Modern cements tend to fall within a narrow range of performance characterics and the cement hydration reaction is predictable and gives reliable and repeatable results. When SCMs are considered using a similar classification system, performance of concrete becomes more difficult to predict. Typical strength activity index (SAI) data is shown in Figure 2 across a range of replacement levels [54]. The poorer correlation between SAI test data and concrete strength for SCM concrete is due to the following [40]:

- PC has consistent density values whereas SCMs may be considerably lighter than cement such that replacement levels cannot be made based on weight but should be by volume
- Classification tests are generally done on mortar mixes where no chemical admixtures are used to compensate for the higher absorption of some pozzolanic materials, which leads to variable effective water/binder ratios during the test
- The testing age is typically at 28 days or less which tends to favour more reactive SCMs and which often means that natural pozzolans are excluded on the basis of their comparatively slower strength development

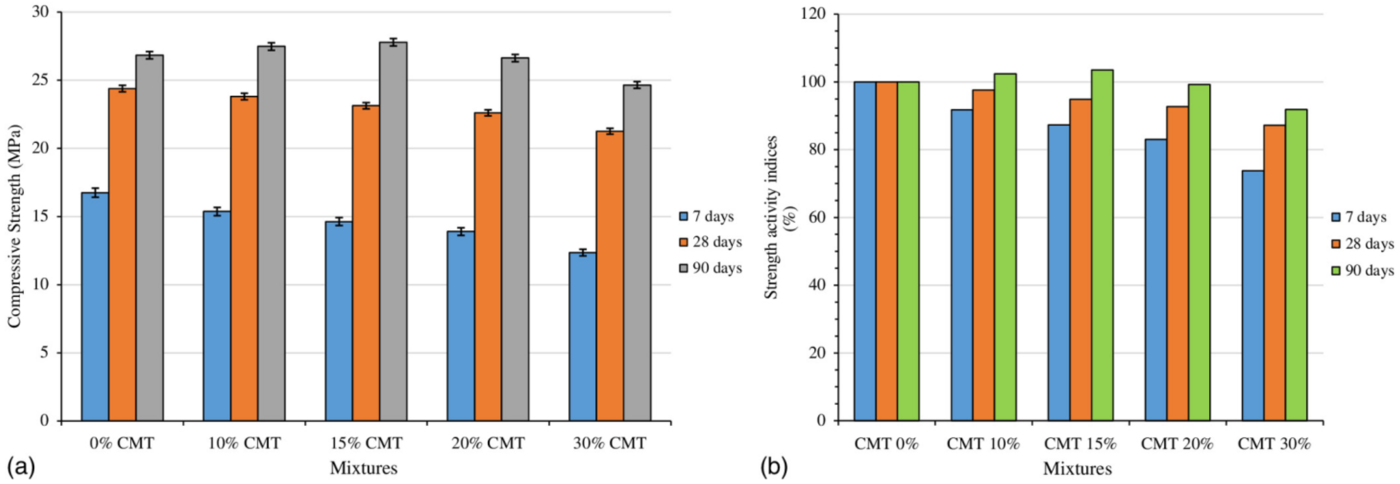

Figure 2: Typical strength activity test data from ASTM C311 – Copper mine tailings (54)

There is considerable debate in the research community about current classification methods such as those quoted in standards such as NZS3122 and ASTM C618 [42,43]. These testing methodologies are generally reliable for industrial SCMs but could be an obstacle for more widespread adoption of new materials and may even unfairly discriminate against some natural pozzolans.

2.4.1 Current classification methods for SCMs

Most cementitious materials are initially assessed based on the inherent chemical and physical properties since these materials properties directly affect the performance of hardened concrete. Industrial SCMs may be assessed in terms of the following general properties of the powder:

- Fly ash reactivity is dependent on glassy phases of SiO_2, Al_2O_3 and Fe_2O_3 with an additional contribution from CaO when using higher calcium fly ash
- Silica fume is a highly reactive amorphous silica where SiO_2 content is usually above 90%
- Blast-furnace slag is a latent hydraulic binder where reactivity increases with increasing CaO, MgO and Al_2O_3 concentrations but decreases with increasing SiO_2 content

Natural pozzolans in contrast to the above consist of a wide range of chemical and physical compositions such that its reactivity cannot be broadly predicted without considering specific categories.

Characterisation of the reactivity of SCMs is done with laboratory techniques that have been developed decades ago but these are increasingly being criticised for being unable to accurately predict the properties and performance of hardened concrete. ASTM C618 specifies chemical and physical requirements for industrial and natural pozzolans [43]. Pozzolanic activity is identified by the minimum sum of SiO_2, Fe_2O_3 and Al_2O_3 despite it being known that reactivity is dependent on mineralogy rather than chemistry. The strength activity index specified in ASTM C311 is also used to assess pozzolanic activity and consists of testing mortar samples with 20% pozzolan replacement by mass regardless or density differences [44]. The reactivity is defined as being suitable when a strength is obtained which corresponds to at least 75% of the strength of control concrete made with 100% PC.

EN 196-5 uses the Fratinni test to assess the reactivity of SCMs were 25% pozzolan and 75% PC (CEM-I) are hydrated in distilled water and the lime consumption and hydroxyl ion concentration are measured after 8 days at a temperature of 40 ^{0}C [45]. The pozzolan is then considered to be reactive or not depending on whether the result plots below the lime solubility curve given in the standard. Such chemical tests cannot measure performance but are simply screening tests for non-reactive materials.

The Chapelle test is a more rapid version of the Fratinni test where 3g of CaO and 1g of pozzolan are reacted in distilled water at 90 ^{0}C for 16 hours [46]. Lime consumption is then measured and compared with a control sample of pure CaO. Some standards specify a minimum amount of lime that should be consumed in the reaction, which is typically 66% of the weight of pozzolan.

NZS 3123:2009 provides guidance on assessing the relative strength of blends of PC and SCMs such as fly ash and slag [47]. The New Zealand standard references AS 3583.6:2018 for this testing make special allowance for fly ash or slag in terms of density and typical replacement levels (e.g. 30% or 50%) [48]. Table 1 in AS 3583.6 makes mortar mix proportions fairer for these materials by allowing to differing densities. Unfortunately, neither standard makes the same allowance for natural pozzolans and when assessing these materials, the standard provisions in ASTM C311 apply (20% replacement of Portland cement with pozzolan but with no allowance for differences in densities).

2.4.2 Alternative classification methods for SCMs

New characterisation techniques are currently being developed and several methods show promise and would allow future alternative binder systems to be more objectively quantified. Development of better characterisation methods for SCMs would be beneficial for both natural pozzolans and industrial SCMs and help prevent PC substitution with inferior materials. The following methodologies have been proposed to replace current methods used to characterise the reactivity of pozzolans.

The modified strength activity index (SAI) is based on testing mortars with constant water/binder ratio and adjusting the workability using chemical admixtures [39,40]. Fairer comparison also requires compensation for the lower density of pozzolans compared with PC. Some recommendations also suggest the curing temperature should be 40 ^{0}C as this accelerates maturity and allows assessment of longer-term strength performance [39].

Calorimetry is an accurate method of quantifying cementitious reactions using thermodynamic principles rather than measuring strength. Isothermal calorimetry can measure heat flow in cementitious pastes during hardening and the heat evolution provides an accurate measure of strength development as shown in Figure 3 [41]. The technology is relatively new and associated equipment expensive to purchase. The application of this method is therefore currently mostly limited to research and higher-level quality control.

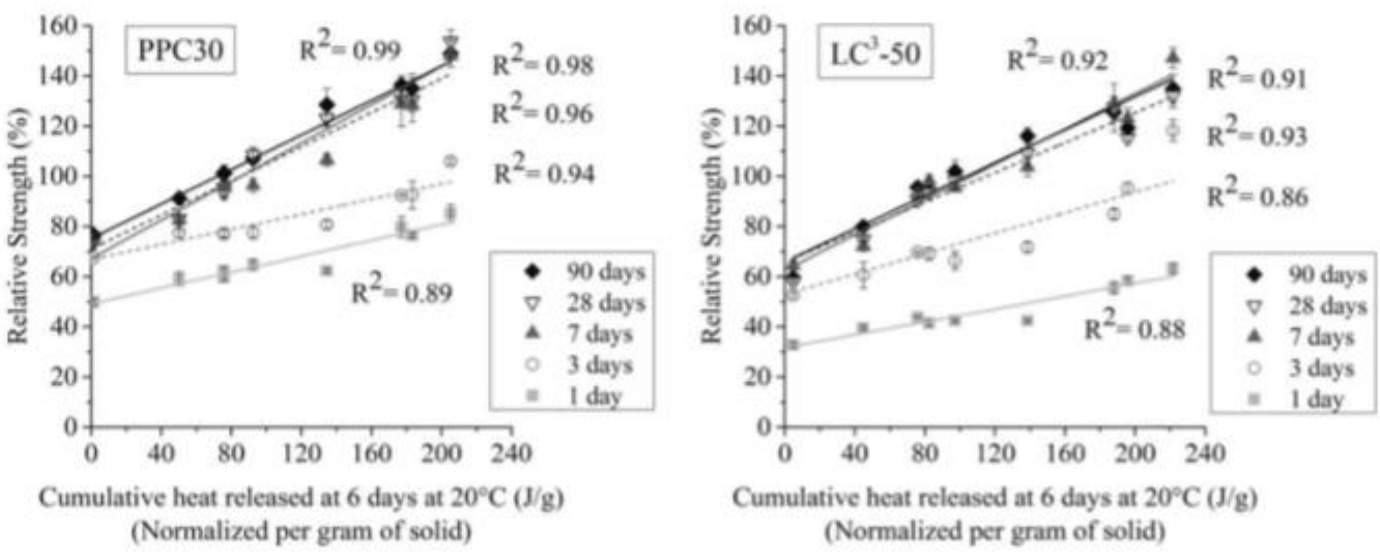

Figure 3: Correlation between relative mortar strength and cumulative heat at 20 ^{0}C by isothermal calorimetry [41]

Determining the bound water content of cementitious paste is relatively easy to conduct by weight loss across a defined temperature limits of 110 to 400 ^{0}C. Bound water found in hydration products has been shown to be an accurate measure of microstructural development [41]. Reactivity of pozzolans blends can therefore be quickly assessed in terms of bound water percentage, which in turn is correlates well with strength of concrete made with the same materials.

2.4.3 Proposed methodology for standards revision

Changing existing classification systems that are used to infer reactivity of pozzolans can only be considered when systematic investigations are reviewed that consider the following:

- Full characterisation of a range of PC blends using proposed testing methodology
- Optimised concrete mixes for the trialled materials being reviewed
- Measurement of fresh and hardened concrete performance of structural concrete

This approach was undertaken by Kasaniya et al who showed that a strength activity test could be improved to assess natural pozzolans more reliably [39]. Similarly, Pourkhorshidi et al were critical of standard methods such as ASTM C311 and recommended that any physical test for reactivity must be conducted at constant water/binder ratio [40]. A new methodology was recommended by Avet et al that consisted of microstructural assessment using bound water and this was found to be a reliable predictor for concrete made with calcined clay [41].

Research is needed to assess these modified and new testing methods for New Zealand cementitious materials and results of these will provide valuable insights for the relevant standards committee. Given the conservative nature of standards review it is likely that the strength activity index test will be retained is some modified form.

2.5 Concrete performance with SCMs

The fresh, hardened and durability performance of concrete made with SCMs is well known with many years of research and field data. Some newer materials such as natural pozzolans have less of a track record and locally produced materials would need some testing to confirm that the performance is consistent with international studies. Much of this development can easily be done by cement companies except for durability studies such as chloride or carbonation resistance and alkali silica reaction that are best done in specialist research laboratories. The general performance characteristics of concrete are often inferred from more widely known properties such as slump and compressive strength. The causes and interactions affecting concrete are quite complex as shown in Figure 4 for fresh concrete properties [49].

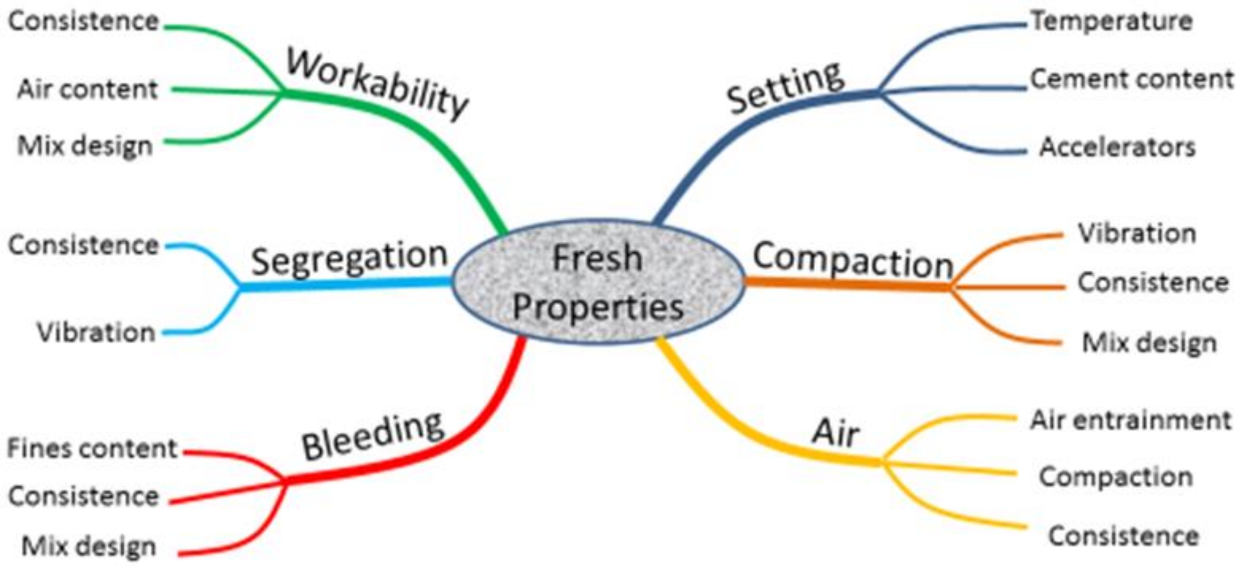

Figure 4: Map showing fresh properties of concrete and influences [49]

2.5.1 Fresh properties of SCM concrete

While it is true that the fresh properties of concrete can be easily adjusted by using chemical admixtures, the addition of finer SCMs into concrete may have significant effect that requires some adjustments when handling concrete containing these materials. Some notable differences that are commonly found with concrete containing SCMs include the following [22]:

- Water requirements may vary with materials such as fly ash generally reducing water demand while some natural pozzolans potentially may increase the amount of water to achieve equivalent workability
- Extra fines in concrete generally reduces the amount of bleed water, which means that the concrete may be more vulnerable to plastic shrinkage
- Workability of concrete is generally improved with the addition of SCMs when concrete mixes are correctly designed, which is most notable when using powders with rounded particles such as fly ash
- Air contents of air entrained concrete may require more monitoring when using SCMs since these materials often contain carbon and if porous will absorb some admixture
- Replacement of PC with significant amounts of SCM will affect the setting time of concrete and some adjustment may be required using chemical admixtures that accelerate cement hydration

The above changes to the fresh properties of concrete can be mitigated by appropriate concrete mix design adjustments but optimised performance does require trialling by experienced engineers and technicians. Adoption of new cements and binders is challenging if changes are made without appropriate preparation and monitoring of performance in construction.

2.5.2 Mechanical properties of SCM concrete

Mechanical properties of concrete include compressive and tensile strength, elastic modulus, drying shrinkage and creep. These properties are important in the structural design of concrete structures but typically only compressive strength is measured while the other properties are inferred. The assumption that compressive strength is a reliable predictor of mechanical properties of concrete is reasonable to assume for normal replacement levels of SCMs [11]. This is due to secondary cementing reactions from SCMs producing similar calcium silicate hydrates to those produced by PC hydration. While the final hardened products are similar, strength development of SCM concrete may be significantly slower and longer compared to similar PC concrete as shown in Figure 5 [50].

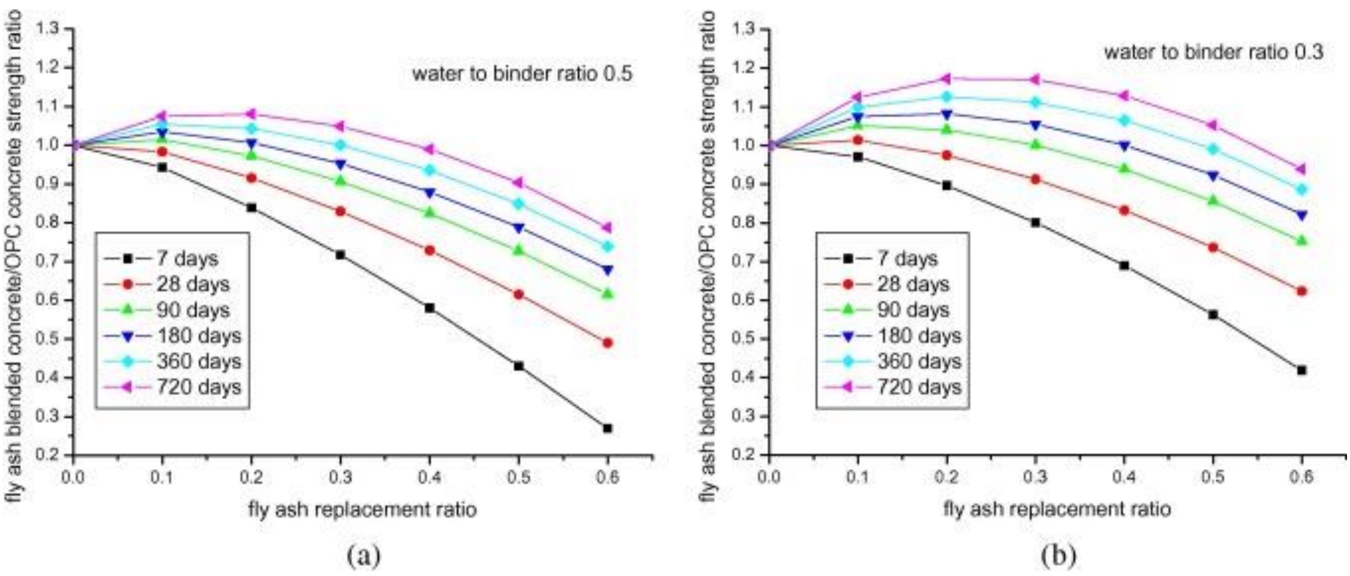

Figure 5: Strength development of fly ash concrete at different replacement levels and ages [50]

Strength development of SCM concrete depends on the type and blend of binders used in the concrete such that:

- Some slag blends with even 50% replacement of PC may show only a slight reduction in early age strengths but similar long-term strengths compared to PC
- Replacement of 8% PC with silica fume may show a marginal reduction in strength at early ages (e.g. 3-7 days) but higher strength at 28 days and later ages
- Replacement of 30% PC with SCMs such as fly ash will result in concrete with significantly lower early age strength but similar long-term strengths (e.g. 91 days)

The slower strength development of concrete made with pozzolans such as fly ash or pumicite is due to the lower reactivity of these materials compared to PC. While most concrete structures are only expected to go into service several months after construction, slower strength development may have cost implications. This can be due to extra curing times, delayed demoulding and de-propping and overall slower speed of construction at higher SCM replacement levels. Some compensation for this slower strength development can be made by using special chemical admixtures, chemical or thermal activators or simply by using more binder overall [27].

2.5.3 Durability of SCM concrete

Concrete durability can be significantly enhanced by using SCMs in concrete such that in New Zealand these materials are mandatory when designing concrete structures exposed to severe exposure conditions such as marine conditions that can cause chloride-induced corrosion of embedded steel reinforcement. Known benefits of SCM concrete when designing for durability include the following [23]:

- Improvement in the chloride ingress resistance of concrete by pore refinement and chemical binding of chloride ions by aluminate phases [55]
- Reduction in the risk of expansion and cracking of concrete from alkali silica reaction where alkali ions (e.g. sodium and potassium) from cement react with glassy silica phases found in some aggregates [11]
- Reduction in the risk of cracking related to heat of hydration associated with large volumes of concrete since SCMs moderate internal heat build-up [10]
- Improvement in the protection of concrete exposed to aggressive waters containing acids and/or sulphates by improved waterproofing and improved microstructure [13]

These durability advantages of SCM concrete may be achieved when the material is mature after good construction practice that includes good compaction and curing. This full durability potential may however not be achieved in some cases that include [51]:

- Some highly technical concrete mixes containing SCMs may have poor workability and this can make compaction challenging, potentially resulting in higher than intended porosity
- The lower bleed rate and extended setting time of some SCM concretes may make the material more vulnerable to plastic shrinkage cracking
- Slower strength development of SCM concrete may require extended periods of curing to ensure that drying of the cover concrete does not compromise durability potential

These negative issues associated with SCM concrete can be overcome with experience and following guidelines for good construction practice. Many countries have years of experience using SCM concrete and these differences no longer represent a significant challenge to achieving durable concrete on site. Optimisation of concrete mix designs can also mitigate many of the above technical issues.

3.0 EXPERIMENTAL PROGRAMME

3.1 Introduction

Based on the literature review, an experimental programme was proposed in 2020 to assess how locally available SCMs can be best classified and utilised in concrete production around New Zealand. This proposed research consists of the following components:

- Identify a range of suitable local pozzolans (e.g. perlite, ignimbrite, calcined clay and amorphous silica) to be compared with industrial SCMs such as fly ash and silica fume
- Classification of SCMs using existing and proposed techniques together with full characterisation testing of materials (e.g. XRF, XRD, SEM, fineness, SAI, calorimetry, TGA and microstructural assessment) [12, 47]
- Trialling and optimisation will be essential to ensure materials are used in a beneficial manner and that concrete mixes are consistent with industry norms and practice
- Fresh concrete properties while only transitory are essential to ensure that the material can be produced in a practical manner without impacting significantly on productivity or risking the hardened properties of concrete (consistence, rheology, bleed, setting) [56]
- Hardened properties of concrete such as strength and durability are important for structural design and performance needs to be compared with initial classification of SCMs (e.g. compressive strength development, porosity, permeability chloride resistance, carbonation and alkali silica reaction) [56, 57, 58, 59 & 60]

Results from the experimental programme will allow an independent assessment of international recommendations found in this literature review and provide confidence in the suitability of SCM sources both locally and imported. Recommendations can then be made for design, specification, testing and production of SCM concrete in New Zealand concrete construction.

This type of practical testing may also assist with assessing additional technical issues that also sometimes become important in terms of concrete performance. These include issues such as workability, surface finish, colour variations and other aesthetic considerations that affect market acceptance.

3.2 Materials and mix designs

A wide range of Portland cements and SCMs were investigated as part of this experimental research. These materials were first analysed in terms of chemical and physical properties before being assessed using paste, mortar and concrete mixes.

3.2.1 Materials

Materials used in the experimental research included the following (refer also to Appendix A for detailed analysis of these materials):

Four different Portland cements (PC) were used and came from Golden Bay Cement (ex. Whangarei) and Holcim Cement (ex. Japan and Vietnam). The use of HE cement was to investigate if a more finely ground cement would provide some advantage when considering the strength development of SCM concrete mixes. Details of the PC used in the research are shown below:

- General purpose (type GP) Portland cement (S1) – GBC or Holcim
- High early strength (type HE) Portland cement (S8) – GBC or Holcim

Supplementary cementitious materials (SCMs) used included industrial and natural pozzolans together with a General blended (type GB) cement containing blast-furnace slag (denoted SD with 65% Pc and 35% slag). GP cement (S1) was of primary interest and was combined with the following SCMs:

- Fly ash (ex. Huntly, NZ) that was ASTM class C material (S2)
- Fly ash (ex. Adani, India) that was ASTM class F material (S3)
- Natural pozzolan consisting of ground ignimbite from NZ (S4)
- Natural pozzolan consisting of ground perlite powder from NZ (S5)
- Calcined clay from raw clay (ex. Geraldine, NZ) containing 55% kaolinite (S6)
- Condensed silica fume (ex. Sika, China) (S7)

Details on grading, XRF and XRD analysis of cementitious materials are given in Appendix A

Aggregates used in these laboratory trials were those typically found in Christchurch, New Zealand. Local material is a greywacke sandstone using either 13mm coarse aggregate and a natural sand with fineness modulus of 2.70 and fines content below 150 microns of 6%.

Chemical admixtures used in these laboratory trials were supplied by BASF/Masterbuilders and consisted of the following:

- MasterPolyheed 8840 water-reducing admixture
- MasterAir 905 air entraining agent

3.2.2 Concrete mix designs

A series of concrete mixes were designed to assess the performance of SCM concrete across a broad range of applications. Details of these concrete mixes are given in Appendix C and these are summarised below:

- Higher strength concrete mixes used to assess structural and durability performance
- Lower strength concrete mixes used to assess strength development and fresh properties
- High cementitious content used together with admixed sodium hydroxide for alkali silica reaction studies

Concrete mixes were designed to maintain constant total cementitious content and water/binder ratio and this was achieved by varying the admixture dosage in the concrete. Concrete was produced at consistence levels of 120 ± 30mm, which is the standard level of workability used in New Zealand concrete production.

Concrete specimens were kept at a temperature of 21±2 ^{0}C overnight after casting followed by curing in water at 21±2 ^{0}C until testing for most hardened properties. Concrete prisms used for accelerated carbonation testing were cured in water for either 3, 7 or 28 days followed by drying in air at 21 ^{0}C and 50% R.H. until exposure in the carbonation chamber.

4.0 CLASSIFICATION OF SCMS FOR CONCRETE

Characterising different methods of classifying SCMs was a key part of this SCM research programme. The current approach specified in NZS 3123 was compared with alternative methodologies used internationally either already in practice or proposed by researchers. The performance of the mortar and pastes in these initial experiments was compared with the strength of concrete made with the same materials.

4.1 Relative Strength (mortar w/b ratio varies)

NZS 3123 requires that relative water demand and strength methodology be used when assessing SCMs. Relative strength index is measured using AS3583.6, which is similar to ASTM C311 and specifies 20% replacement level of SCM. The correlation between mortar strengths from this test and concrete strengths is often poor due to:

- Differing water requirements of industrial and natural pozzolans that affect water demand and therefore strength (since water/binder ratio varies)
- Single replacement level of 20%, which is lower than those often used in concrete mixes (typically 25-30% replacement)
- Variable plastic viscosity of mortar due to the absence of admixtures that can influence the quality of compaction and therefore entrapped air levels due to relatively low consistence of mortar

The relative strength test is a basic screening test that is suitable for identifying poorly reactive pozzolanic materials or those materials that create excessive water demands. This can be seen in Appendix B where Table B2 shows the range of water demands and strengths achieved. Results of this research found the correlation between mortar and concrete strengths was poor when comparing a range of SCMs with no clear relationship, shown by a very low R^2-value. This was found even when using 56-day comparisons that are also included in the analysis shown in Figure 6 below (concrete strengths are given in section 5.1) and a nominal water/binder ratio of 0.45.

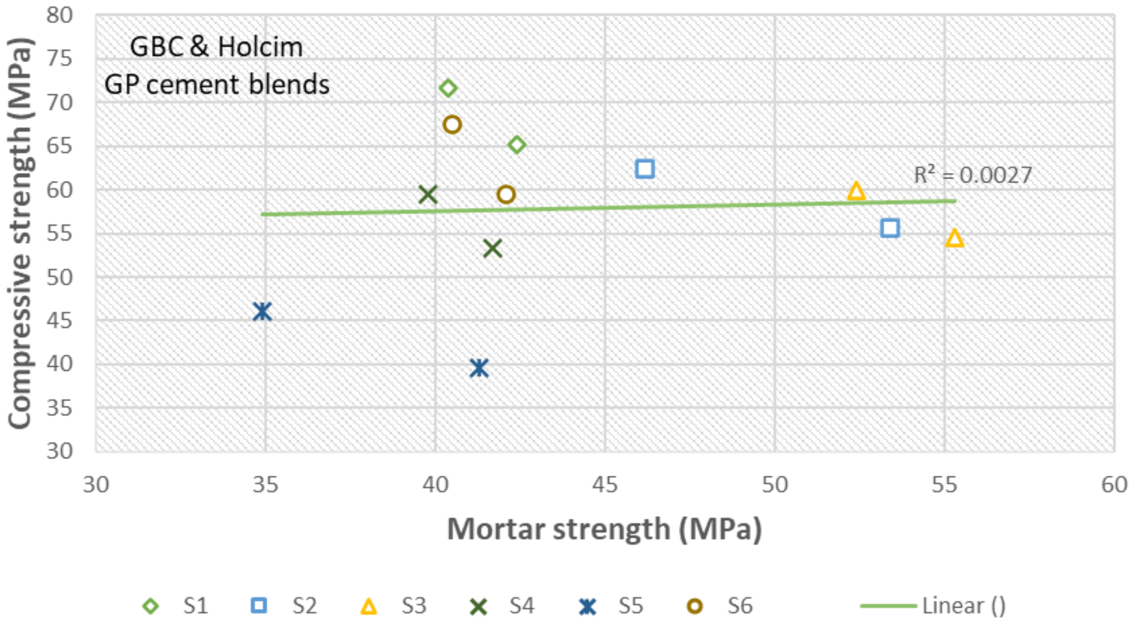

Figure 6: Comparison between mortar strength from AS3583.6 and concrete strengths at 28 and 56 days

Mortar strengths using AS3583.6 protocols were compromised in some cases by higher water demands of SCMs, notably natural pozzolans such as calcined clays. Industrial pozzolans such as fly ash typically have relative water requirements of less than 100%, which helps ensure better strength performance using this technique.

4.2 Modified strength activity index testing (mortar w/b = 0.50)

The modified strength activity index was done in accordance with EN 196-1 but using a water reducing admixture to achieve similar mortar consistence at a constant w/b ratio of 0.50. Mortar strengths with 30% replacement of SCMs at 7, 28 and 90 days were then compared with compressive strengths for concrete mixes with similar replacement and water/binder ratios of 0.45. Figure 7 shows the relationship between mortar and concrete strengths tested at 7, 28 & 90 days.

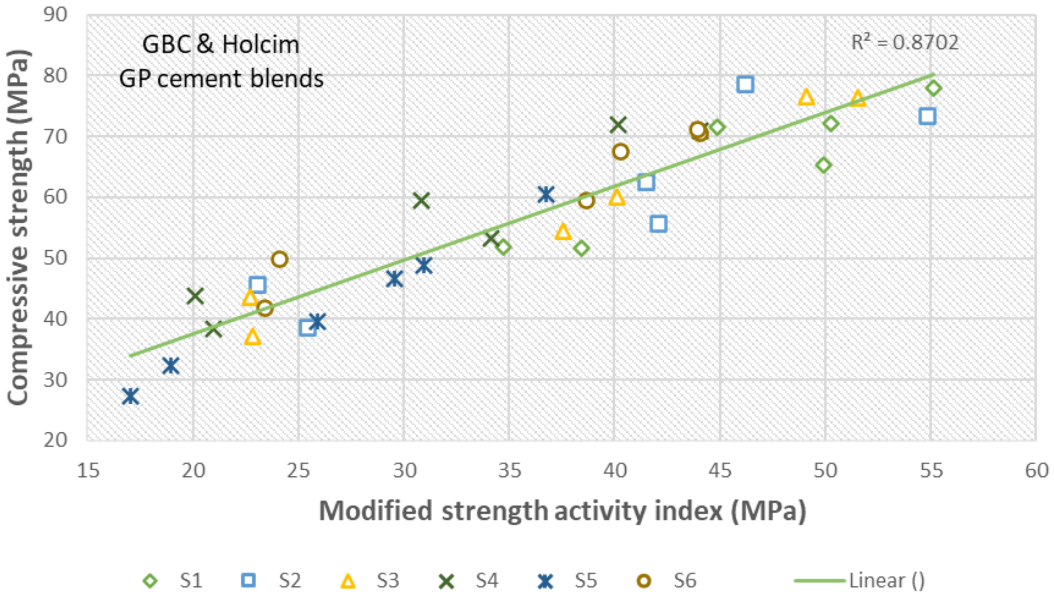

Figure 7: Compressive strength versus modified strength activity index at 7, 28 and 90 days

A better correlation between mortar and concrete strength was achieved by adjusting the dose of water reducing admixtures to maintain a constant water content. This adjustment of the mortar mixes is easy to do and is typically the approached used in practice when undertaking standard concrete mix design. Natural pozzolans typically have higher water demands than materials such as fly ash, and adjustment for this difference provides a fairer overall assessment of potential reactivity of pozzolans.

4.3 Isothermal calorimetry (paste w/b = 0.50)

Testing using isothermal calorimetry was done in accordance with ASTM C 1679 using small paste samples with a water/binder ratio of 0.50 and at 30% SCM replacement levels [62]. The isothermal calorimeter maintains constant temperature at 20 ^{0}C and measures the net energy and heat flow associated with cementing reactions. Figure 8 shows the relationship between isothermal energy and compressive strength of concrete after three and seven days.

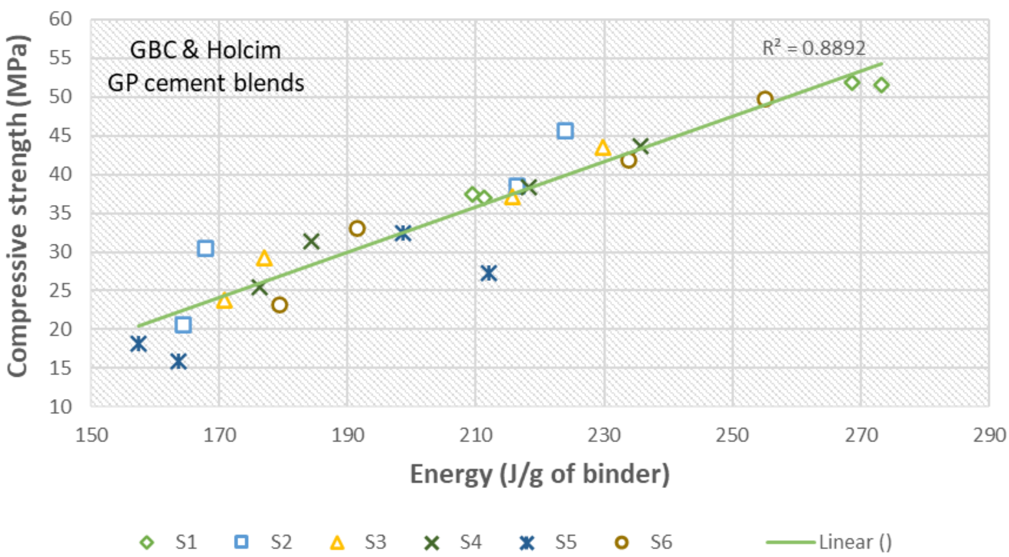

Figure 8: Compressive strength at 3 & 7 days versus isothermal energy

Using isothermal calorimetry on paste samples provides a reliable method of assessing the reactivity of pozzolans as shown by the good correlation between paste energy output and concrete strengths (e.g. R^2-value of 0.89). The methodology does require sophisticated testing equipment not available outside of specialist laboratories but is relatively quick to perform.

4.4 Bound water from thermogravimetric analysis (paste w/b = 0.50)

Hydration studies were undertaken on paste samples that were cured in water for periods of 3, 7, 28 and 90 days before being subject to thermogravimetric analysis (TGA). The bound water of hydration was determined from the mass difference found between 110 and 400 ^{0}C due to thermal desorption effects [41]. Figure 9 shows the relationship between the measured bound water and compressive strength on similar concrete at ages of 3, 7, 28 and 90 days. Note that TGA was only done for GBC GP cement blends due to limited resources and time available for this experimental work.

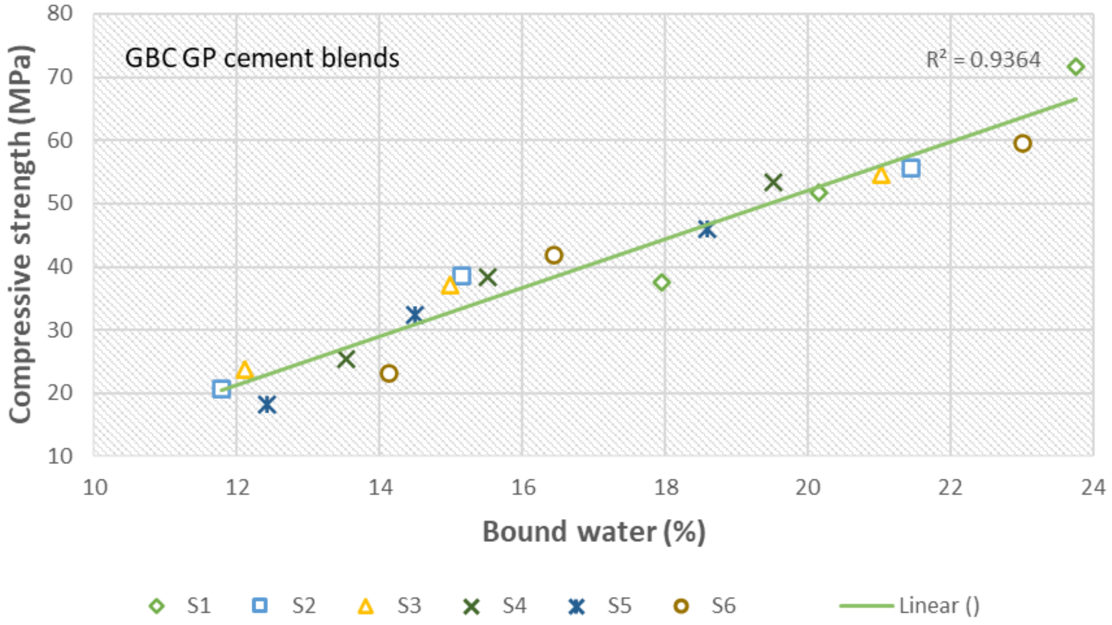

Figure 9: Compressive strength at 3, 7 & 28 days versus bound water percentage of paste

A good correlation was found between bound water content of SCM pastes and concrete strengths of similar binder systems when measured after 3, 7 & 28 days. Thermo-gravimetric analysis (TGA) does not require expensive equipment for testing and could be used to measure the potential performance of SCMs. This confirms that bound water is a useful technique for assessing the reactivity of SCMs and this could be run in scientific laboratories with moderate testing resources.

4.5 Summary of classifications systems for SCMs

The current classification system for SCMs in New Zealand is not able to accurately predict the reactivity of these materials in concrete. While techniques such as relative strength may be a useful screening test for industrial pozzolans such as fly ash, it is unreliable for natural pozzolans that exhibit higher water demands. Other classification techniques are far more reliable in predicting reactivity of SCMs.

The relative merits of the existing and alternative classification methods are summarised in Table 2 and should be considered in the future revision of NZS 3123.

Table 2: Comparison between classification systems for SCMs in concrete

Classification method	Standard or reference	Advantages	Limitations	Correlation with concrete strengths
Relative strength	AS 3583.6	Simple equipment well established	Water demand variable which affects w/b ratio	Poor (R^2 = 0.003)
Modified strength activity index	EN 196.1 (constant w/b)	Simple equipment easy adjustment	Require careful dosing & testing	Good (R^2 = 0.87)
Isothermal calorimetry	EN 196-8 2010	Quick and very accurate	Specialist test equipment – expensive	Good (R^2 = 0.89)
Bound water analysis	Avet et al [18]	Accurate and easy with correct gear	Specialist test gear – moderate costs	Very good (R^2 = 0.93)

5.0 FRESH PROPERTIES OF CONCRETE

A limited range of fresh properties were assessed during initial trials of different concrete mixes. Detailed test results are summarised in Appendix D. These properties were useful to include in this research as whilst the data is not comprehensive it highlights practical issues associated with using SCMs in concrete.

5.1 Workability of concrete

An assessment was made on the overall workability using subjective assessment and using the reverse slump methodology sometimes specified in Australia (using an inverted slump cone that is filled with concrete and lifted to assess if the material will flow under its own weight). Details of these estimates of workability are shown at the bottom of Tables C1, C2, C3 & C4 in Appendix C. These estimates of workability can be summarised as follows:

- Concrete made without SCMs (i.e. Portland cement only) had moderately good workability when visually assessed and using the reverse slump test
- Concrete made with fly ash was found to have good workability, being cohesive but without excessive plastic viscosity that allowed the concrete to slip through the inverted slump cone at a slump range of 120-150 mm
- Concrete made with natural pozzolans (e.g. S4, S5 & S6) was found to have higher plastic viscosity, which meant the concrete did not slip through the inverted slump cone even at slumps of 140 mm

Concrete mixes used in this study were not optimised for workability and so it is not surprising that those mixes requiring higher dosages of water-reducing admixture exhibited increased stickiness (e.g. higher apparent viscosity of the fresh concrete). None of the concrete mixes were significantly poor in terms of workability and mix optimisation should be able to resolve these issues.

5.2 Bleeding of concrete

A significant concern with SCM concrete is that the increased fineness of the binder will stifle bleeding of concrete and therefore increase the risk of plastic shrinkage cracking. Bleeding of lower strength concrete mixes (w/b ratio of 0.65) were assessed with full results shown in Appendix D. These lower strength concrete mixes are typically used in residential and commercial applications where poor protection during casting and finishing often results in plastic shrinkage cracking problems. A comparison of bleed rates and volumes is shown below in Figure 10 and can summarised as follows:

- Concrete made with General Purpose (GP) Portland cement had reasonably high levels of bleeding with bleed rates of greater than 0.5 $L/m^2/hr$ and bleed volumes of 9-10 L/m^3
- Concrete made with fly ash or perlite had moderate levels of bleeding that were typically about 75% of those for GP concrete (in terms of both bleed rate and bleed volume)
- Concrete made with High Early (HE) Portland cement of blends of GP cement and either calcined clay or silica fume had low bleed that was typically about 50% of GP concrete with respect to bleed rate and volume

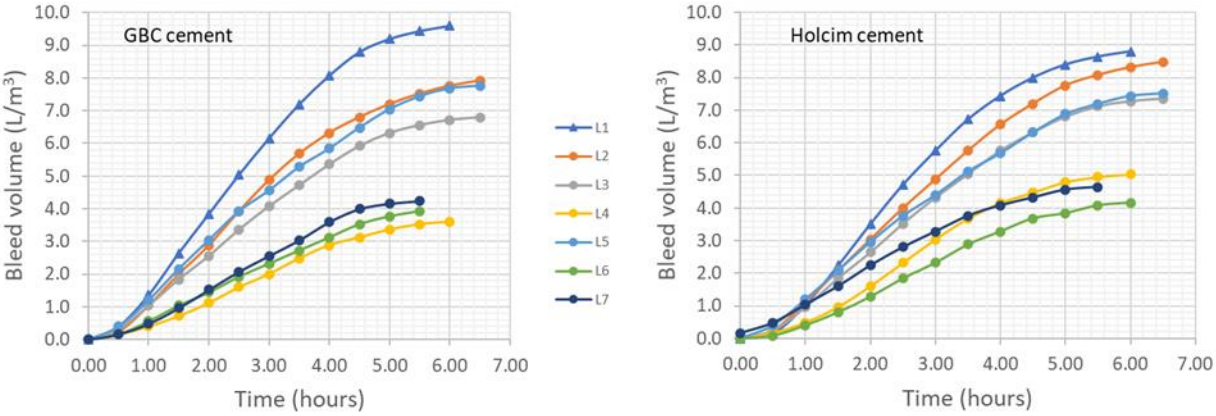

Figure 10: Cumulative bleeding of concrete for lower strength concrete mixes (w/b ratio of 0.65)

5.3 Plastic shrinkage cracking

A limited trial on plastic shrinkage cracking was undertaken using lower strength concrete mixes with water/binder ratio of 0.65. This testing was only run on lower strength mixes since these are more likely to be unprotected from rapid drying when used in residential and commercial applications. Plastic shrinkage cracking was assessed using a modified version of ASTM C1579 where the concrete surface was exposed to a fan blowing air across the surface that created an evaporation rate of approximately 0.50 L/m^2/hr (confirmed using a shallow water pan) and an estimated wind speed of 20 km/hour. Concrete mixes L1 (GP cement control) and L4 (GP pozzolana blend) were redesigned to provide a range of bleed volumes ranging from 5-9 L/m^3 for both control and SCM concretes.

From this limited study the risk of plastic cracking was found to be inversely proportional to the bleed rate of concrete rather than being primarily dependent on the concrete mix type. Plastic cracking risk was found to be relatively high when bleed rate was less than 50% of the evaporation rate (e.g. less than 0.25 L/m^2/hr).

6.0 STRENGTH OF CONCRETE

Compressive strength of concrete was tested in accordance with NZS 3112 Part 2 using 100x200 mm cylinders (see Appendix E for a full summary of strength results). Strength development was reported for periods of 3-180 days and SCM concrete compared against control mixes using either GP or HE cement (typically used for in situ or precast concrete in New Zealand). Testing after one day was dropped from this research due to resource issues and will be covered in a separate research project.

6.1 Higher strength concrete mixes

Strength development of concrete made with either GBC or Holcim cement are shown in Figure 11a and 11b. As expected control concrete containing either GP or HE cement gained strength more rapidly than SCM concrete and achieved better long-term strength compared to SCM concrete (except for concrete containing silica fume).

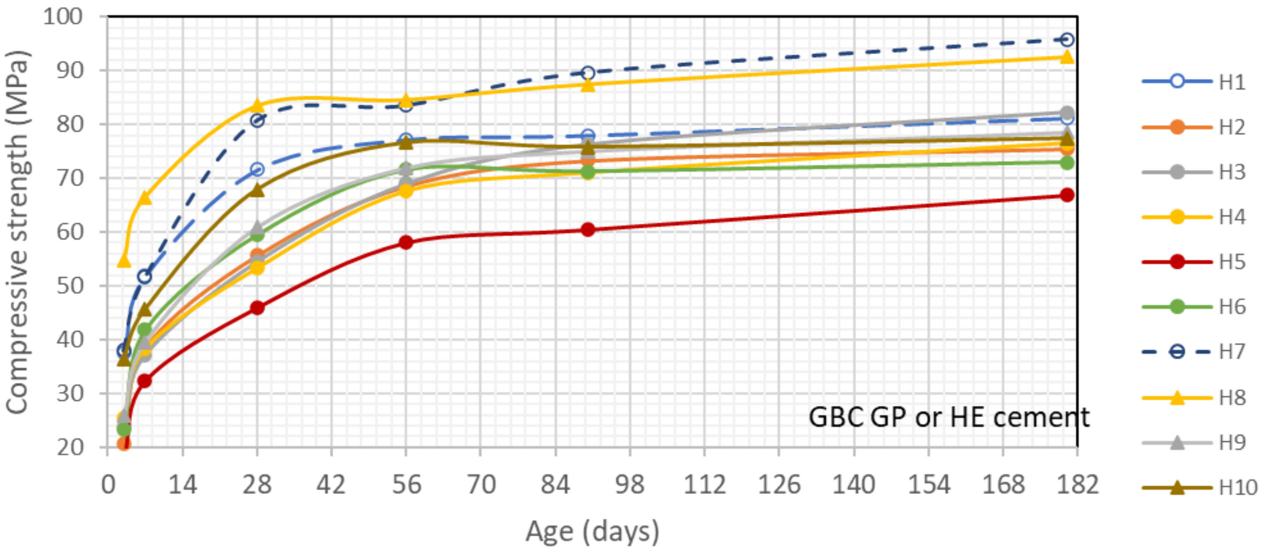

Figure 11a: Strength development of higher strength concrete mixes made with GBC

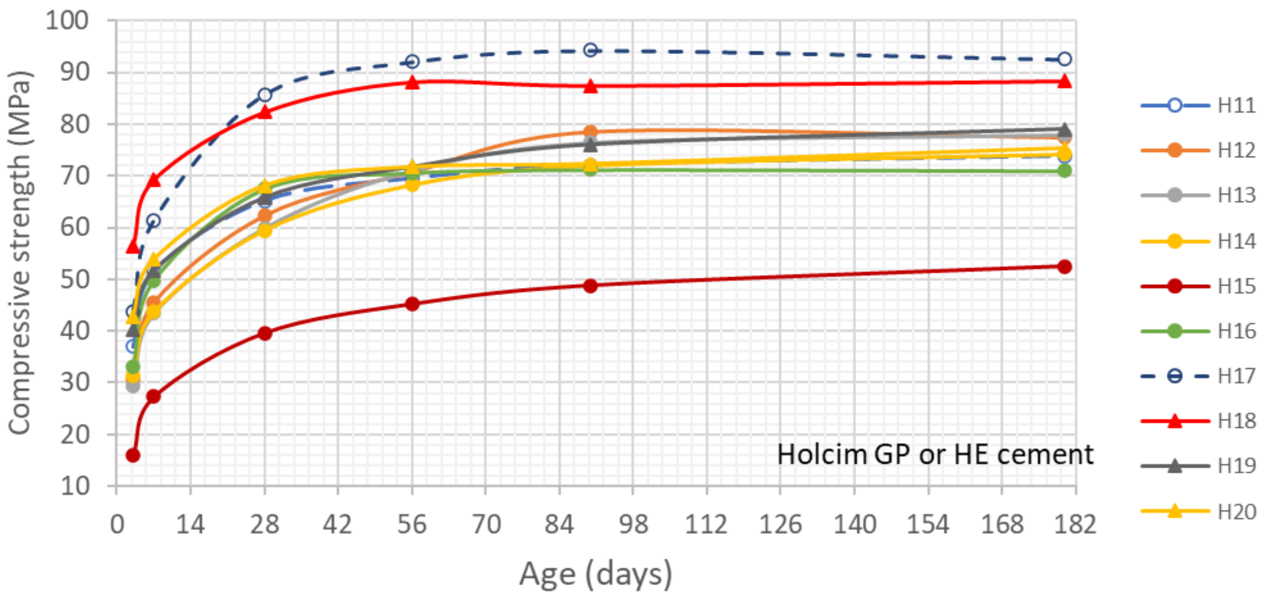

Figure 11b: Strength development of higher strength concrete mixes made with Holcim cement

6.2 Lower strength concrete mixes

Lower strength concrete made with a nominal water/binder ratio of 0.65 had expected 28-day strengths of 30-40 MPa. All compressive strengths achieved in this testing programme were at the top of the expected range and higher than likely during production (higher performance most probably due to good mixing and full compaction on a vibrating table). Concrete made with fly ash, natural pozzolan or calcined clay had 28 day strength lower than control concrete or concrete containing silica fume (e.g. typically 80-90%). Concrete made with 30% S5 (perlite) achieved 28-day compressive strength less than 30 MPa due to the relatively poor reactivity of this coarsely ground powder (e.g. 70% of control strength).

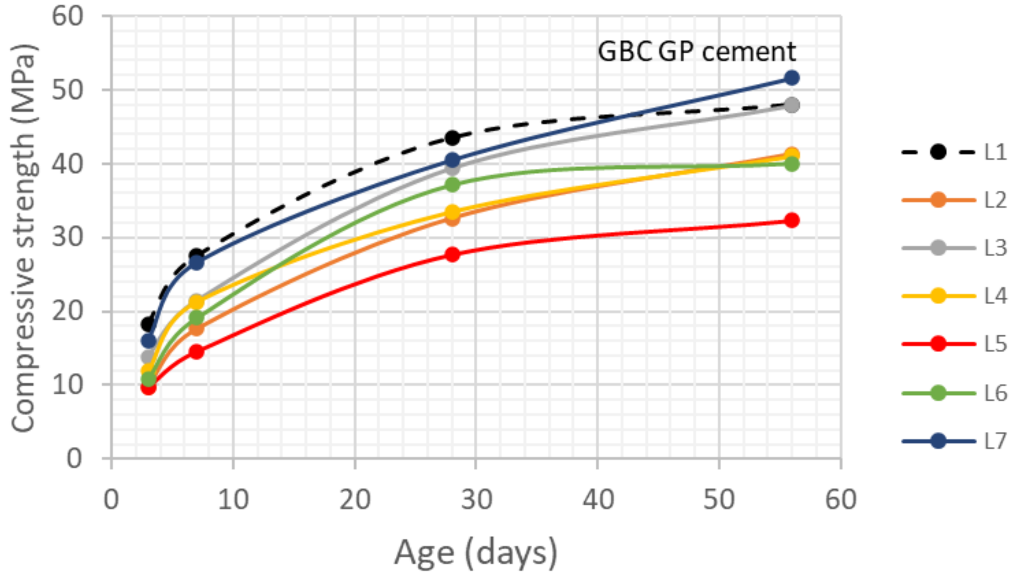

Figure 12a: Strength development of lower strength concrete mixes (GBC cement)

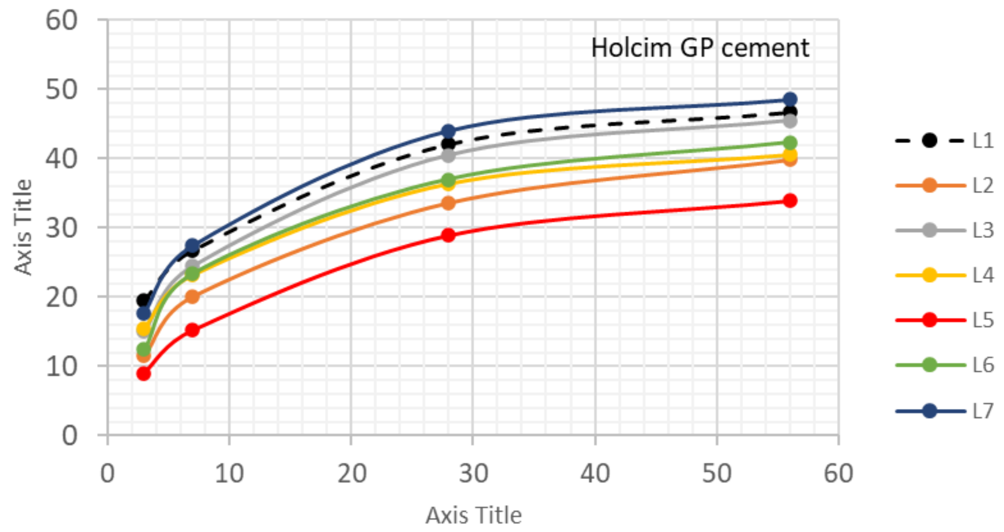

Figure 12b: Strength development of lower strength concrete mixes (Holcim cement)

6.3 Strength development of concrete

Strength development of SCM concrete is expected to differ compared with control concrete made with Portland cement. The lower reactivity of most SCMs makes slower strength development the norm in comparison to PC concrete. This was found to be the case when compressive strength results were analysed (see Figure 13 below). The rate of strength development was found to dependent on the type of SCM as well as the type of GP cement.

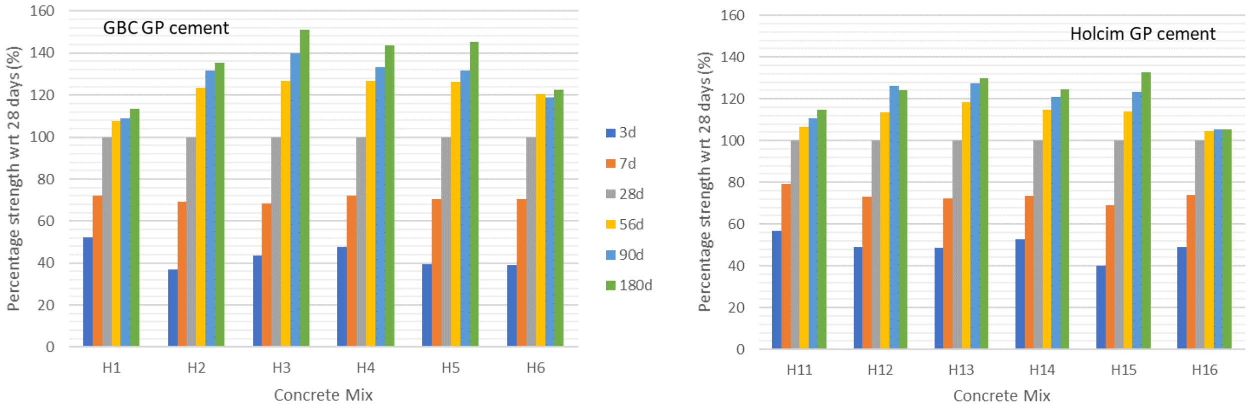

Figure 13: Strength development as a percentage of 28-day strength

Subtle differences were found in the strength development of concrete made with either GBC or Holcim cement. This was not surprising for the two GP cements given the different cement chemistry of these two materials, namely that GBC GP cement has lower C_3S and higher C_2S contents that those found in Holcim GP cement. This resulted in consistently higher long-term strength development of concrete containing GBC GP cement (shown in the left chart in Figure 13).

6.4 Cement efficiency

Concrete is typically specified in terms of 28-day compressive strength although allowance does exist for later age testing of SCM concretes that gain a significant amount of the strength after 28 days. An assessment of the reactivity of SCMs used in concrete can be made by looking at the cement efficiency within any binder combination (e.g. dividing the 28 day strength in MPa by the Portland cement content in kg). Average results for the two types of GP cement are compared in Figure 14 for concrete mixes with either water/binder ratios of 0.45 or 0.65. Results all show positive cement efficiency when using SCMs except for perlite (S5) where strengths were so compromised to show no structural advantage with this binder combination.

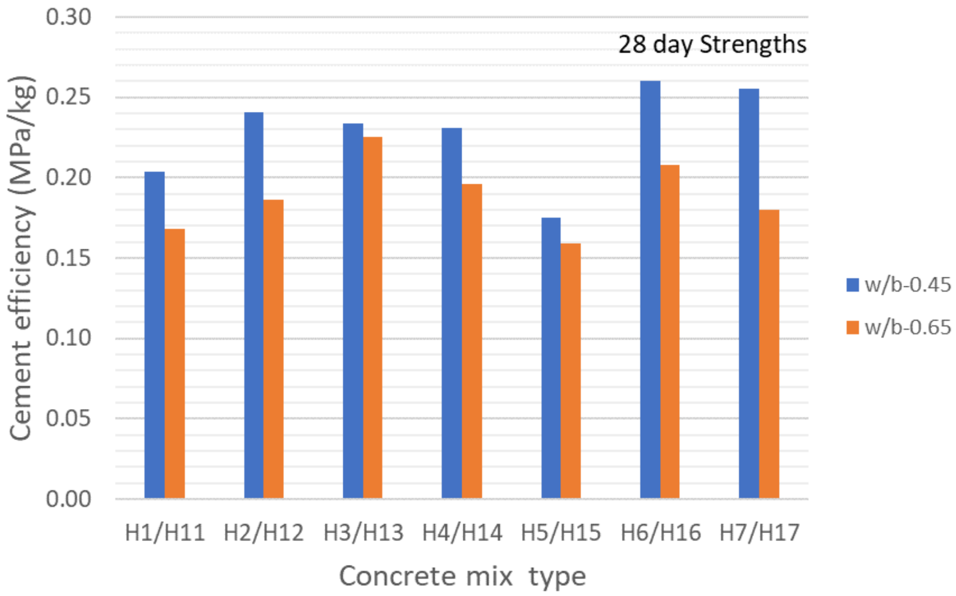

Figure 14: Cement efficiency comparisons – average values for GBC & Holcim mixes at 28 days

6.5 Embodied carbon comparisons based on compressive strength

Comparisons of embodied carbon for different concrete mixes was made by normalising strength at 50 MPa. This is shown in Table 3 where the average 28-day strength of concrete mixes made with either GBC and Holcim were averaged to provide a simpler comparison. A linear approximation was made to determine the water/binder ratio of each concrete mix to produce a 28-day strength of 50 MPa. From this calculation, the total binder content was determined assuming a water demand of 170 L/m^3, which represents the national average value for structural concrete mixes.

Table 3: Embodied carbon content of 50 MPa concrete based on 28-day strengths (binder contribution only)

Property	**H1** 100% PC	**H2** 30% FAG	**H3** 30% FAH	**H4** 30% Pozz	**H5** 30% Perl	**H6** 30% CC	**H7** 8% SF	**HD** 50% Slag
f_{28} w/b=0.65	42.8	33.1	40.0	35.0	28.3	37.1	42.3	25.0
f_{28} w/b=0.45	68.4	59.1	57.3	56.4	42.8	63.5	83.1	46.8
w/b ratio for 50 MPa	0.593	0.520	0.533	0.509	0.352	0.552	0.611	0.425
Total binder content (kg/m^3)	286.7	326.9	318.9	334.0	483.0	308	278.2	400.0
PC (kg/m^3)	286.7	228.8	223.3	233.8	338.1	215.6	256.0	200.0
SCM (kg/m^3)	0	98.1	95.7	100.2	144.9	92.4	22.3	200.0
eCO_2/T of binders	850	850/25	850/25	850/50	850/50	850/330	850/25	850/100
eCO_2/m^3 for 50 MPa	243.7	197.0	192.2	203.7	294.6	213.7	218.1	190.0
Percentage eCO_2 vs. PC	100.0	80.8	78.9	83.6	120.9	87.7	89.5	78.0

Embodied carbon dioxide contents for PC and SCM were based on international average values but could vary depending on supply location. Based on this simple analysis it is apparent that embodied carbon dioxide in structural concrete could achieve reductions of 20% using a range of different SCMs. Poorly reactive SCMs could also contribute to an increase in total embodied carbon dioxide for SCM concrete. This highlights the need for careful characterisation of any potential SCM source before use in concrete production.

7.0 DURABILITY OF CONCRETE

A range of durability-related tests were used to better understand the benefits and risks of using SCM concrete over the longer term. Properties investigated included porosity, oxygen permeability, accelerated carbonation, resistivity, chloride resistance and expansion when subject to alkali silica reaction. All durability testing was conducted on concrete with water/binder ratio of 0.45 except for ASR expansion testing which was conducted on mixes with a nominal water/binder ratio of 0.35.

7.1 Porosity

Effective porosity of concrete was measured after 28 and 90 days of curing in water. This was measured by oven-drying concrete samples of 30 mm thickness for 14 days before vacuum-saturation [58] with values below 10.0% indicating a dense microstructure [27]. Porosity results are shown in Figure 15 with both control and SCM concrete showing low porosity values after 90 days wet curing. SCM concrete had higher porosity values than control concrete with the exception of concrete containing calcined clay.

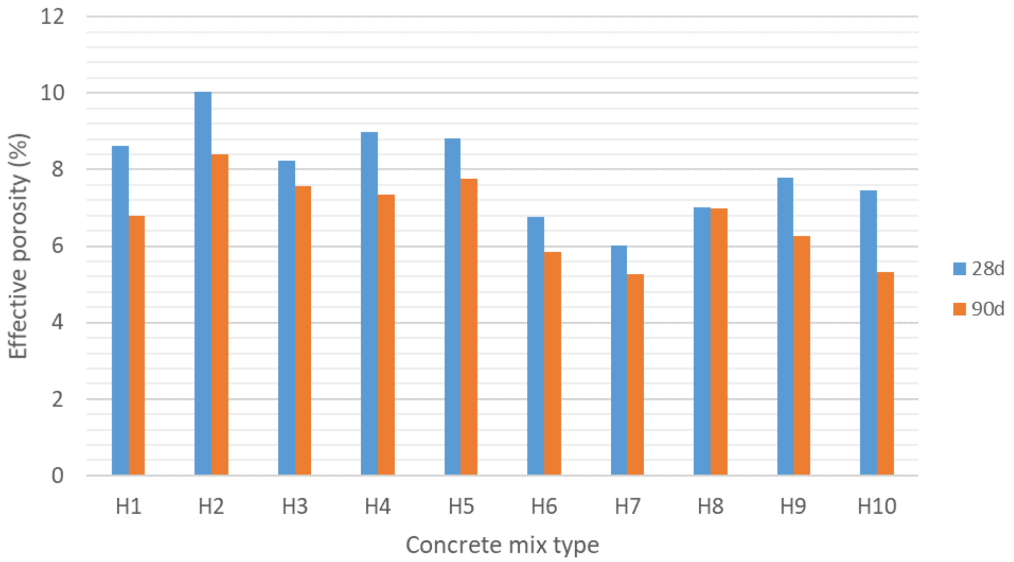

Figure 15: Effective porosity of concrete after 28 or 90-days wet curing (GBC)

7.2 Oxygen permeability

Oxygen permeability testing of concrete uses a falling head permeameter where the Darcy coefficient of permeability is calculated. Oxygen permeability are generally expressed in terms of an oxygen permeability index (OPI which is defined as the negative log of the Darcy coefficient of permeability). Dense and well cured concrete typically achieves OPI values of greater than 10.3 with very low permeability being typically above 10.5. Figure 16 shows the results of oxygen permeability across the range of concrete mixes with control mixes highlighted (e.g. H1 – GP cement control and H8 – HE cement control).

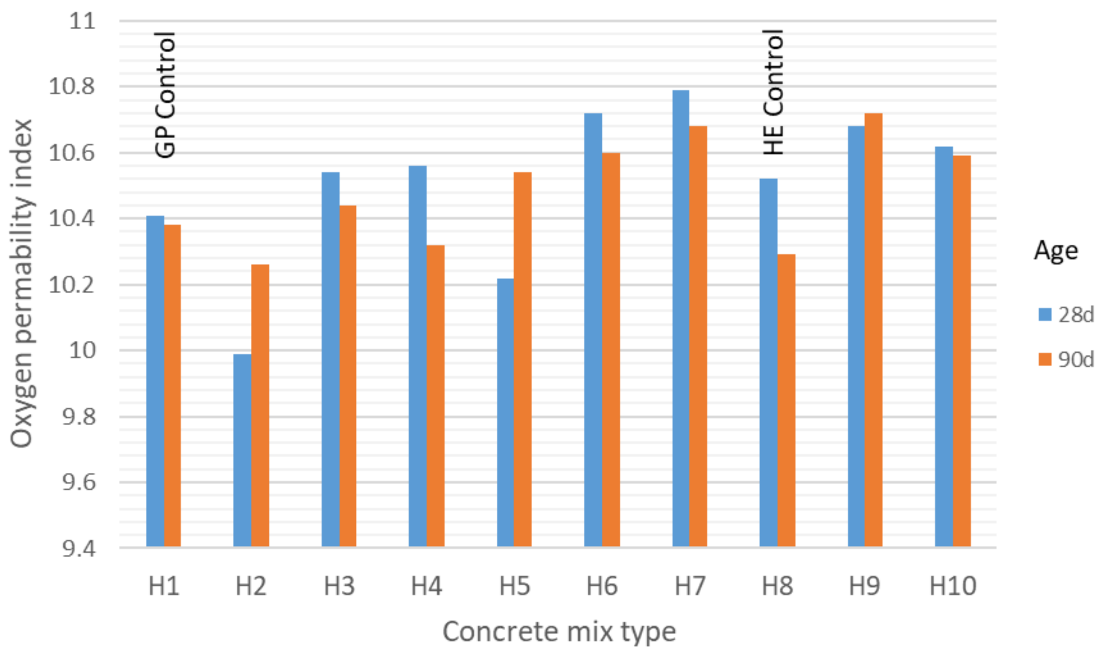

Figure 16: Oxygen permeability index values after 28 or 90 days of wet curing (GBC)

Results from oxygen permeability were found to have a significant amount of scatter, which can be seen when comparing 28 and 90-day results. The expectation would be increasing oxygen permeability index values with increased age but this was not consistent seen in this research. Concrete containing SCMs was found to similar to slightly lower permeability compared with PC concrete except for concrete containing Huntly fly ash (H2) that had higher permeability at both 28 and 90 days.

7.3 Accelerated carbonation

Concrete specimens were exposed to a range of curing conditions being wet cured for either 3, 7 or 28 days before drying at 21 ^{0}C and 50% R.H. until 35 days. After this initial curing, concrete specimens were being placed in a carbonation chamber (21 ^{0}C, 60% R.H. and 2.5% carbon dioxide) for a period of 56 days [57]. This accelerates the rate of carbonation of concrete to levels approaching 1 mm per week, which are orders of magnitude higher than natural carbonation rates of less than 1mm per year. A summary of results is shown in Figure 17 while more detailed findings can be reviewed in Appendix F and G.

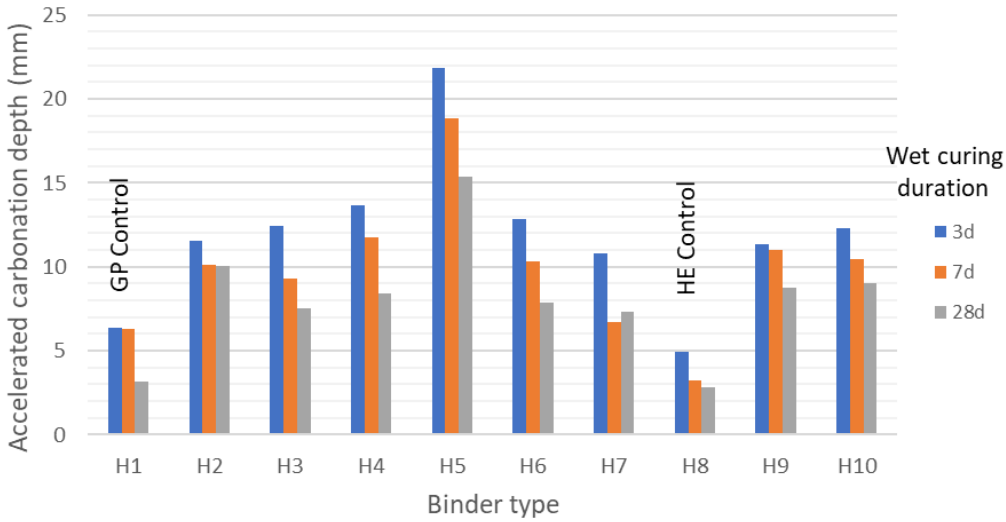

Figure 17: Accelerated carbonation depths measured after 56 days exposure (GBC)

In summary, SCM concrete had higher carbonation depths than control concrete especially for specimens receiving only three days wet curing. SCM concrete with extended wet curing of 28 days exhibited improved carbonation resistance but this was still more than 50% higher than PC concrete. Concrete made with ground perlite (H5) had significantly higher carbonation depths than other concrete mixes that was not predicted from porosity or permeability results.

7.4 Electrical resistivity

Electrical resistivity testing of concrete was undertaken to provide a quick assessment of the quality of the microstructure in limiting corrosion rates after depassivation of embedded steel reinforcement. Typically SCM concrete exhibit increasing resistivity values in the longer-term whereas PC concrete tend to have relatively low resistivity values of around 10-15 kOhm.cm. Figure 18 shows a comparison between resistivity values with results being quite varied as shown below. Full results are listed in Appendix F.

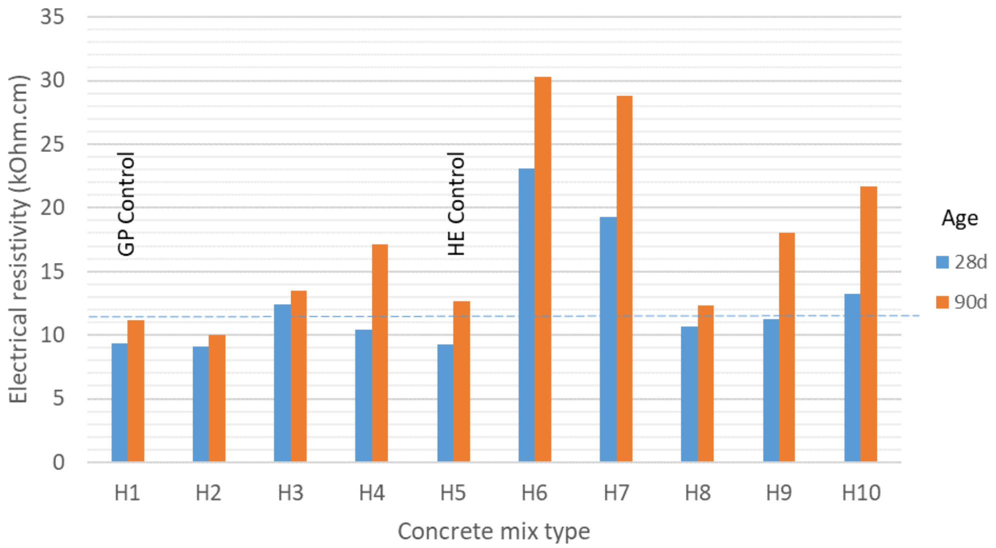

Figure 18: Electrical resistivity after 28 or 90 days of wet curing (GBC)

Longer-term resistivity results measured after 90 day showed three groupings of the data:

- PC controls had resistivity values of approximately 12 kOhmcm that are not expected to increase with time
- Concrete made with Huntly fly ash had resistivity of 10 kOhmcm that may slowly increase with time
- Other SCM concrete had resistivity values above 12 kOhmcm that should increase further with time

7.5 Migrating chloride diffusion

The chloride resistance of concrete was assessed in accordance with NTB 492 where the chloride migration diffusion coefficient was measured [59]. Results are shown in Figure 19 for concrete mixes made with either GBC or Holcim Portland cement tested after either 28 or 90 days of water curing. Concrete considered to have high levels of chloride resistance will have migration coefficient values below 4 x10 $^{-12}$ m^2/s. Details of all chloride migration testing are also given in Appendix F.

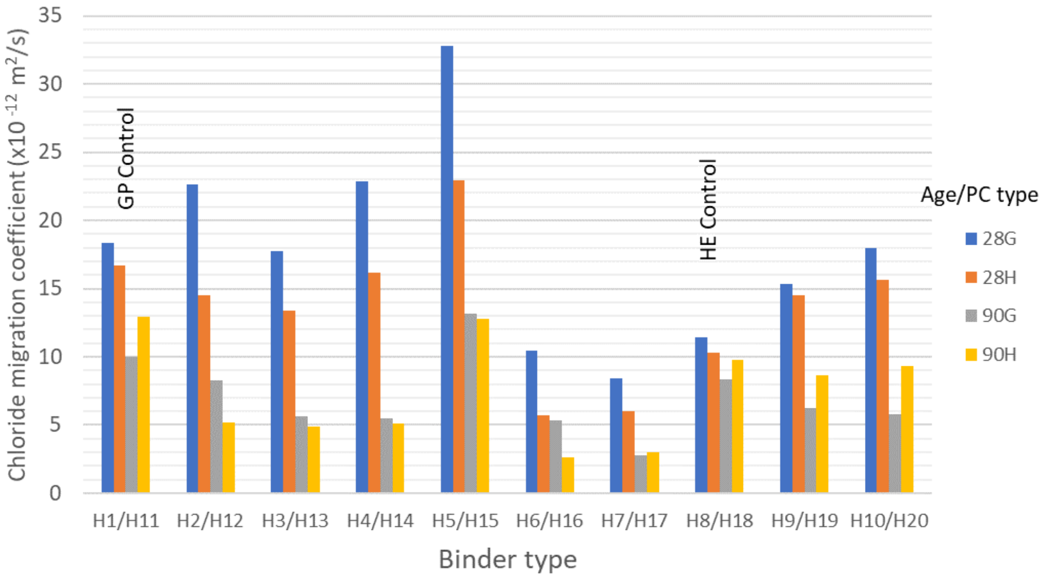

Figure 19: Chloride migration coefficient of concrete mixes after water curing for either 28 or 90 days

Comparison of chloride migration coefficients at 28 days showed lower chloride resistance of SCM concrete compared with PC concrete control (except for concrete mixes with calcined clay or silica fume). At 90 days the comparison showed that all SCM concrete except that containing ground perlite had better chloride resistance than control concrete. When SCM concrete mixes containing GP cements were compared, it was found that Holcim mixes were generally had lower chloride migration coefficients than GBC.

7.6 Expansion from alkali silica reaction

Concrete prism testing (CPT38 & CPT50) was undertaken to assess the ability of SCM in reducing expansion due to alkali silica reaction. This testing used concrete mixes containing a reactive sand (Bay of Plenty andesite from Poplar Lane quarry) together with a raised alkali level (e.g. 5.25 kg/m^3 using admixed sodium hydroxide in accordance with ASTM C1293) [61]. Typical measurements from concrete prism testing are shown in Figure 20 (note that 50 ^{0}C was used rather than 60 ^{0}C due to limitations in oven space). More details can be found in Appendix H.

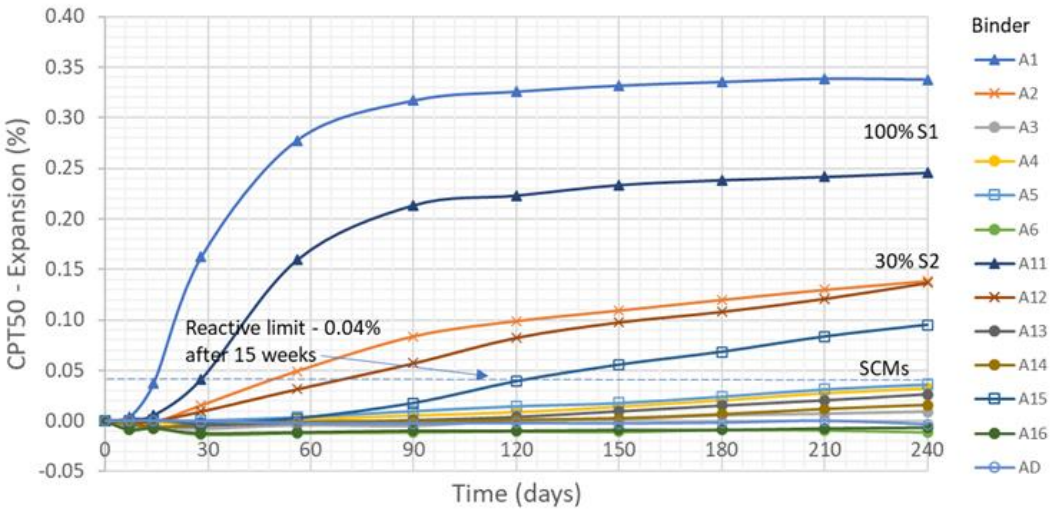

Figure 20: Expansion of concrete prism testing done at 50 ^{0}C

Figure 21 shows a comparison between the final expansion levels measured using CPT38 (360 days) and CPT50 (240 days). Most SCMs showed effective mitigation of expansion although S2 (Class C fly ash) was unable to perform as effectively as the other SCM at 30% replacement. Further trials were started in April 2021 to investigate higher replacement levels for concrete containing S2 and lower replacement levels for S4 SCM (see Appendix H for details).

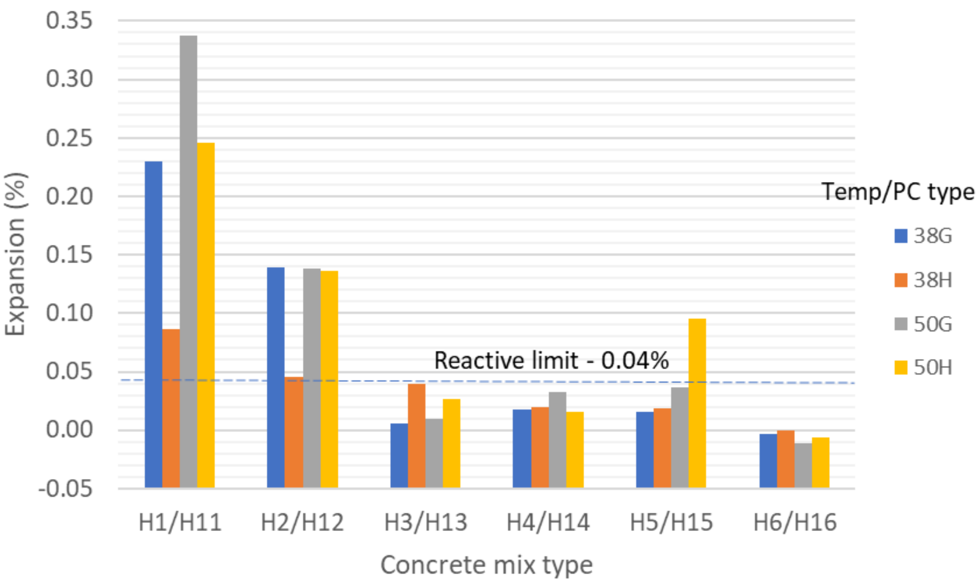

Figure 21: ASR-related expansion from CPT38 (360 days) and CPT50 (240 days)

7.7 Durability summary

Testing a wide range of SCMs of variable quality produced a range of durability properties that are summarised in Table 4 below. These results are given semi-quantitatively to allow easy comparison with the results from control concrete mixes (e.g. 1 - very good, 2 – good, 3 – moderate, 4 – moderate/poor 5 - poor).

Table 4: Qualitative assessment of the durability performance of different concrete mixes (90 days)

Durability Property	**H1/H11** 100% GP	**H2/H12** 30% FAG	**H3/H13** 30% FAH	**H4/H14** 30% Pozz.	**H5/H15** 30% Perl.	**H6/H16** 30% CC	**H7/H17** 8% CSF	**H8/H18** 100% HE	**H9/H19** HE30% FAH	**H10/H20** HE30% Pozz.
Porosity	2	3	2	2	3	1	1	2	2	2
Oxygen Permeability	2	2	2	2	2	1	1	2	1	2
Accelerated Carbonation	2	3	3	3	4	2	2	1	2	2
Resistivity	2	2	2	1	2	1	1	2	1	1
Chloride resistance	4	3	2	2	4	1	1	3	3	3
ASR-expansion	5	3	1	1	2	1	-	-	-	-

Based on overall performance the following durability performance was found for different binder systems:

- Perlite and class C fly ash showed reasonable durability performance in terms of the tested properties but were not able to improve chloride resistance of concrete significantly or fully prevent longer-term expansion associated with alkali silica reaction
- Class F fly ash, pozzolana from ignimbrite and calcined clay SCMs were shown to significantly enhance durability of concrete except for carbonation resistance

The above comparison in durability performance was undertaken across concrete mixes designed with the same water/binder ratios and cementitious contents. In practice these concrete mixes would be compared at similar strength grades, which would increase binder content of SCM concretes by 10-20%. This would improve the durability performance of SCM concrete mixes and the poorer carbonation resistance of these materials would be reduced. The sustainability of using high binder contents in SCM concrete must however be considered and this is addressed in Section 8.6.

8.0 CONCLUSIONS

This experimental programme was able to assess the technical issues associated with SCM utilisation in structural concrete for construction in New Zealand. While the limited testing time frame and budget did not allow exploration of all the practical issues, there is sufficient information to draw some conclusions about classification methods, workability, strength development, durability, construction practice precautions and sustainability benefits.

8.1 Classification of SCMs

The biggest hurdle to a broader adoption of SCMs into concrete construction is the reliance on a test method (AS 3583.6) that is unable to accurately predict the reactivity of SCMs, especially when assessing natural pozzolans. This is best illustrated by comparing the poor relative water requirement and relative strength of concrete containing calcined clay assessed using AS 3583.6 with the excellent concrete strengths achieved. It is recommended that the New Zealand standard NZS 3123 be revised and alternate classification systems be adopted (e.g. modified EN 197.1, isothermal calorimetry and/or bound water from thermogravimetric analysis).

8.2 Fresh properties of concrete

The workability of concrete was found to vary for SCM concrete mixes but this was not significant and can be allowed for by adjusting materials and admixtures. Increasing dosages of SCMs in concrete are known to reduce bleeding and extend the setting time of concrete and this was seen in these trials. The potential for plastic shrinkage cracking will increase when using SCMs in concrete unless mixes are optimised and sensible construction practice is followed on site.

8.3 Strength development

Replacement of Portland cement with SCMs will reduce early strength development of concrete but long-term strength development is better than control concrete. This trend was found with SCM concrete mixes showing slower development than control concrete. While there was steady long-term strength gain of SCM concrete this still resulted in lower compressive strength at 180 days. Variable performance was observed between different SCMs in concrete but this was well predicted using appropriate classification methods discussed in section 8.1 above.

8.4 Durability of concrete

SCM utilisation in concrete is often done to improve the microstructure of concrete, which produces a more durable structural material. This research showed that SCMs may have variable performance in concrete when durability properties are assessed although there was a general improvement in most cases. More reactive SCMs such as fly ash, ignimbrite, calcined clay and silica fume were shown to consistently lower porosity and permeability, which should also improve resistivity and chloride resistance. All SCMs showed a beneficial effect in reducing expansion associated with alkali silica reaction although some materials were more effective than others in this regard.

All SCM concretes were found to have poorer carbonation resistance compared with control concrete regardless of the curing regime. It should also be noted that carbonation as such does not pose a durability problem for concrete structures, but is generally is considered regarding its potential depassivating effect on embedded reinforcing steel, which may lead to corrosion initiation and propagation. The generally superior hardened properties of SCM concrete with regards to penetrability and resistivity are expected to assist in reducing reinforcement corrosion rates, such that the overall effect of using SCMs in the design of reinforced concrete structures needs further consideration [63].

8.5 Curing of SCM concrete

Carbonation of concrete is not a major problem in New Zealand despite curing of concrete is sometimes ignored or poorly done. Findings from this research show that control concrete containing either GP or HE cement was subject to limited carbonation even when little effective wet curing was undertaken. This limited influence of poor curing on carbonation is due to the rapid maturity of these concrete mixes that limits the effects of early drying and therefore maintains a reasonable near-surface microstructure. Slower reacting SCMs in concrete have the potential to increase carbonation depths both from more rapid drying of the surface and less cement to maintain internal pH levels. This was found in this research where all SCMs had higher carbonation depths than PC controls regardless of curing regime. Better construction practices are required when dealing with SCM concrete otherwise carbonation-induced corrosion of reinforcement could become more common on reinforced concrete structures.

8.6 Sustainability of SCM concrete

A major motivation for utilising SCMs in concrete is that this will help reduce the reliance on Portland cement in concrete. Findings from this SCM research show that replacement of 30% Portland cement with SCMs was not able to achieve almost comparable strengths at equal water/binder ration but did achieve superior durability properties in some cases. SCMs with higher surface area such as calcined clay and silica fume were found to be most effective in concrete with lower water/binder ratios that achieve higher compressive strength. Fly ash was more effective in lower strength grades since workability was not negatively affected by water demand issues. Some SCMs such as the relatively coarse perlite trialled in the research was found to have no benefit from a sustainability viewpoint (see comparisons shown in Table C6).

8.7 Barriers to significant SCM utilisation

The most significant barrier to more widespread utilisation of SCMs in concrete production is the current classification system of these materials. The relative strength methodology on simple mortar mixes is dated and shown to be extremely poor in predicting the reactivity of SCMs in concrete. Replacement of this approach with modern methods is crucial, especially for utilisation of natural pozzolans from New Zealand. Other barriers that will stifle adoption of SCMs in concrete production exist in the potential for poor quality concrete if construction practices are not adequate. Curing of concrete requires attention to limit the risk of cracking and improve the durability potential of reinforced concrete.

8.8 Overall conclusions

A significant conclusion from this research is that local natural pozzolans such as ground ignimbrite or calcined clay can produce similar structural and durability performance to that produced by more well-known industrial pozzolans such as fly ash or silica fume. Further improvements could possibly be made in the reactivity of natural pozzolans by optimisation including better grinding or inter-grinding with cement clinker. Development of these resources is likely given the promising results achieved in this study and the local availability of these natural resources. Table 4 shows a high-level summary of issues associated with the utilisation of SCMs in concrete.

Table 4: Summary of benefits and risks using SCMs in concrete

Issue	Risks or Benefits	Adjustments
Lower bleeding	Plastic shrinkage	Protection from rapid drying
Delay in setting time	Exacerbated in winter conditions	Use of set accelerators
Strength development	Lower early strength	Improved long-term strength
Carbonation resistance	Reduced especially if curing is poor	Improved curing and mixes
Chloride resistance	Generally improved	Correct SCM classification
Alkali silica reaction	Reduced expansion risk	Correct SCM classification
Sustainability	Up to 20% lower embodied carbon	Benefit depends on SCM reactivity

8.9 Future research needs

Based on the findings of this research programme, several lines of investigation could be considered in the future. These future research needs are summarised as follows:

- Improved synergies between PC and SCMs both in terms of grinding improvements and effects of changes in composition of the cementing materials
- Improving the potential reactivity of SCMs using different chemical admixtures and additives that are known to increase hydraulicity and pozzolanicity of SCMs
- Concrete mix design optimisation of SCM concretes containing a wider range of fine and coarse aggregate combinations from around New Zealand
- More details study of the embodied carbon content of different SCM concrete mixes and comparison with structural and durability performance

ACKNOWLEDGEMENTS

This research was undertaken at the University of Canterbury with funding provided by BRANZ and Concrete NZ. Hydration studies, binder classification, oxygen permeability and accelerated carbonation was undertaken by Dr Vineet Shah, formerly of University of Canterbury. The remaining experimental work was undertaken by the author under the funding of Concrete NZ.

9.0 REFERENCES

1. Scrivener, K.L., John, V.M. and Gartner, E.M., (2016), Eco-efficient cement: potential economically viable solutions for a low CO_2 cement-based materials industry, UNEP, Paris.

2. Collis, V., (2020), The history and sustainability of concrete, In Fulton's Concrete Technology, Ed. M.G. Alexander, Tenth Edition – 2021, South Africa.

3. Favier, A., De Wolf, C., Scrivener, K. and Habert, G., (2018), A sustainable future for the European Cement and Concrete Industry: Technical assessment for full decarbonisation of the industry by 2050. ETHZ & EPFL, Switzerland.

4. Chandler, D.L., (2018), New approach suggests path to emission-free cement, MIT News Office, 7 October2018, [Online] Available: https://news.mit.edu/2019/carbon-dioxide-emissions-free-cement-0916.

5. International Energy Agency, (2018), Low carbon transition in cement industry, IEA technical report, France, Available online.

6. Vickers, Jeff., (2020), Carbon footprint validation for the New Zealand cement and concrete industry – Table 1: Changes in GHG emissions from cement and concrete in NZ between 2005 and 2018, Thinkstep ANZ, Report for Concrete New Zealand, Feb. 2020, Wellington.

7. Thinkstep ANZ, (2019), Under construction – hidden emissions and untapped potential of buildings for New Zealand's 2050 zero carbon goal, Report for NZGBC, Wellington.

8. Rahman, A., Rasul, M.G., Khan, M.M.K. and Sharma, S.C., (2017), Assessment of energy performance and emission control using alternative fuel in cement industry through a process model, MDPI Energies, 10(12).

9. Scrivener, K.L., (2014). Options for the future of cement. Indian Concrete Journal, 11–21.

10. Aitcin, P.C., (2007), Binders for durable and sustainable concrete, CRC Press.

11. Thomas, M.D.A., (2013), Supplementary cementitious materials in concrete, CRC Press.

12. European Standard, (2011), EN197-1 – Cement – Part 1 Composition, specification and conformity criteria for common cements, European Committee for Standardization, Brussels.

13. Wang, G.C., (2016), The utilization of slag in civil infrastructure construction, Woodhead Publishing, Elsevier.

14. Wesche, K., (2019), Fly ash in concrete – properties and performance, CRC Press.

15. Malhotra, V.M., (2018), Condensed silica fume in concrete – Second edition, CRC Press.

16. Mackechnie, J.R., (2018), Visual guide to concrete technology, Concrete New Zealand, Wellington.

17. Chisholm, D.H., (1997), Performance characteristics of concrete incorporating an amorphous silica, Proc. of third ACI/CANMET Conf. on Concrete Durability, Auckland, 1997.

18. Avet, F., Snellings, R., Diaz, A.A., Haha, M.H. and Scrivener, K., (2016), New rapid, relevant and reliable test method to evaluate the pozzolanic reactivity of calcined kaolinitic clays. Cement and Concrete Research, 85, pp 1-11.

19. Dhandapani, Y., Sakthivel, T., Santhanam, M., Gettu, R., Pillai, R.G., (2018). Mechanical properties and durability performance of concretes with Limestone Calcined Clay Cement (LC3). Cem. Concr. Res. 107, 136–151.

20. Emmanuel, A.C., Haldar, P., Maity, S., Bishnoi, S., (2016). Second pilot production of limestone calcined clay cement in India: The experience. Indian Concr. J. 90, 22–27.

21. South, Warren, (2009), A study of the compressive strength and drying shrinkage of cementitious binders prepared using natural pozzolans, PhD thesis, University of Wollongong, Australia.

22. Dedeloudis, C. et al (2018) Natural Pozzolans. In: De Belie, N., Soutsos, M., Gruyaert, E., (eds) Properties of fresh and hardened concrete containing supplementary cementitious materials, RILEM Stat-of-the-Art Reports, Vol. 25, Springer.

23. Ramezanianpour, A.A (2013), Cement Replacement Materials – Properties, Durability, Sustainability, Springer Publishing.

24. Christie, A.B., Thompson, B., Brathwaite, R., (2007), Mineral commodity report 20 – Clays, Institute of Geological and Nuclear Sciences, Wellington.

25. Kennerley, R.A., and Clelland, J., An investigation of New Zealand pozzolans – Part 1 & 2, Bulletin 133, NZ DSIR, Wellington, 1959.

26. Mason, Blair, The analysis of Taupo pumice as an effective partial cement replacement in concrete', Masters thesis, University of Canterbury, 2012.

27. Mackechnie, J.R., (2020), Sustainable and durable binder systems for concrete bridge structures in New Zealand, IABSE Conference, September 2020, Christchurch.

28. Dhir, R.K. and Paine, K., (2020), ICE Themes – Low Carbon Concrete, ICE Publishing, London.

29. Guo, Z., (2020), Mechanical and durability properties of sustainable self-compacting concrete with recycled concrete aggregates and fly ash, slag and silica fume, Construction and Building Materials, 231.

30. Deep Foundations Institute, (2018), Guide to tremie concrete for deep foundations: Second edition, EFFC/DFI, London.

31. Wilinska, I., Pacewska, B., Ostrowski, A., (2019), Investigation of different ways of activation of fly ash – cement mixtures: Part 1 – Chemical activation by Na_2SO_4 and $Ca(OH)_2$, Journal of Thermal Analysis and Calorimetry, 138.

32. Fernandez-Jimenez, A., Garcia-Lodeiro, I., Maltseva, O., Palomo, A., (2019), Mechanical-chemical activation of coal fly ashes: An effective way of recycling and making cementitious materials, Frontiers in Materials.

33. Fang, G., Ho, W.H., Tu, W., Zhang, M., (2018), Workability and mechanical properties of alkali-activated fly ash and slag geopolymer concrete cured at ambient temperature, Construction and Building Materials, 172.

34. Crown Construction World, (2017), Civil Engineering Contractor Awards: Loeriesfontein wind farm and Khobab wind farm, December 2017, South Africa.

35. Agarwal, M., (2019), Evaluation of the mechanical properties of concrete having high volumes of industrial waste, Masters project thesis, University of Auckland, New Zealand.

36. Ramezanianpour, A.A., (2014), Effect of calcined perlite powder as a SCM on the strength and permeability of concrete, Construction and Building Material, 66.

37. Khan, K., Amin, M.N., Qadir, M.G., (2019), Effect of fineness of basaltic volcanic ash on pozzolanic reactivity, alkali silica reaction, and drying shrinkage of blended cement mortars, MDPI Materials, Online open access journal.

38. Karein, S.M.M., Joshaghani, A., Ramezanianpour, A.A., Isapour, S., Karakouzian, M., (2018), Effects of the mechanical milling method on transport properties of self-compacting concrete containing perlite powder as a supplementary cementitious material. Construction and Building Materials, 172.

39. Kasaniya, M., Thomas, M.D.A., Moffat, E.G., (2019), Development of rapid and reliable pozzolanic reactivity test method, ACI Materials Journal, 116, July 2019.

40. Pourkhorshidi, A.R., Najimi, M., Parhizkar, T., Jafarpour, F., Hillemeier, B., (2010), Applicability of the standard specifications of ASTM C618 for evaluation of natural pozzolans, Cement and Concrete Composites, 32.

41. Avet, F., Snellings, R., Diaz, A.A., Haha, M.B., Scrivener, K.L., (2016), Development of a new rapid, relevant and reliable (R^3) test method to evaluate the pozzolanic reactivity of calcined kaolinitic clays, Cement and Concrete Research, 85.

42. Standards New Zealand, (2009), NZS 3122 – Specification for Portland and blended cements (general and special purpose), Wellington.

43. American Society for Testing and Materials, (2003), ASTM C618 – Standard specification for coal fly ash and raw and calcined natural pozzolans for use in concrete, ASTM International.

44. American Society for Testing and Materials, (2002) ASTM C311 – Standard test methods for sampling and testing fly ash or natural pozzolans for use in Portland cement concrete, ASTM International.

45. European Standard, (2005), EN 196-5 – Methods of testing cements Part 5 – Pozzolanicity tests for pozzolanic cements, European Committee for Standardization, Brussels.

46. Pontes, J., Santos Silva, A., Faria, P., (2013), Evaluation of pozzolanic reactivity of artificial pozzolans, Material Science Forum,730-732.

47. Standards New Zealand, (2009), NZS 3123 – Specification for Portland pozzolan cement (type PP cement), Wellington.

48. Australian Standards, (2018), AS 3583.6 - Methods of test for supplementary cementitious materials, Method 6: Determination of relative water requirement and strength index, Australia.

49. Mackechnie, J.R., Fresh concrete performance guidelines in New Zealand, SESOC Journal, 31(2), Wellington, New Zealand.

50. Wang, X.Y., Park, K.B., (2015), Analysis of the compressive strength development of concrete containing high volume fly ash, Construction and Building Materials, 98.

51. Bentur, A., Alexander, M.G., Durability of Concrete: Design and Construction, CRC Press.

52. Standards New Zealand, NZS 3101 – Concrete Structures standard – amendment 3, 2016, Wellington.

53. Sanchez de Roja Gomez, M.I. and Frias Rojas, M., (2013), Natural pozzolans in eco-efficient concrete, In: Jalali, S., Torgal, F.P, John, V.M.(eds) Eco-Efficient Concrete, Woodhead Publishing.

54. Esmaeili, J., Aslani, H., Onuaguluchi, O., (2020), Reuse potentials of copper mining tailings in mortar and concrete composites, Journal of Materials in Civil Engineering, ASCE, 32(5).

55. Bai, J., Wild, S., Sabir, B.B., (2003), Chloride ingress and strength loss in concrete with different PC-PFA-MK binder compositions exposed to synthetic seawater, Cement and Concrete Research, 33.

56. Standards New Zealand, NZS 3112 – method of test for fresh and hardened concrete, 1988, Wellington.

57. International Standards Organization, ISO 1920-12: Determination of the carbonation resistance of concrete – accelerated carbonation method, Geneva, 2015.

58. Alexander, M.G., Mackechnie, J.R. and Ballim, Y., (2009), Durability index testing procedure manual, COMSIRU, University of Cape Town.

59. Nordtest Method, NT Build 492 – Chloride migration coefficients from non-steady-state migration experiments, 1999, Finland.

60. RILEM. RILEM Recommendations for the Prevention of Damage by Alkali Aggregate Reactions in New Concrete Structures. State-of-the-Art Report of RILEM Technical Committee 219-ACS. Eds Nixon, P.J. and Sims, I. RILEM State-of-the Art reports v.17, 2016.

61. American Society for Testing and Materials, ASTM C1293-20a, Standard test method for determination of length change of concrete due to alkali-silica reaction, ASTM, 2020.

62. American Society for Testing and Materials, ASTM C1679-17, standard practice for measuring hydration kinetics of hydraulic cementitious mixtures using isothermal calorimetry, ASTM, 2017.

63. Angst, U., Moro, F., Geiker, M., Kessler, S. Beushausen, H., Andrade, C., Lahdensivu, J., Köliö, A., Imamoto, K., von Greve-Dierfeld, S., Serdar, M. (2020), 'Corrosion of steel in carbonated concrete – mechanisms, practical experience, and research priorities', RILEM Technical Letters (2020) 5: 85-100.

Appendix A: Binder Classification

Table A1: Characterisation of Portland cements and SCMs (GBC & Holcim cement)

Symbol/ Name	S1 GP	S2 FAG	S3 FAH	S4 PM	S5 PL	S6 CC	S7 SF	S8 HE
Description	Portland cement	Huntly fly ash	Adani fly ash	Natural pozzolan	Perlite	Calcined clay	Silica fume	Portland cement
Processing of material	As received	As received	As received	As received	Milled to powder	Milled & calcined	As received	As received
Blaine fineness (m^2/kg)	350 325	426	279	595	133*	1445	19.4 m^2/g BET	500 445
S.G.	3.17 3.15	2.72	2.65	2.56	2.39	2.83	2.20	3.15 3.15

Note: Slag denoted SD (GGBS) was added to this research but was used as a General Blended (GB) cement

Table A2: XRF oxide analysis of Portland cements and SCMs

Compound	S1	S2	S3	S4	S5	S6	S7	S8
CaO	64.10	21.98	14.65	4.46	0.91	0.21	0.43	0.27
SiO_2	21.04	36.64	42.15	70.43	74.56	66.20	91.55	94.85
Al_2O_3	3.80	15.73	18.71	13.02	12.17	26.70	0.71	0.57
Fe_2O_3	2.63	13.02	11.39	2.52	2.18	2.13	2.45	0.33
SO_3	2.46	0.91	0.99	0.03	0.01	0.01	2.20	0.05
Na_2O	0.20	1.06	1.52	3.54	3.62	0.03	0.07	0.33
K_2O	0.49	0.75	1.57	2.44	3.79	2.28	0.25	0.76
LOI	3.34	0.45	0.24	2.35	2.51	0.62	2.14	1.94

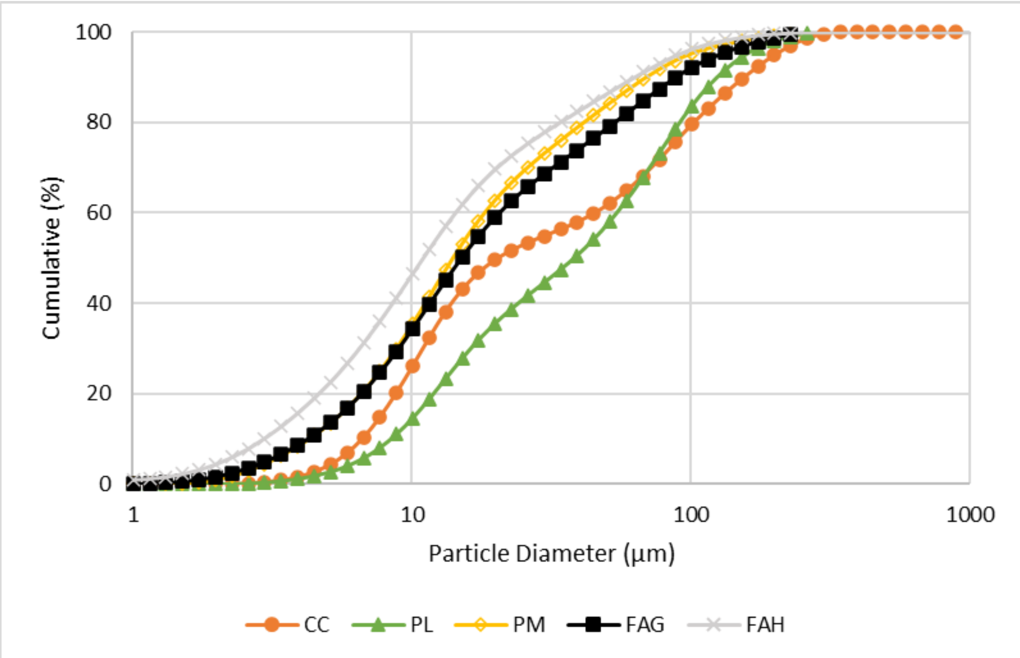

Figure A1: Particle size grading of main SCMs used in research project

Table A3: TGA analysis of bound water contents of paste samples with 30% SCM replacement (%)

Age (days)	S1	S2	S3	S4	S5	S6
3	17.95	11.79	12.11	13.54	12.43	14.13
7	20.16	15.15	14.99	15.51	14.50	16.44
28	23.75	21.45	21.02	19.52	18.59	23.01

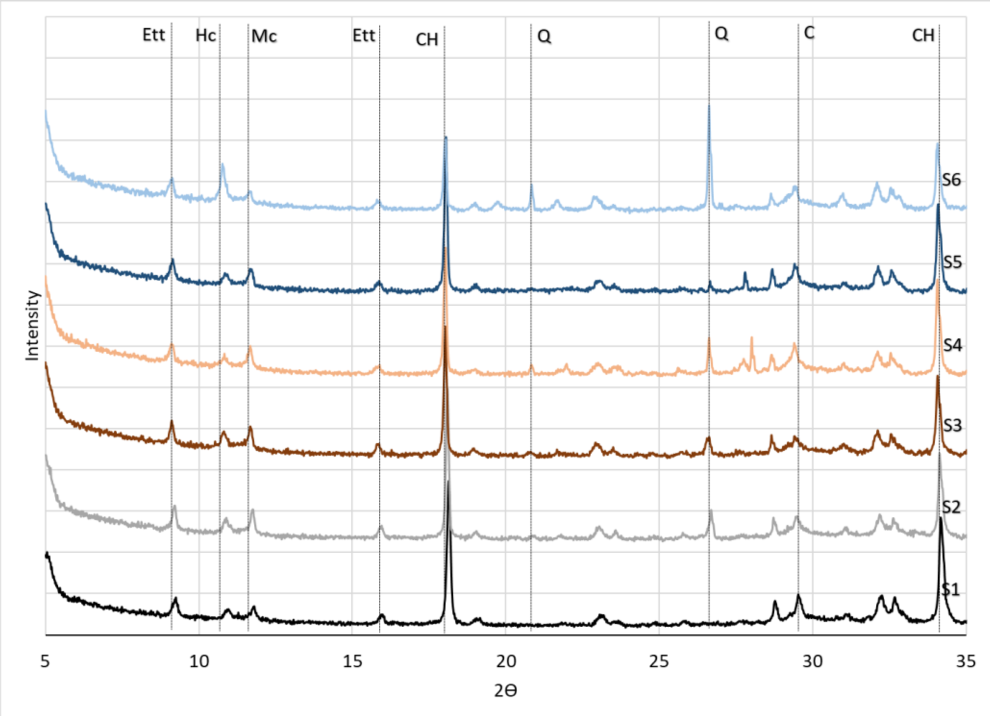

Figure A2: XRD analysis of paste samples (30% SCM replacement)

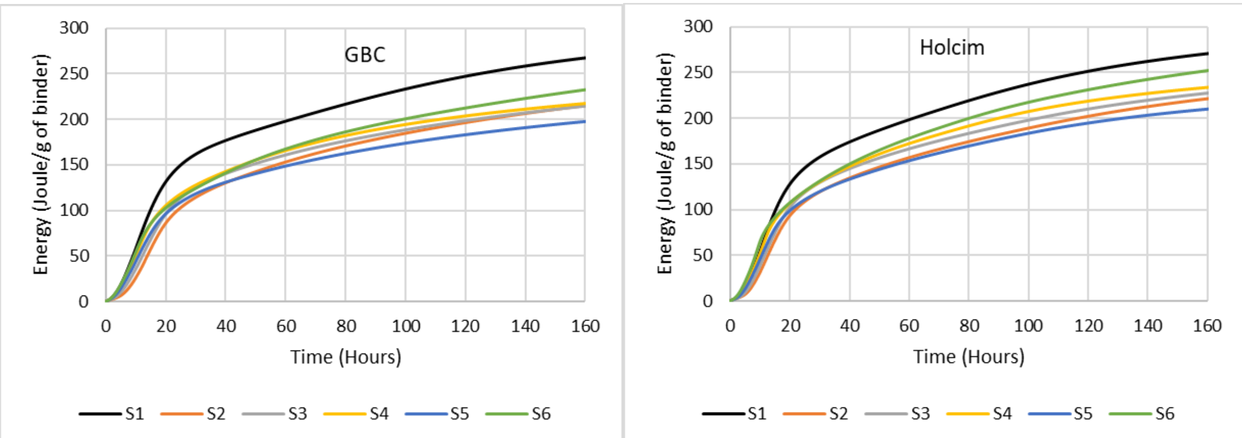

Figure A3: Isothermal calorimetry energy curves for Portland cement and 30% SCM blends

Appendix B: Classification of SCMs

Mortar testing was done in accordance with AS 3583.6 with the concrete mixes shown in Table B1 while strength results are shown in Table B2.

Table B1: Mortar mixes for GBC and Holcim blends testing in accordance with AS 3583.6

Material	M1 / M11	M2 / M12	M3 / M13	M4 / M14	M5 / M15	M6 / M16
GP cement	450 S1	360 S1	360 S1	360 S1	360 S1	360 S1
SCM	0	177 S2	172 S3	166 S4	155 S5	184 S6
Sand	1350	1350	1350	1350	1350	1350
Water	240.3/239.0	224.1/222.8	216.0/216.0	252.5/249.7	249.8/244.4	279.5/276.8
RWR	100.0/100.0	88.6/88.6	85.4/85.9	100.3/99.3	98.7/97.1	110.5/110.0
w/b ratio	0.534/0.531	0.417/0.415	0.406/0.406	0.475/0.475	0.485/0.475	0.514/0.509
Flow (mm)	125 / 130	120 / 125	125 / 130	130 / 125	130 / 130	125 / 120
TD (kg/m^3)	2286/2288	2313/2314	2319/2319	2262/2266	2254/2261	2245/2248

Yellow shading denotes values of relative water requirement (RWR) e.g. above 100%

Table B2: Mortar strength using GBC or Holcim blends

Age	Property	M1 / M11	M2 / M12	M3 / M13	M4 / M14	M5 / M15	M6 / M16
7 days (50 ^{0}C)	HD	2119/2126	2223/2199	2224/2221	2168/2155	2141/2160	2120/2152
	Strength	40.6 / 38.5	63.8 / 51.8	64.5 / 58.8	50.3 / 42.7	45.7 / 41.7	44.4 / 41.5
	RSI	100.0/100.0	149.3/127.8	150.9/145.1	117.7/105.4	106.9/102.9	103.9/102.4
28 days (21 ^{0}C)	HD	2114/2122	2206/2188	2214/2212	2150/2142	2132/2147	2102/2142
	Strength	40.4 / 42.4	53.4 / 48.3	55.3 / 52.4	41.7 / 39.8	34.9 / 41.3	42.1 / 40.5
	RSI	100.0/100.0	132.2/112.5	136.9/123.6	103.2/93.9	86.4 / 97.4	104.2/95.5
56 days (21 ^{0}C)	HD	2112/2132	2185/2190	2197/2209	2174/2149	2137/2153	2103/2125
	Strength	42.3/44.8	61.1/52.1	57.7/60.7	49.5/45.2	44.2/45.9	42.8/42.7
	RSI	100.0/100.0	144.4/116.3	136.4/135.5	117.0/100.9	104.5/102.5	101.2/95.3

Yellow shading denotes non-conformance of relative strength index (RSI) e.g. below 105%

Figure B1: Mortar mixing equipment, cube samples and flow table equipment

Table B3: Mortar mix ratios for strength activity index testing in accordance with EN197.1

Material	**M1 / M11**	**M2 / M12**	**M3 / M13**	**M4 / M14**	**M5 / M15**	**M6 / M16**
GP cement	1.0 [S1]	0.7 [S1]	0.7 [S1]	0.7 [S1]	0.7 [S1]	0.7 [S1]
SCM	0.0	0.3 [S2]	0.3 [S3]	0.3 [S4]	0.3 [S5]	0.3 [S6]
Sand	3.0	3.0	3.0	3.0	3.0	3.0
Water	0.5	0.5	0.5	0.5	0.5	0.5
Admixture	Low	Very low	Very low	Moderate	Moderate	Moderate
w/b ratio	0.50	0.50	0.50	0.50	0.50	0.50

Table B4: Mortar strengths from strength activity testing to EN197.1

Cement Supplier	Age (days)	M1 / M11	M2 / M12	M3 / M13	M4 / M14	M5 / M15	M6 / M16
GBC	7	34.7	25.5	22.8	21.0	18.9	23.4
	28	44.9	42.1	37.6	34.2	29.5	38.7
	90	55.2	54.8	51.6	44.1	36.7	44.0
Holcim	7	38.4	23.1	22.7	20.1	17.0	24.1
	28	49.9	41.5	40.1	30.8	25.9	40.3
	90	50.3	46.2	49.1	40.2	30.9	43.9

Appendix C: Concrete mixes

Table C1: Concrete mix designs with a nominal water/binder ratio of 0.45 using GBC (kg per cubic metre)

Material/ Property	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
GBC PC	350 S1	245 S1	245 S1	245 S1	245 S1	245 S1	322 S1	350 S8	245 S8	245 S8
SCM	0	105 S2	105 S3	105 S4	105 S5	105 S6	28 S7	0	105 S3	105 S4
13 mm	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100
Sand	835	805	805	805	805	805	825	835	805	805
Water	160	158	157	159	159	161	160	159	158	159
HRWR admixture	1750 ml	1350 ml	1000 ml	2000 ml	2000 ml	2150 ml	2000 ml	2150 ml	1200 ml	2200 ml
w/b ratio	0.457	0.451	0.449	0.454	0.454	0.460	0.457	0.454	0.451	0.454
Slump (mm)	140	150	130	150	130	120	120	150	140	130
Observations	Ok	Good	Good	Sticky	Bleed	Sticky	Sticky	Ok	Good	Sticky

Table C2: Concrete mix designs with a nominal water/binder ratio of 0.45 using Holcim (kg per cubic metre)

Material/ Property	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	HD 50% Slag
Holcim PC	350 S1	245 S1	245 S1	245 S1	245 S1	245 S1	322 S1	350 S8	245 S8	245 S8	123 S1
SCM	0	105 S2	105 S3	105 S4	105 S5	105 S6	28 S7	0	105 S3	105 S4	227 SD
13 mm	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100
Sand	835	805	805	805	805	805	825	835	805	805	835
Water	161	159	158	160	161	163	161	161	158	160	160
HRWR admixture	1750 ml	1350 ml	1000 ml	2000 ml	2000 ml	2200 ml	2000 ml	2000 ml	1500 ml	2000 ml	2000 ml
w/b ratio	0.460	0.454	0.451	0.457	0.460	0.465	0.460	0.460	0.451	0.457	0.457
Slump (mm)	160	160	150	160	150	130	150	140	160	140	130
Observation	Ok	Good	Good	Ok	Stiff/Seg	Sticky	Ok	Ok	Good	Ok	Sticky

Table C3: Concrete mix designs with w/b ratio of 0.35 for ASR CPT testing using GBC or Holcim cement

Material / Property	A1/A11	A2/A12	A3/A13	A4/A14	A5/A15	A6/A16	AD 50% Slag
GP cement	450 S1	315 S1	315 S1	315 S1	315 S1	315 S1	225 S1
SCM	0	135 S2	135 S3	135 S4	135 S5	135 S6	225 SF
13mm stone	1100	1100	1100	1100	1100	1100	1100
Greywacke sand	365	345	345	345	345	345	355
Andesite sand	365	345	345	345	345	345	355
Water	160	156	155	163	162	165	161
MRWR admix. (ml)	1750	1500	1500	2000	2000	2000	2000
NaOH	4.00	5.00	5.00	5.00	5.00	5.00	5.00
w/b ratio	0.65	0.64	0.63	0.66	0.66	0.67	0.66
Slump (mm)	160/140	150/150	150/130	130/120	140/110	120/100	130
Comments on mix	Ok/Ok	Good/Good	Good/Good	Ok/Ok	Ok/Ok	Ok/Ok	Ok

Table C4: Lower strength concrete mixes with water/binder ratio of 0.65 (GBC GP cement)

Material / Property	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**
GP cement	255 S1	178 S1	178 S1	178 S1	178 S1	178 S1	235 S1
SCM	0	77 S2	77 S3	77 S4	77 S5	77 S6	20 S7
13mm stone	1000	1000	1000	1000	1000	1000	1000
Sand	960	935	935	935	935	935	950
Water	165	165	165	165	165	165	165
MRWR admix. (ml)	1350	1000	1000	1500	1750	2000	1500
w/b ratio	0.65	0.64	0.63	0.66	0.66	0.67	0.66
Slump (mm)	155	160	130	130	130	130	140
Reverse slump	Yes	Yes	Yes	No	No	No	No

Table C5: Lower strength concrete mixes with water/binder ratio of 0.65 (Holcim GP cement)

Material / Property	**L11**	**L12**	**L13**	**L14**	**L15**	**L16**	**L17**
GP cement	255 S1	178 S1	178 S1	178 S1	178 S1	178 S1	235 S1
SCM	0	77 S2	77 S3	77 S4	77 S5	77 S6	20 S7
13mm stone	1000	1000	1000	1000	1000	1000	1000
Sand	960	935	935	935	935	935	950
Water	166	163	162	165	165	165	165
MRWR admix. (ml)	1350	1000	1000	1500	1750	2000	1500
w/b ratio	0.66	0.64	0.64	0.66	0.66	0.67	0.66
Slump (mm)	130	155	145	150	140	135	135
Reverse slump	Yes	Yes	Yes	Yes	No	No	No

Table C6: Embodied carbon dioxide from binders at 28-day strength of 50 MPa (avg. of GBC & Holcim)

Property	H1/H11 100% PC	H2/H12 30% FA	H3/H13 30% FA	H4/H14 30% Pozz	H5/H15 30% Perl	H6/H16 30% CC	H7/H17 8% SF	HD 50% Slag
w/b ratio [1]	0.593	0.520	0.533	0.509	0.352	0.552	0.611	0.425
Binder (kg/m^3) [2]	269.8	307.7	300.2	314.3	454.5	289.9	261.9	376.5
PC (kg/m^3)	268.8	215.4	210.1	220.0	318.2	202.9	240.9	188.2
eCO_2 (kg/kg) [3]	0.850	0.850	0.850	0.850	0.850	0.850	0.850	0.850
SCM (kg/m^3)	0	92.3	90.1	94.3	136.4	87.0	20.9	188.2
eCO_2 (kg/kg) [4]	0.000	0.025	0.025	0.050	0.025	0.330	0.025	0.100
Total eCO_2 (kg/m^3)	**228.5**	**185.4**	**180.9**	**191.8**	**273.9**	**201.2**	**205.3**	**178.8**

Notes: 1 – Based on average 28-day compressive strengths shown in Appendix E (Tables E1-E4)

2 – Binder content of concrete is based on a constant water demand of 160 L/m^3

3 – Embodied carbon dioxide is based on average level for GP cement in New Zealand

4 – Embodied carbon dioxide is based on international figures (tbc for New Zealand)

Appendix D: Fresh properties of concrete

Table D1: Cumulative bleed (L/m^3) of lower strength concrete (w/b = 0.65) – GBC GP cement

Time (hour:min)	L1 100% S1	L2 30% S2	L3 30% S3	L4 30% S4	L5 30% S5	L6 30% S6	L7 30% S7
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0:30	0.40	0.24	0.32	0.16	0.40	0.16	0.16
1:00	1.36	1.04	1.04	0.40	1.20	0.56	0.48
1:30	2.64	2.00	1.84	0.72	2.16	1.04	0.96
2:00	3.84	2.88	2.56	1.12	3.04	1.44	1.52
2:30	5.04	3.92	3.36	1.60	3.92	1.92	2.08
3:00	6.16	4.88	4.08	2.00	4.56	2.32	2.56
3:30	7.20	5.68	4.72	2.48	5.28	2.72	3.04
4:00	8.08	6.32	5.36	2.88	5.84	3.12	3.60
4:30	8.80	6.80	5.92	3.12	6.48	3.52	4.00
5:00	9.20	7.20	6.32	3.36	7.04	3.76	4.16
5:30	9.44	7.52	6.56	3.52	7.44	3.92	4.24
6:00	9.60	7.76	6.72	3.60	7.68		
6:30		7.92	6.80		7.76		

Table D2: Cumulative bleed (L/m^3) of lower strength concrete (w/b = 0.65) – Holcim GP cement

Time (hour:min)	L11 100% S1	L12 30% S2	L13 30% S3	L14 30% S4	L15 30% S5	L16 30% S6	L17 30% S7
0:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0:30	0.16	0.24	0.24	0.16	0.40	0.08	0.16
1:00	1.04	1.12	0.96	0.48	1.20	0.40	0.48
1:30	2.24	2.08	1.84	0.96	2.08	0.80	1.04
2:00	3.52	3.04	2.64	1.60	2.96	1.28	1.60
2:30	4.72	4.00	3.52	2.32	3.76	1.84	2.24
3:00	5.76	4.88	4.32	3.04	4.40	2.32	2.80
3:30	6.72	5.76	5.04	3.68	5.12	2.88	3.28
4:00	7.44	6.56	5.76	4.16	5.68	3.28	3.76
4:30	8.00	7.20	6.32	4.48	6.32	3.68	4.08
5:00	8.40	7.76	6.80	4.80	6.88	3.84	4.32
5:30	8.64	8.08	7.12	4.96	7.20	4.08	4.56
6:00	8.80		7.28	5.04	7.44	4.16	4.64
6:30			7.36		7.52		

Appendix E: Compressive strength of concrete

Table E1: Concrete mix trials with a nominal water/binder ratio of 0.45 using GBC (kg per cubic metre)

Material/ Property	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
Hardened Density (kg/m^3)	2425	2410	2425	2415	2430	2405	2402	2450	2413	2424
f_3 (MPa)	37.5	20.6	23.8	25.5	18.2	23.2	38.0	54.8	25.8	36.4
f_7 (MPa)	51.8	38.5	37.2	38.4	32.4	41.8	51.6	66.5	39.0	45.7
f_{28} (MPa)	71.6	55.7	54.5	53.3	46.0	59.5	80.7	83.7	60.9	67.9
f_{56} (MPa)	77.2	68.6	69.0	67.6	58.1	71.6	83.5	84.6	71.9	76.6
f_{90} (MPa)	78.0	73.3	76.3	71.0	60.5	70.6	89.6	87.5	75.0	74.8
f_{180} (MPa)	81.2	75.5	82.3	76.5	66.9	73.0	95.8	92.6	78.5	77.4

Table E2: Concrete mix trials with a nominal water/binder ratio of 0.45 using Holcim (kg per cubic metre)

Material/ Property	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20	HD
Hard Density (kg/m^3)	2450	2431	2413	2433	2442	2427	2428	2441	2431	2457	2455
f_3 (MPa)	37.0	30.5	29.3	31.4	15.9	33.1	43.8	56.5	40.2	42.9	18.4
f_7 (MPa)	51.6	45.6	43.5	43.7	27.3	49.8	61.5	69.3	51.8	53.9	24.5
f_{28} (MPa)	65.2	62.4	60.0	59.5	39.6	67.5	85.8	82.4	65.9	68.1	46.8
f_{56} (MPa)	69.5	70.8	71.1	68.3	45.2	70.6	92.1	88.2	71.8	71.7	54.7
f_{90} (MPa)	72.1	78.6	76.5	72.0	48.8	71.2	94.3	87.5	76.1	72.3	60.7
f_{180} (MPa)	74.8	77.5	78.0	74.2	52.5	71.0	92.6	88.4	79.1	75.3	62.8

Table E3: Compressive strength and hardened density of lower strength mixes (GBC GP cement)

Material / Property	L1	L2	L3	L4	L5	L6	L7
Hard. density (kg/m^3)	2385	2425	2420	2436	2390	2375	2396
3-day strength	18.3	9.8	13.8	11.9	9.7	10.8	16.1
7-day strength	27.5	17.6	21.4	21.3	14.6	19.1	26.6
28-day strength	43.5	32.5	39.4	33.5	27.7	37.1	40.5
56-day strength	48.0	41.3	47.9	41.0	32.3	40.0	51.6

Table E4: Compressive strength and hardened density of lower strength mixes (Holcim GP cement)

Material / Property	L11	L12	L13	L14	L15	L16	L17
Hard. density (kg/m^3)	2380	2435	2415	2403	2385	2381	2386
3-day strength	17.5	11.5	15.0	15.5	9.0	12.4	17.7
7-day strength	26.8	20.1	24.5	23.2	15.2	23.4	27.4
28-day strength	42.1	33.6	40.5	36.4	28.9	37.0	44.0
56-day strength	46.7	39.8	45.5	40.6	33.9	42.3	48.5

Appendix F: Transport properties and durability of concrete (water/binder ratio of 0.45)

Table F1: Concrete durability results recorded after 28 & 90 days (GBC & Holcim cements)

Durability Property	Age (days)	H1 H11	H2 H12	H3 H13	H4 H15	H5 H15	H6 H16	H7 H17	H8 H18	H9 H19	H10 H20
Effective Porosity (%)	28 28 90 90	8.61 - 6.78 7.34	10.05 - 8.39 6.32	8.22 - 7.56 5.82	8.98 - 7.35 5.68	8.81 - 7.76 8.54	6.75 - 5.85 5.05	6.00 - 5.27 5.69	7.00 - 6.97 5.85	7.80 - 6.27 5.84	7.45 - 5.31 7.06
Oxygen Perm. index	28 28 90	10.41 - 10.38 10.40	9.99 - 10.26 10.64	10.54 - 10.44 10.49	10.56 - 10.32 10.20	10.22 - 10.54 NR	10.72 - 10.60 11.14	10.79 - 10.68 10.29	10.52 - 10.29 10.53	10.68 - 10.72 10.37	10.62 - 10.59 10.10
Accel. Carb. 3-days	28 56	5.82 6.34	9.76 11.52	11.30 12.46	11.39 13.66	15.94 21.82	10.66 12.85	5.93 10.78	4.58 4.95	8.60 11.35	8.48 12.31
Accel. Carb. 7-days	28 56	6.04 6.28	9.35 10.13	9.01 9.32	9.67 11.77	12.12 18.85	8.42 10.33	4.98 6.73	3.33 3.22	7.58 11.02	6.87 10.47
Accel. Carb. 28-days	28 56	2.57 3.20	6.81 10.03	6.09 7.50	8.08 8.40	9.32 15.39	5.47 7.90	2.57 7.30	2.24 2.81	6.78 8.76	6.31 9.00
Resistivity (kOhm.cm)	28 56	9.32 11.18	9.13 10.05	12.42 13.51	10.40 17.09	9.23 12.66	23.11 30.27	19.26 28.81	10.71 12.32	11.24 18.01	13.28 21.69
Chloride Migration Diff. ($x10^{-12}m^2/s$)	28 90	18.33 16.71 9.99 12.95	22.63 14.50 8.26 5.16	17.76 13.38 5.65 4.90	22.88 16.17 5.49 5.09	32.76 22.94 13.18 12.80	10.43 5.71 5.35 2.65	8.40 5.99 2.81 3.03	11.45 10.27 8.35 9.79	15.32 14.53 6.23 8.62	18.00 15.64 5.76 9.33
Expansion CPT38 (%)	300 365	0.2296 0.0864 TBA Aug21	0.1396 0.0460	0.0060 0.0040	0.0176 0.0196	0.0160 0.0184	-0.003 0.0000				
Expansion CPT50 (%)	120 240	0.3378 0.2232 0.3378 0.2456	0.0988 0.0824 0.1384 0.1364	0.0008 0.0040 0.0092 0.0264	0.0084 0.0008 0.0324 0.0156	0.0148 0.0392 0.0364 0.0952	-0.010 -0.009 -0.011 -0.006				

HD: NTB492 – $10.78x10^{-12}$ (28 days) $8.66x10^{-12}$ (90 days), OPI – 10.87 (28 days),

Appendix G: Accelerated carbonation of concrete

Table G1: Carbonation depth (mm) of high strength concrete mixes with w/b = 0.45 (GBC)

Expose. (days)	Curing (days)	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
28	3	5.82	9.76	11.30	11.39	15.94	10.66	5.93	4.58	8.60	8.48
	7	6.04	9.35	9.01	9.67	12.12	8.42	4.98	3.33	7.58	6.87
	28	2.57	6.81	6.09	8.08	9.32	5.47	2.57	2.24	6.78	6.31
56	3	6.34	11.52	12.46	13.66	21.82	12.85	10.78	4.95	11.35	12.31
	7	6.28	10.13	9.32	11.77	18.85	10.33	6.73	3.22	11.02	10.47
	28	3.20	10.03	7.50	8.40	15.39	7.90	7.30	2.81	8.76	9.00

Table G2: Carbonation depth (mm) of lower strength concrete mixes with w/b = 0.65 (GBC)

Expose. (days)	Curing (days)	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
14	3	9.62		16.83		20.20	18.27				
	7	7.46		12.32		17.34	12.25				
	28	5.95		8.67		11.41	8.72				
28	3	12.66		24.51		27.02	NR				
	7	9.52		18.35		23.10	18.44				
	28	5.75		13.60		17.19	12.28				

Appendix H: Alkali silica reaction-induced expansion

Table H1: Expansion (%) of concrete prisms under CPT38 testing – GBC

Sample	0 d	7 d	14 d	28 d	56 d	84 d	112 d	150 d	180 d	210 d	240 d	270 d	300 d	360 d
A1 100% S1	0.000	-0.002	-0.003	-0.003	0.016	0.105	0.167	0.202	0.215	0.219	0.223	0.232	0.230	0.229
A2 30% S2	0.000	0.001	0.003	0.001	0.017	0.042	0.063	0.082	0.102	0.108	0.115	0.134	0.140	0.146
A3 30% S3	0.000	-0.003	-0.004	-0.007	-0.006	-0.004	-0.002	-0.001	0.001	0.002	-0.001	0.007	0.006	0.010
A4 30% S4	0.000	0.003	-0.004	-0.003	-0.008	0.002	0.002	0.004	0.008	0.009	0.007	0.012	0.018	0.022
A5 30% S5	0.000	0.000	0.001	-0.003	0.000	0.002	0.003	0.003	0.006	0.009	0.008	0.014	0.016	0.021
A6 30% S6	0.000	-0.003	-0.004	-0.006	-0.006	-0.006	-0.006	-0.006	-0.004	-0.004	-0.006	-0.006	-0.003	-0.004

Table H2: Expansion (%) of concrete prisms under CPT38 testing – Holcim cement

Sample	0 d	7 d	14 d	28 d	56 d	84 d	112 d	150 d	180 d	210 d	240 d	270 d	300 d	360 d
A11 100% S1	0.000	0.002	0.002	0.002	0.006	0.008	0.033	0.060	0.079	0.084	0.087	0.085	0.086	0.087
A12 30% S2	0.000	-0.002	-0.003	-0.005	-0.002	0.002	0.004	0.006	0.017	0.024	0.033	0.040	0.046	0.053
A13 30% S3	0.000	-0.002	-0.003	-0.006	-0.001	0.001	0.002	0.006	0.011	0.022	0.027	0.031	0.040	0.047
A14 30% S4	0.000	-0.001	-0.001	-0.004	-0.001	0.003	0.004	0.004	0.005	0.013	0.011	0.016	0.020	0.024
A15 30% S5	0.000	-0.002	-0.002	-0.005	-0.002	0.000	0.000	0.003	0.006	0.014	0.016	0.020	0.018	0.034
A16 30% S6	0.000	-0.002	-0.003	-0.009	-0.005	-0.005	-0.005	-0.003	-0.002	-0.002	-0.004	-0.003	0.000	0.002
AD 50% SD	0.000	0.003	0.005	0.001	0.005	0.006	0.007	0.008	0.009	0.007	0.006	0.005	0.004	0.004

Table H3: Expansion (%) of concrete prisms under CPT50 testing – GBC

Sample	0 d	7 d	14 d	28 d	56 d	84 d	112 d	150 d	180 d	210 d	240 d
A1 100% S1	0.000	0.004	0.037	0.162	0.278	0.317	0.326	0.332	0.335	0.339	0.338
A2 30% S2	0.000	-0.004	-0.004	0.015	0.049	0.084	0.099	0.109	0.120	0.130	0.138
A3 30% S3	0.000	-0.007	-0.006	-0.008	-0.004	-0.005	0.001	0.002	0.006	0.007	0.009
A4 30% S4	0.000	-0.003	-0.002	-0.002	0.001	0.005	0.008	0.014	0.020	0.028	0.032
A5 30% S5	0.000	0.004	0.001	0.001	0.004	0.010	0.015	0.018	0.024	0.032	0.036
A6 30% S6	0.000	-0.008	-0.006	-0.014	-0.012	-0.011	-0.010	-0.011	-0.009	-0.009	-0.011

Table H4: Expansion (%) of concrete prisms under CPT50 testing – Holcim cement

Sample	0 d	7 d	14 d	28 d	56 d	84 d	112 d	150 d	180 d	210 d	240 d
A11 100% S1	0.000	0.002	0.006	0.042	0.160	0.214	0.223	0.234	0.238	0.242	0.246
A12 30% S2	0.000	-0.002	0.000	0.009	0.032	0.057	0.082	0.098	0.108	0.121	0.136
A13 30% S3	0.000	-0.002	-0.006	-0.005	-0.002	0.001	0.004	0.010	0.015	0.020	0.026
A14 30% S4	0.000	-0.002	-0.007	-0.003	-0.001	-0.001	0.001	0.002	0.006	0.012	0.016
A15 30% S5	0.000	0.000	0.001	-0.002	0.002	0.018	0.039	0.056	0.068	0.084	0.095
A16 30% S6	0.000	-0.009	-0.007	-0.012	-0.012	-0.010	-0.001	-0.009	-0.009	-0.007	-0.006
AD 50% SD	0.000	0.000	0.001	0.000	-0.002	-0.002	-0.002	-0.002	-0.002	-0.002	-0.003

Table H5: Expansion (%) of concrete prisms under CPT50 testing – GBC (25% & 35% replacement)

Sample	0 d	7 d	14 d	28 d	42 d	56 d	84 d	120 d	150 d	180 d
A2R 35% S2	0.0000	0.0019	-0.0008	-0.0011	0.0013	0.0023	0.0048	0.0057	0.0093	
A4R 25% S4	0.0000	0.0024	-0.0007	-0.0028	-0.0021	-0.0006	0.0008	0.0009	0.0055	