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Towards High-Strength and Low-Carbon Concrete Masonry Blocks Using Locally Available Materials

Zarrinkoub, Mohammad

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Towards High-Strength and Low-Carbon Concrete Masonry Blocks
Using Locally Available Materials

by

Mohammad Zarrinkoub

A THESIS

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ABSTRACT

High-strength concrete masonry blocks are attracting attention to be used for loadbearing applications, such as tall walls. Such blocks can be achieved via modification of the dry mixture design and production methods. These modifications, however, may increase the carbon footprint of the concrete masonry blocks upon manufacturing. Careful selection of the mixture parameters is, therefore, necessary for the production of concrete blocks that have higher compressive strengths yet low carbon footprints. This study explored the effectiveness of using locally available materials for the production of dry concrete mixtures that can be used for the masonry block manufacturing. First, the suitability of utilizing pumice, sourced in British Columbia, as an alternative for Class F fly ash to partially replace the Portland cement in the concrete mixtures was studied. That was important as the availability of Class F fly ash is declining in Alberta and finding alternative replacements is imperative. To overcome the lower reactivity and strength development of pumice, a performance enhancing chemical admixture was used. Finally, recycled aggregates were obtained by crushing and pulverizing concrete masonry blocks that were used for structural testing in the laboratory. The so-produced aggregates were used as a replacement for the natural aggregates in the production of the dry concrete mixtures without and with pumice and chemical admixture. The resulting dry concrete mixtures were categorized into different classes of 30, 35, 40, and 50 MPa based on their average compressive strength at the age of 28 days in the laboratory conditions. Their mixture proportion with respect to their cement intensity (cement content per unit of strength) and application was discussed, and recommendations for future research were made. It is worth noting that although the results of this study were obtained for producing dry concrete mixtures, they can be extended for other concrete applications.

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To my beloved family

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List of Abbreviations

PC	Portland Cement
C&D	Construction and Demolition
RA	Recycled Aggregate
NA	Natural Aggregate
PLC	Portland Limestone Cement
SCM	Supplementary Cementitious Material
GBFS	Granulated Blast Furnace Slag
LC ³	Limestone Calcined Clay Cement
SAI	Strength Activity Index
RAC	Recycled Aggregate Concrete
NAC	Natural Aggregate Concrete
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CMU	Concrete Masonry Unit
FRA	Fine Recycled Aggregate
GWP	Global Warming Potential
LCA	Life Cycle Assessment
XRF	X-ray Fluorescence
SP	Superplasticizer
SSD	Saturated Surface Dry
ANOVA	Analysis of Variance
CI	Cement Intensity

Chapter 1 Introduction

1.1 Background

Concrete masonry blocks can be used for both nonloadbearing and loadbearing masonry applications. They are popular in building constructions due to their properties, such as good durability, thermal and acoustic insulation, fire resistance, and ease of construction [1]. Masonry walls, for instance, are one of the loadbearing masonry applications that have been constructed in numerous tall buildings in some countries such as Brazil. Their application in Canada, however, has been less substantial. This is partially because of the requirement specified in the Canadian Standard for the design of masonry structures (CSA S304 [2]). A primary limitation in these tall masonry structures is the compressive strength of the masonry units. The cross section of the wall at the base has to increase to withstand the high compressive forces of a tall masonry structure [3]. This limitation becomes more significant if the compressive strength of the masonry unit is low. Therefore, there is a need for further development of concrete masonry blocks with higher compressive strengths for loadbearing applications. To achieve this goal, some modifications are required in the mixture design of the concrete blocks. Use of conventional materials and methods to reach high compressive strength concrete, however, may not be beneficial from the environmental point of view. In fact, the concrete industry is facing challenges with regards to reducing its carbon footprint. Therefore, achieving high-strength and low-carbon concrete mixtures that can be used for the manufacturing of masonry blocks would be imperative.

1.2 Objectives

The main objective of this research was to develop concrete masonry mixtures with high compressive strength and low carbon footprint. This objective was achieved through an experimental study that could be divided into two main parts. Part I focused on developing a low-carbon cementitious matrix by comparing the pozzolanic reactivity of locally available pumice and fly ash, and evaluating their performance in paste and mortar mixtures. Part II studied the granular skeleton of concrete mixtures, and evaluated the use of recycled aggregates (RA) instead of natural aggregates (NA) for the production of high-strength concrete masonry mixtures without and with the modified cementitious matrix obtained in Part I.

1.3 Thesis organization

The thesis is comprised of five chapters. Following this chapter, which is the introduction, a review of the literature on the carbon footprints of concrete industry and the strategies to mitigate them is presented in Chapter 2. The experimental program, including the description of materials and experiments, is then described in Chapter 3. The experiments are categorized into two parts. Part I was mainly focused on the cementitious matrix, and Part II was on the granular skeleton. The results obtained from Part I and II are presented and discussed in Chapter 4. Finally, the main conclusions from this study and recommendations for future research are presented in Chapter 5.

Chapter 2 Literature Review

2.1 Introduction

Concrete is the most used material in the world after water [4]. It is a composite material composed of aggregates (such as sand and gravel) and a paste (typically a mixture of cement, water, and admixtures/additives). The fact that concrete is by far the most used construction material [5], makes it an important subject to investigate since any enhancement in the concrete engineering properties or reductions of its carbon footprint will be significant when it comes to the total production globally. The energy use and carbon dioxide (CO₂) emissions per unit weight of common construction materials are presented in Table 2.1. Compared to other construction materials, one unit weight of concrete has a low carbon footprint. The vast quantities of concrete consumption, however, has made it responsible for large impacts on the environment. The main environmental impact of concrete production is the carbon footprint which is associated with the Portland cement (PC) consumption. Therefore, to reach Canada's 2050 net-zero emissions goals, one of the industries that should play a major role would be the concrete industry. Consumption of raw materials and production of construction and demolition (C&D) wastes are among important environmental impacts of concrete industry, and it is essential to provide practical solutions to reduce them.

In this study, we focus on producing high-strength and low-carbon concrete masonry mixtures suitable for concrete masonry blocks manufacturing by modifying both the paste and the granular skeleton of the concrete. Although the implementation of the proposed methods in this study is revolved around production of concrete masonry blocks in Alberta, Canada, it can be extended to various concrete applications around the globe.

Table 2.1. Energy use and CO₂ emissions of common construction materials [6].

Material	Energy usage	CO₂ emissions
	MJ/Kg	KgCO ₂ /Kg
Concrete	0.95	0.13
Masonry	3.0	0.22
Wood	8.5	0.46
Steel: virgin	35	2.8
Steel: Recycled	9.5	0.43
Aluminum: virgin	218	11.46
Aluminum: recycled	28.8	1.69
Glass	15.7	0.85

2.2 Carbon footprint of PC production

The cement industry is among the three largest industrial energy consumers, and it is responsible for about 7% of the global greenhouse gas emissions [7]. Production of every tonne of PC results in emission of about 0.87 tonnes of CO₂ [8], out of which about 55% originate from limestone decomposition, about 31% result from fuel combustion, and about 14% are due to the electricity use and indirect emissions [9]. During the production of PC, limestone (CaCO₃), which is one of the main raw materials used, goes through a thermal decomposition and changes into calcium oxide (CaO) and CO₂. This process is called calcination of limestone and has the largest share in the total CO₂ emissions of PC production. The CaO, then, reacts with other elements from the raw materials to produce calcium silicates and calcium aluminates which are the main chemical compounds found in PC. These reactions happen at high temperatures of about 1400 °C [10],

requiring considerable fuel consumption, and result in formation of clinker. Finally, the clinker is ground and mixed with a small amount of gypsum creating PC. Electricity that is used to run the equipment, such as crushers and grinders, and the indirect emissions incorporated with other activities, such as transportation of the raw materials and the final product are responsible for the rest of CO₂ emissions from the PC production.

2.3 Resource consumption and demolition waste production

Large quantities of concrete are used globally every year. In 2012, over 25 Gt of concrete were produced worldwide [11]. Such a huge number requires consumption of massive amounts of raw materials, especially aggregates as they account for 70 to 85% of the total concrete weight. The global consumption of NA, in 2015, was reported to be around 48 billion tonnes per year [12]. It is expected that the demand for concrete, and as a result for the NA, follows an increasing trend as the population of the world is anticipated to reach about 10 billion people by 2060 [13]. All those people require houses, schools, roads, and other infrastructure. Such new constructions inevitably need consumption of the raw materials. Consumption of the natural sand and gravel as aggregates in concrete may not appear as a critical issue at first glance as the earth is covered with them. However, it should be noted that not all the sand and gravel on the earth are suitable for use in concrete as they do not have desired properties. The sand that is used in the construction industry is typically provided from pits, rivers, lakes, or seabed. Therefore, the geological availability of these resources, more specifically sand, is limited in some countries. In addition, in many regions, the uncontrolled extraction of the sand from the riverbeds has already caused some environmental impacts, such as erosion and threats for the biodiversity [14], creating an urge for practical actions in the near future to control or prevent such problems.

The issue is not just limited to the consumption of these natural resources. When the service life of a structure is over, demolition has to happen. The C&D waste that is produced is mostly disposed of in landfills. In China, for instance, approximately 1.8 billion tonnes of C&D waste are generated annually which mainly end up in landfills [15]. As a result, the sand and gravel along with other types of raw materials that are becoming scarcer and more valuable every day, are being disposed of in the landfills at the end.

2.4 Strategies to reduce the environmental impacts of concrete

Different strategies have been implemented to reduce the environmental impacts of concrete. In this section, some of these strategies are presented in two categories. First, some strategies that are currently being used in the industry or have the potential to be used in large scale with today's technology are discussed. Then, some emerging methods and technologies are introduced.

2.4.1 Current strategies

2.4.1.1 Structural design efficiency

Studies have shown that in many applications, concrete elements are designed inefficiently and there is room for optimization in terms of structural design that results in reduction of material usage. Such structural design optimization is an effective way of reducing the CO₂ emissions associated with the construction industry [16–18].

2.4.1.2 Efficiency in cement production

The type of kiln that is used for production of PC mainly determines the efficiency of cement plant in terms of energy use. There are generally four types of kilns that have been used for the production of PC which vary in the amount of energy required to produce one tonne of clinker.

The least efficient type is the long rotary kiln burning raw materials in a wet state which requires about $6000 \text{ MJ}/t_{clinker}$ [19]. On the other hand, the modern rotary kiln that burns raw materials in a dry state and is equipped with preheater, precalciner and recovery system is the most efficient type that requires as low as $3100 \text{ MJ}/t_{clinker}$ [19]. The amount of energy required for other kiln types falls in between these two ranges depending on the process being wet, semi-dry, or dry and other pieces of equipment being used. The oil crisis in 1973, which increased the energy costs, forced many cement plants to use more energy-efficient methods in their production line. Today, more than 85% of the cement plants are using dry process for their kilns [20].

The theoretical enthalpy that is required for the production of one tonne of clinker is 1760 MJ [21]. Therefore, there is still room for improvement in the efficiency of the kilns. It is, however, inevitable to lose some energy in the production process. It has been reported that it may not be possible to improve the efficiency of kilns to a state requiring less than $2500 \text{ MJ}/t_{clinker}$ [22]. Therefore, with the today's technology, retransforming of the kilns may not be a cost-effective option. Yet, there is potential in using dry process with preheater and precalciner in more cement plants.

2.4.1.3 Alternative fuels

The modern kilns that are being used for production of PC are very flexible in terms of the type of fuel required for combustion. In many regions, waste materials are being used as the fuel to create the thermal demand for PC production [23]. Many of the waste materials used to be burnt in incineration plants, and using them instead of fossil fuels in cement plants has a great effect on the net CO_2 reduction.

2.4.1.4 Utilization of higher volumes of limestone in the PC composition

It is common to replace a small portion of clinker with ground limestone, which is one of the raw materials used for production of PC and can be found in large volumes in diverse geographical regions around the world, without observing any negative effect on the properties of the final product [23]. The PC incorporated with limestone is known as Portland limestone cement (PLC) which is a product of intergrinding the PC clinker, limestone, and gypsum. While in countries like Canada the share of limestone in PLC is limited to 15% [24], in the European countries the replacement levels are allowed to go up to 35% [25].

Limestone can affect the hydration kinetics of the PC by its physical and chemical properties. The physical effect of limestone is associated with its filler effect. In addition, it can react with the alumina present in the matrix and form phases that can help the durability and strength [23]. However, the alumina content is limited in conventional cementitious matrix. Therefore, the effect of limestone would be mostly restricted to its filler effect for the higher replacement levels. The filler effect of limestone, however, is also constrained by the current technology being used for intergrinding the clinker and limestone for PLC production. This would result in a reduction in the mechanical properties of final product [23]. Therefore, unless extra alumina is provided by means of introducing another material to the matrix (a ternary blended cement) [26], it may not be possible to increase the clinker replacement level with limestone without the expense of poorer mechanical properties.

2.4.1.5 Efficient use of PC

Studies have shown that PC content of concrete mixtures can be reduced to some extent without affecting their performance [27–29]. Compressive strength of concrete, for example, which is known as one of the most important properties of the concrete, was reported unchanged by

decreasing up to 30% of the cement content at a constant water-to-cement ratio (w/c) as long as there was sufficient paste volume in the concrete mixture. Moreover, the mixtures with lower cement content outperformed those with higher cement content in durability tests [28]. Therefore, another method to reduce the total CO₂ emissions of concrete would be careful selection of the mixture proportions. Some methods to improve the efficiency of PC in the concrete include using dispersants (i.e., superplasticizers) [30] and increasing the particle packing of aggregates and cementitious materials [31]. Furthermore, concrete mixtures with higher compressive strength tend to be more efficient in delivering each unit of strength by requiring a lesser amount of binder [29].

2.4.1.6 Use of supplementary cementitious materials

The use of supplementary cementitious materials (SCMs) as partial replacement of PC, alongside with more efficient mixture proportioning, is known as the most practical immediate solution to reduce the CO₂ emissions related to cement and concrete industry [32]. In addition to reduction in CO₂ emissions, use of SCMs can offer enhancement in the mechanical properties and durability of concrete, and reduction in its manufacturing cost [33]. Considering the significant advantages of using SCMs, there has been a growing tendency in the concrete industry to further increase the substitution of clinker with SCMs. It has been reported that in 2003, clinker made up about 85% of the PC; however, in 2010, the corresponding figure was about 77% [34]. The most commonly used SCMs, such as fly ash, granulated blast furnace slag, and natural pozzolans, are either industrial by-products or natural materials that are blended with clinker to make blended cements or are added to concrete as partial replacement of PC. Common SCMs are described in greater details in the following sections.

Fly ash

Fly ash is a by-product of coal combustion in electric power plants. According to the ASTM C618 [35], it is categorized into two classes, class F and class C, based on its chemical composition. While class F fly ash only has pozzolanic properties, class C fly ash shows cementitious properties in addition to pozzolanic.

Although burning coal will remain one of the main sources to produce electricity in many regions around the globe for the foreseeable future, it has already started to phase out in some countries [23]. In Alberta, Canada, for example, around 55% of the electricity was produced by coal combustion in 2014. However, by switching to consumption of natural gas rather than coal, it was reported that the share of coal combustion to produce electricity in Alberta will reach zero by the end of 2023 [36]. Therefore, fly ash supply would not be able to meet the demand of concrete industry in countries like Canada. There has been research on this topic suggesting beneficiated (treated fly ashes that do not meet the ASTM requirements originally) and reclaimed (retrieved from landfills) fly ashes to be used in concrete industry [37]. However, the urge of looking for an alternative for fly ash is tangible.

Granulated blast furnace slag

Granulated blast furnace slag (GBFS) is a by-product of pig iron production. During the pig iron production, the molten GBFS stands on top of the molten iron due to the density difference. If the GBFS is rapidly quenched, a glassy material with cementitious properties is formed [38]. Factors such as type of the raw material used, method and rate of quenching affect the quality and the cementitious properties of the GBFS produced [39]. ASTM C989/C989M [40] classifies GBFS into three grades of 80, 100, and 120 based on the compressive strength development potential at 28 days. The numbers represent the ratio of compressive strength of standard mortar samples when

50% of the PC is substituted with GBFS to the compressive strength of reference standard mortar samples.

The annual global production of GBFS in 2022 was estimated to be between 330 to 390 million tonnes [41]. Over 90% of the global GBFS production is already being used as SCM [32]. However, there are two main challenges facing the use of GBFS in concrete industry. First, the availability of GBFS is mainly limited to industrialized countries and regions with iron production plants. In Canada, for example, most of the iron ore is produced in the east side of the country. Therefore, for provinces in the west side of Canada, GBFS is not locally sourced and needs to be transported from the east or from other countries. Second challenge for the use of GBFS in concrete is a declining trend in the GBFS production due to the spread of recycling of steel [23]. Hence, other sources of SCMs need to be explored to be used in cement and concrete industry in regions like Alberta.

Natural Pozzolans

Natural pozzolans are the materials that can be found in the nature and show pozzolanic properties after being processed, calcined, or both. The use of natural pozzolans in concrete has been common throughout history and goes back to the ancient times when mixtures of lime and natural pozzolans were used for construction purposes [42]. Less than a century ago, they were still being used in the concrete industry for different applications. However, fly ash, with extensive availability and a competitive price, found its way to the concrete industry in the 20th century leaving not much room for natural pozzolans [43]. With the increasing global demand for SCMs and the recent shortcomings in the conventional resources of SCMs such as fly ash and GBFS, the use of natural pozzolans has received interest again in the concrete industry.

Kaolinite, which is one of the clay minerals that is abundantly found in the earth's crust, can have cementitious properties if it is activated through heating up to a high temperature (around 600 to 800 °C) [44]. Calcined kaolinite, also known as metakaolin, has been used previously as SCM. Metakaolin, however, has other applications, such as paper treatment, ceramic and refractory industries, for which strict requirements on purity and color need to be met [45]. Although pure metakaolin can be used in production of high performance concrete [46], it is considered as an expensive SCM due to its application in other industries. On the other hand, research has shown that low-grade metakaolin could also provide satisfactory properties as SCM [47]. Recently, a blend of low-grade metakaolin and limestone has been incorporated in cement production to substitute approximately 50% of the PC clinker. The resulting type of cement is referred to as limestone calcined clay cement (LC³) [48,49].

As it can be seen in the Figure 2.1, kaolinite can be found in many regions around the world especially in some of the countries that demand concrete the most in the near future. However, in some countries like Canada, the use of metakaolin in concrete industry is challenging due to the limited availability of kaolinite.

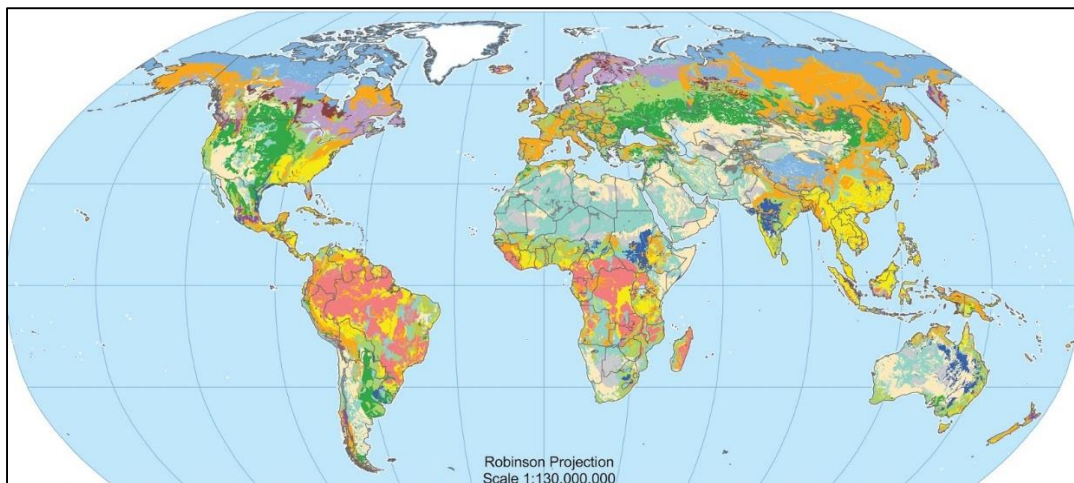


Figure 2.1. Kaolinite distribution (pink (oxisols), yellow (ultisols), and pale green (alfisols)) around the globe [50].

Diatomaceous earth is a sedimentary material that can have pozzolanic properties and can be found in vast quantities in the western states of the US and many other countries [51]. The use of diatomaceous earth as a PC replacement for casting concrete and mortar samples has been investigated and promising results have been published [51–53]. Although the high water demand of diatomaceous earth limits its substitution level, with the help of superplasticizers, up to 40% substitution can be achieved as reported by Li et al. [51].

Volcanic materials are another group of natural pozzolans that can be used in the concrete industry. Pumicites, perlites, zeolites, tuffs, and volcanic ashes contain high contents of amorphous silica and alumina making them perfect candidates for being used as SCMs in concrete [32]. It is noteworthy to mention that not all the volcanic rocks can be considered as potential sources of SCMs [54]. Figure 2.2 shows the global distribution of the volcanic rocks. Although they can be found in many countries across the globe, limited regions have been reported to have deposits of volcanic materials with pozzolanic properties.



Figure 2.2. Global distribution of volcanic rocks (grey regions) and reported natural pozzolan deposits (red dots) [54].

The use of natural pozzolans as SCMs in the concrete industry can be seen as a promising method to mitigate the carbon footprint of production of PC in regions where other types of SCMs are not locally available. In Alberta, for instance, with diminishing sources of fly ash and limited access to local GBFS, the interest in the utilization of natural pozzolans has been increased. In this study, pumice is used as an SCM to further investigate its potentiality to replace fly ash in the concrete masonry blocks production.

Need for new SCMs and reactivity measurement methods

The availability issue of different common SCMs was discussed before. In summary, we are facing a shrinkage in the supply of the conventional SCMs, such as fly ash and GBFS. Therefore, there is a necessity to look for new SCMs, and methods to measure the reactivity of these new sources.

ASTM C618 [35] has been employed for many years to determine whether a certain type of fly ash or natural pozzolan is qualified for being used in concrete. This standard defines some requirements for chemical composition and physical properties of the materials being tested. It also uses strength activity index (SAI) as an indicator of the reactivity of the testing material. The SAI is the relative compressive strength at 7 or 28 days of the testing mortar mixture to the reference mortar mixture. If the SAI of the mortar mixture containing 20 wt% of the testing fly ash or natural pozzolan as replacement of PC is at least 75% at the age of 7-day or 28-day, the SCM passes the reactivity requirement for use in concrete.

The SAI criterion is misleading and has been criticized in the literature [55,56]. The reason is that it is only limited to 7 or 28 days, and in case the requirement is met at any of these ages, the SCM is considered reactive. The compressive strength at ages as early as 7 days, however, can be affected by the physical properties (such as particle size and the filler effect) of the materials being used for casting the mortar samples. This would result in acceptance of materials based on their

physical properties rather than chemical reactivity. In fact, Kalina et al. [55] have shown that ASTM C618 [35] has the potential to approve some inert materials as reactive SCMs suitable to be used in concrete industry [55]. In addition, many SCMs react at longer ages than 7 and 28 days. ASTM C618 has other technical issues such as using variable water-to-binder ratios (w/b) for the mortar samples used for the SAI criterion. The testing procedures of the requirements stated in ASTM C618 [35] should comply with testing methods proposed in ASTM C311/C311M [57]. In ASTM C311/C311M [57], the water content of the testing mortar mixture must be adjusted so that the flow of the testing mixture equals (± 5) to the flow of the reference mixture. Based on this method, the w/b ratio of the testing mixture may be different from that of the reference mixture. This will affect the SAI of the mortar samples as w/b ratio is a major factor affecting the compressive strength. Consequently, the SAI may not be a good indication of the chemical reactivity of the tested SCM.

Recently, there have been several studies on new test methods to assess the reactivity of SCMs. For example, Avet et al. [58] proposed a “rapid, relevant, and reliable” (R^3) method that can provide acceptable correlations with the compressive strength results of mortar mixtures. Similar method has been specified by the ASTM C1897 [59] and RILEM TC-267TRM [60–62] to measure the reactivity of the SCMs.

In this study, ASTM C1897 was used for the reactivity measurement of the SCMs (i.e., pumice and fly ash). Furthermore, after addressing the main issues of the SAI, such as the age of testing and the variable w/b ratio presented in the ASTM C618, mortar samples were cast for comparison with the results of the reactivity measurement.

2.4.1.7 Use of performance enhancing admixtures

Some types of chemical admixtures, such as synthetic C-S-H nanocomposites, can enhance the performance of cementitious mixtures by increasing the rate of PC hydration reactions particularly at the early ages (prior to 28 days). Mixtures incorporating these admixtures, therefore, are able to develop a higher compressive strength at an earlier time. These admixtures can also be used for production of low carbon cementitious mixtures. Generally, higher levels of clinker replacement with SCMs can lead to a decrease in the mechanical properties of cementitious mixtures especially at the early ages. This can limit the use of SCMs to lower replacement levels for applications that the early age properties of concrete are of significant importance. Utilization of performance enhancing admixtures can potentially compensate the lower compressive strength gain of the cementitious mixtures incorporating higher level of SCMs. In this regard, Zhao and Khoshnazar [63] reported that paste mixtures incorporating 40% low-grade metakaolin showed comparable strength to that of the reference cement paste after addition of C-S-H seed.

2.4.1.8 Use of recycled aggregates

The use of recycled materials, such as RA, in the concrete industry has attracted attention for a variety of reasons such as conservation of non-renewable natural resources, reduction of the quantity of materials being disposed of in the landfills, reduction of the materials cost, and mitigation of the environmental issues such as erosion due to uncontrolled extraction of natural aggregates [64–66]. Nevertheless, there are some limitations on using RA in the concrete industry. For example, recycled aggregate concrete (RAC) generally shows inferior mechanical and durability properties compared to natural aggregate concrete (NAC) [12,67]. In addition, the properties of RA may vary from one source to another.

There are numerous methods proposed in the literature to enhance the performance of RAC. Applying various types of treatments on the RA [68–73], increasing the cement content [74], incorporating SCMs [75,76], using fibers in the concrete mixture [77,78] and modifying mixing approaches [79–81] have proven to be effective methods to improve the performance of RAC. A practical and effective method for enhancing the performance of RAC is to use the RA in a saturated rather than dry state. This method not only controls the effective w/b ratio of the RAC [82], but also is reported to result in a denser interfacial transition zone between the aggregate and the paste, enhancing the mechanical properties of the RAC [83].

A recent study by Théréne et al. [84] has shown that the European standard method for determining water absorption of aggregates (EN 1097-6 [85]) may not be suitable for measuring the water absorption of RA and cause an overestimation. This overestimation is due to creation of porosity and removal of some of the bound water in the cement paste of the RA at the temperature prescribed in the standard (i.e., 105 °C). It is, therefore, suggested that the water absorption measurement of RA should be done at a lower temperature [84]. ASTM C128 [86] specifies an almost similar method and temperature to that described in the European standard for the water absorption of aggregates. The overestimation of the water absorption results in extra free water in the mix which increases the effective w/b ratio. This could account for the inferior performance of RAC compared to NAC.

Chu et al. [87] studied the effect of packing density of NA and RA on the properties of concrete paving blocks. Their results showed that increasing the packing of the RA can improve the compressive strength of RAC by 156% and to a comparable level with a well-packed NAC [87]. These results demonstrate that RA could be successfully used in production of concrete without compromising its mechanical performance.

2.4.2 Long term strategies

2.4.2.1 Alternative binders

Alternative binders are materials that can be used instead of PC in mortar or concrete and create a hardened paste that attaches the aggregates together [88]. Some of the examples of the alternative binders include alkali activated binders, calcium aluminate cements, calcium sulfoaluminate cements, magnesium-based cements, supersulfated cements, and carbonation hardening cements. The raw materials, reaction kinetics, properties, opportunities, and challenges of these alternative binders have been discussed in the literature [23,88–92].

Compared to PC, the alternative binders can have lower carbon footprint [89,93,94]. For example, different mixtures made with alkali activated binders can have about 40 to 80% lower CO₂ emissions compared to PC-based mixtures [91]. Nevertheless, the challenges facing these alternative binders, such as the availability of raw materials, cost, and lack of technical knowledge compared to PC has limited the large-scale and widespread application of these alternative binders.

2.4.2.2 Carbon capture, storage, and utilization

An effective method for reducing the carbon footprint of industries with high CO₂ emissions, such as the cement industry, is carbon capture, storage, and utilization. Carbon capture and storage (CCS) refers to a range of technologies that enable transporting the CO₂ emissions from major sources to safe geological storage, rather than being released into the atmosphere. Furthermore, carbon capture and utilization (CCU) offers an industrial process that converts CO₂ into useful chemicals or construction materials. One example of CCU is the carbonation curing technology recently developed for the Portland cement concrete production, which permanently stores CO₂ within the concrete.

Unreacted PC particles and the products of the hydration of PC can react with CO₂ of the atmosphere. This reaction is called carbonation which naturally occurs at a very slow pace. The accelerated carbonation of concrete (carbonation curing) within 24 hours after casting, however, can be an effective method to reduce the carbon footprint of concrete production as well as increasing the concrete performance [95]. Nevertheless, the implementation of carbonation curing demands significant investments, and the process requires carefully controlled condition for the production of concrete products. Commercial concrete products, including concrete masonry blocks, cured based on this technology are available in different countries, including Canada. Although carbon utilization is more commonly used for pre-cast concrete application, it has attracted attention for ready-mix concrete as well [96]. A new study by Ravikumar et al. [97], however, indicated that CCU may not provide any significant net CO₂ reduction benefit when the source of the CO₂ is taken into account. Thus, strategies have to be employed to increase the net CO₂ benefit of this solution in the long term.

2.5 Introduction to concrete masonry blocks

Concrete masonry blocks are an important type of concrete masonry units (CMU) that are largely used for applications such as building and retaining walls. ASTM C1232 [98] defines CMU as a “manufactured masonry unit made of concrete in which the binder is a combination of water and cementitious materials.”

CMUs generally have a low PC and paste content in their mix. This is desired because a dry mix is needed for the CMU production. The dry mix enables an immediate demolding after compaction of the concrete which will increase the production rate. CMUs, despite having a relatively low cement content, have a considerable carbon footprint. It has been reported that the production of

one concrete masonry block is approximately responsible for 2.10 to 2.34 kg of the CO₂ equivalent across Canada [99]. This number can be even greater for high-strength concrete blocks since they typically require a higher cement content compared to blocks with normal strength. Most of the methods described in the previous sections to lower the carbon footprint of concrete production may also be utilized for the concrete masonry block production. In this study, however, our focus has been on the utilization of SCMs and recycled aggregates as they present an easier implementation for the masonry industry.

There are limited recent research publications on the feasibility of using different SCMs for CMU production [100–102]. Partial substitution of PC with SCMs in masonry mixtures, however, is a commonly used practice in the CMU manufacturing industry [103]. Utilization of RA to partially and fully replace NA for CMU production has been investigated in the literature [103–110]. It has been reported that RA can replace NA without any practical issues to cast RAC and with satisfactory properties that meet the requirements for CMU production. A great source for high quality RA in the concrete masonry block manufacturing plants is the broken blocks that are mainly considered as waste. The idea of employing used CMUs for production of new ones has been recently evaluated in the literature. Zhao et al. [109] used RA produced from old CMU to substitute the NA at two different levels (30% and 100%) for production of new CMUs. The results indicated that CMUs produced by RA at both replacement levels could satisfy the mechanical and durability requirements. Rizwan et al. [103] also used fine recycled aggregates (FRA) obtained from waste materials of a concrete masonry block plant to manufacture new blocks. The results showed that it is feasible to use FRA up to 100% to manufacture new concrete masonry blocks and achieve acceptable compressive strength. In addition, Liu et al. [110] evaluated the global warming potential (GWP) of concrete masonry blocks incorporating RA by using the life cycle

assessment (LCA) methodology. Their results demonstrated that the primary factors behind the variation in carbon emissions between NAC and RAC blocks are the methods used to produce the aggregates and transport the materials. They reported a 7.2% lower GWP for RAC blocks with 100% RA compared to NAC ones. Beyond a certain distance range for transporting the aggregates, however, the carbon emission of RAC blocks would exceed that of the NAC blocks [110]. It is worth mentioning the RA used in this study was sourced locally.

2.6 Summary

Concrete, the most widely used construction material, has significant impacts on the environment. The carbon footprint associated with the PC consumption is an important environmental impact of producing concrete materials, including concrete masonry blocks. The carbon footprint of concrete blocks is considerable even though they typically contain a low PC content in their mixture. The low PC content of the concrete block mixtures is typically chosen due to the low compressive strength requirements of this concrete product. There is, however, a need for high-strength concrete blocks for loadbearing applications. Use of common approaches to increase the compressive strength of concrete masonry blocks may even further increase their carbon footprint. Therefore, development of high-strength concrete blocks with a low carbon footprint is imperative. In this chapter, practical strategies to reduce the environmental impacts of concrete were reviewed, and those that can be easily implemented in the industry were identified. Among all the methods, use of SCMs to partially replace PC, and use of RA instead of NA were found to have great potential for the environmental benefits in the large-scale production. There are, however, still research gaps that need to be filled as the supply of conventional SCMs, especially class F fly ash, is declining and finding alternative options has become vital. Furthermore, the use of RA for concrete masonry block production has been mostly limited to mixtures with low compressive

strengths. This study has been designed to fill these gaps through an experimental program that has been described in the next chapter.

Chapter 3 Experimental Program

3.1 Materials

3.1.1 Cementitious materials

The cement used in this research was a general use PC (GU/GUL, Quikrete) complying with the Canadian standard (CSA A3001-18 [111]), with a relative density of 3.15. Pulverized pumice and fly ash were provided by Lafarge, Canada, and were used as supplementary cementitious materials to partially replace PC in the samples. The relative density of pumice and fly ash were 2.4 and 2.6, respectively. Pumice was sourced from British Columbia, and fly ash was sourced from Alberta. The chemical composition of the cementitious materials was determined using X-ray fluorescence (XRF) by the Activation Laboratories Ltd (Actlabs), Canada. The results are presented in Table 3.1. The median particle diameters (D50) for PC, pumice, and fly ash used in this study were 9.2, 13.7, and 24.3 μm , respectively.

Table 3.1. Chemical composition of PC, pumice, and fly ash (wt%).

	SiO₂	Al₂O₃	Fe₂O₃	CaO	MgO	SO₃	Na₂O	K₂O	TiO₂	LOI
PC	18.29	3.79	3.32	60.15	4.53	3.29	0.12	0.39	0.23	5.89
Pumice	57.39	16.38	5.84	6.48	2.09	0.23	2.07	1.33	0.63	6.63
Fly ash	54.96	23.23	3.59	10.99	1.14	0.23	2.57	0.74	0.67	1.15

Reagent grade calcium hydroxide, calcium carbonate, potassium hydroxide, and potassium sulfate were purchased from Fisher Scientific, Canada, and were used as received for the reactivity measurement test.

3.1.2 Chemical admixtures

A polycarboxylate-based superplasticizer (SP) (Glenium 3030, BASF) was used in paste and mortar mixtures containing pumice in order to adjust the flow of the mixture. A commercial synthetic C-S-H (X-Seed 55, BASF, Canada) in the form of a suspension with about 7 wt% of solid content dispersed in polymers was also used as a performance enhancer for the paste, mortar, and concrete mixtures.

3.1.3 Aggregates

Standard sand complying with the ASTM C778 [112] was used for preparing the mortar samples. Two types of aggregates, natural and recycled aggregates, were used for preparing the concrete mixtures. The natural aggregate (NA), as shown in Figure 3.1 (a), was provided by a local supplier. Its gradation is presented in Figure 3.2. The specific gravity and water absorption of the NA, as determined according to ASTM C128 [86], were 2.61 and 1.2%, respectively. The recycled aggregate (RA), as shown in Figure 3.1 (b), was prepared in the laboratory from concrete masonry blocks that had been previously used by the masonry group at University of Calgary, and were supposed to be disposed of. Its gradation is shown in Figure 3.2.

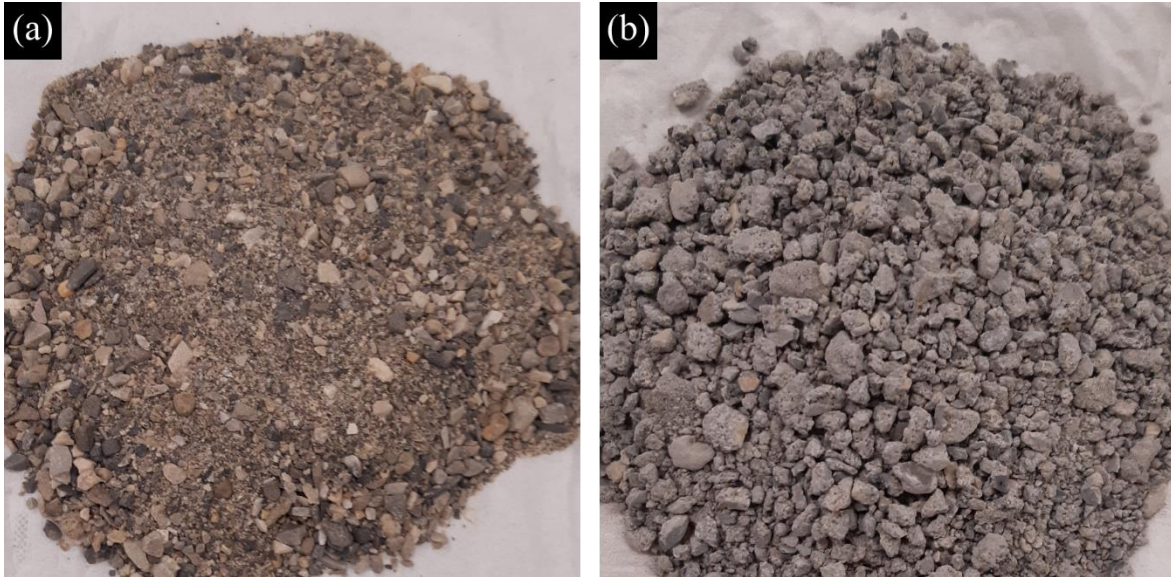


Figure 3.1. (a) natural aggregate and (b) recycled aggregate used in this study.

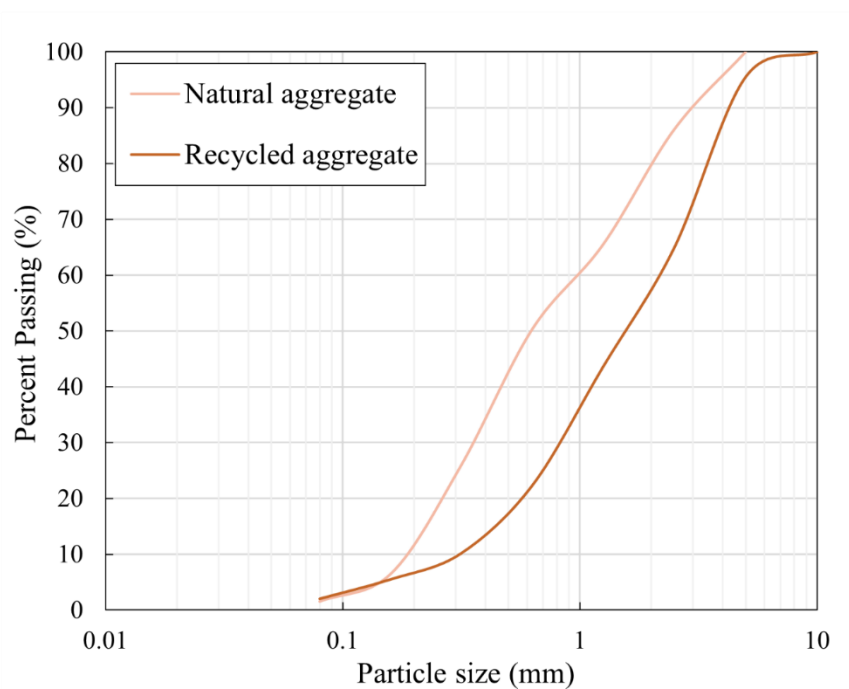


Figure 3.2. Particle size distribution of natural and recycled aggregates.

The process of production of RA (as shown in Figure 3.3) started by firstly crushing used concrete masonry blocks with a hammer. Then, the size of the crushed block pieces was further reduced by using a jaw crusher (BICO Inc.) and subsequently a pulverizer (BICO Inc.) The so-produced RA

was tested for the particle size distribution and water absorption, and was used as a replacement of the NA in the concrete mixtures.

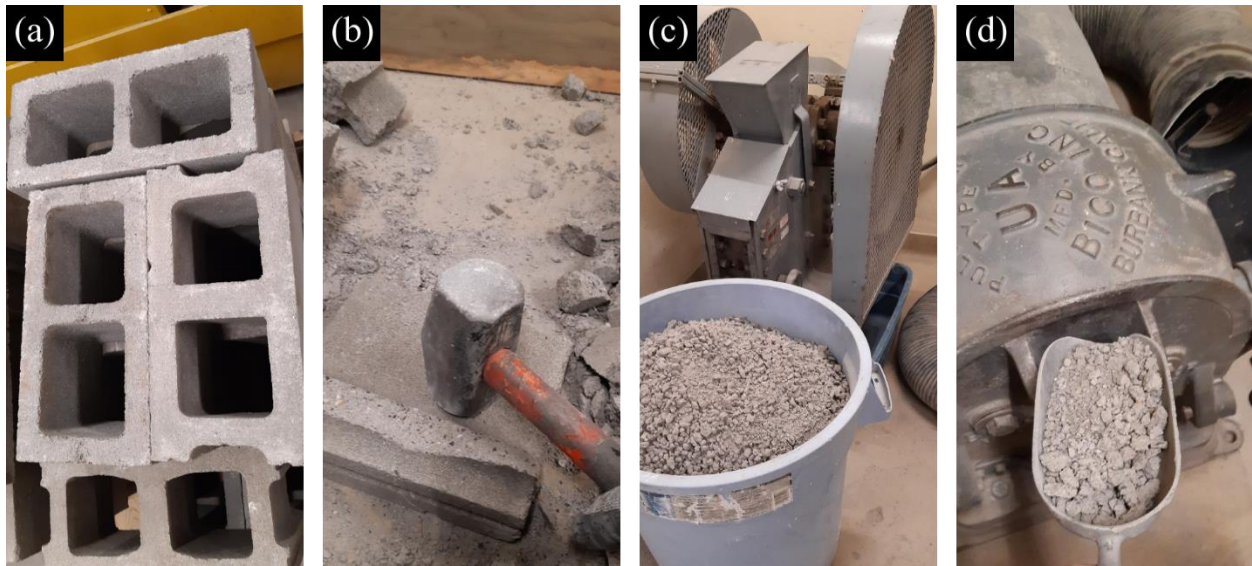


Figure 3.3. (a) used concrete masonry blocks (b) crushing the used concrete masonry blocks with a hammer (c) reducing the particle size by using a jaw crusher (d) further reducing the particle size by using a pulverizer.

The specific gravity of the RA was 2.04 as determined according to the ASTM C128 [86]. The water absorption of the RA was measured based on a method adopted from ASTM C128 [86]. The literature shows that drying the RA at a temperature of 110 ± 5 °C (specified by the standard) overestimates the water absorption of the RA as it removes some of the bound water in the cement paste, and creates more porosity [84]. In this study, to obtain a more accurate measurement of the water absorption of the RA, a lower temperature (40 ± 5 °C) was used. The RA with the saturated surface dry (SSD) condition was kept in an oven until a constant mass was attained (the mass measurements in a 2-hour interval did not differ more than 0.2% from each other). The water absorption was then calculated by Equation 1 and found to be 8%.

$$\text{Water absorption, \%} = 100 \times \left[\frac{S - A}{A} \right] \quad \text{Equation 1}$$

S: mass of SSD aggregates

A: mass of oven-dry aggregates

3.2 Experiments

The experiments were carried out in two parts. In the first part, a series of experiments were conducted to explore a low-carbon cementitious matrix, and the second part included experiments to explore the effect of granular skeleton.

3.2.1 Part I – Cementitious matrix

The experiments performed in this part included reactivity of SCMs, heat of hydration of cement pastes, and compressive strength of mortars.

3.2.1.1 Reactivity of SCMs

The reactivity measurement of SCMs was performed in accordance with ASTM C1897 [59]. This test shows the heat flow and cumulative heat that is released from the reaction of the SCMs with calcium hydroxide under a simulated condition to the blended cement paste.

A paste was formed by mixing the solids in a potassium solution. The liquid to solid ratio was 1.2. The solid part was a homogeneous dry mixture of SCM (in this study pumice or fly ash), calcium hydroxide, and calcium carbonate. The solid part was kept in an oven at 40 °C prior to the test until the temperature of this dry mixture stabilized. The mass ratio of calcium hydroxide to SCM and calcium carbonate to SCM were 3 and 0.5, respectively. The potassium solution was prepared by dissolving 4 g of potassium hydroxide and 20 g of potassium sulfate in 1 L of distilled water. The potassium hydroxide solution was also kept in an air-tight container in an oven at 40 °C until the temperature of the solution stabilized. The empty ampoules were also kept in a preheated oven at 40 °C before starting the test.

The dry mixture and the solution were mixed using a high shear mixer with 1600 r/min in a plastic container for 2 min. By mixing 45 g of the solid part with 54 g of potassium solution, about 100 g of the paste was produced from which 15 g was transferred into an ampoule, then placed in an isothermal calorimeter (TAM Air, TA Instruments). The reference channels of the calorimeter were filled with ampoules containing 9.4 g of distilled water to have similar thermal mass to that of the testing paste. The data from the calorimeter for the first 45 minutes were discarded in order to reduce the fluctuation of the calorimeter output due to temperature differentials. The amount of heat released from the reactions occurring in the paste was recorded for 7 days.

3.2.1.2 Heat of hydration of cement pastes

The heat of hydration measurement for cement pastes incorporating SCMs was performed according to the ASTM C1702 [113]. The test measures the heat flow and cumulative heat of the reactions occurring in the cement pastes.

The cement pastes were prepared by mixing the binder with distilled water at a constant w/b ratio of 0.42. The binder was a homogeneous dry mixture of 80 wt% PC and 20 wt% SCM. The SCM was either pumice (labelled as P) or fly ash (labelled as FA). A reference cement paste mixture incorporating 100 wt% PC was also prepared (labelled as PC). The paste incorporating 20 wt% pumice was tested one more time by adding SP (Glenium 3030) to adjust its fluidity. Extra samples with the addition of X-Seed at a dosage of 1 wt% of the binder were also cast and tested (labelled as PCX, PX, and FAX). The dosage of X-Seed was chosen 1 wt% of the binder based on the literature [63]. The X-Seed and SP were added to the mixing water before mixing with the binder. Both the binder and water were kept in an air-tight container in an oven preheated at 40 °C long enough to reach equilibrium. The empty ampoules were also kept in a preheated oven at 40 °C before starting the test.

A high shear mixer with 1600 r/min was used for mixing the paste in a plastic container for 2 min. About 70 g of the paste was produced by adding 50 g of the binder to 21 g of distilled water. Around 12.7 g of the paste was transferred into an ampoule, then placed in the isothermal calorimeter. The reference channels were filled with ampoules containing 30 g of silica sand to have similar thermal mass to the sample channels. The output data from the calorimeter for the first 45 minutes were discarded in order to reduce the fluctuation of the calorimeter output due to temperature differentials. The amount of heat released from the pastes was recorded for 7 days.

3.2.1.3 Compressive strength of mortar cubes

Mortar cubes (50 mm × 50 mm × 50 mm) were prepared in accordance with ASTM C109/C109M [114] for compressive strength measurements. The mixing procedure for all the mixtures was the same and in accordance with ASTM C305 [115]. The flow of all the mixtures was also measured and reported in accordance with ASTM C230/230M [116].

Similar to the cement pastes samples in the previous test, three sets of mortar samples were cast. They included a reference mortar and mortars incorporating 20 wt% SCM labelled as PC, P, and FA, respectively. The w/b was held constant at 0.485 for all the mortars. The mortar containing 20% pumice was cast and tested once without (labelled as P) and once with (labelled as Psp) addition of SP. The SP was added to increase the flow of the mortar mixture to a comparable level to that of the reference mortar. Additional mortar samples containing 1 wt% (of the total binder content) X-Seed were also cast (labelled as PCX, PX, and FAX). All the samples were demolded after 24 h and cured in a fog room until the testing age.

The mortars were tested for the compressive strength at the age of 7, 28, 56, and 90 days using a standard compression testing machine (ELE international) with a 3000 kN load capacity. The rate

of loading was kept at about 1 kN/s during the test. Three samples from each mortar mixture were tested at each age. The average of the measurements was considered as the compressive strength of each mortar.

3.2.2 Part II – Granular skeleton

In part II, the compressive strength and density of high-strength concretes were measured and compared with a reference baseline concrete. The absorption of selected concretes was also determined. In this regard, a baseline concrete, containing about 207 kg/m³ PC as the binder and w/b of 0.42, was firstly prepared. This concrete was developed based on the dry mixtures prepared under laboratory conditions that can be suitable for the concrete masonry blocks application provided in the literature [103,109,117]. A 15 MPa target compressive strength was chosen for the baseline concrete as it is the most commonly produced concrete masonry block across Canada for both nonloadbearing and loadbearing applications.

For producing the concretes with higher compressive strength, the mix design was modified by increasing the amount of binder to 320 kg/m³ in all the concrete mixtures. The water-to solid (w/s) ratio, calculated by Equation 2, was adjusted to obtain a dry mixture with the optimum compressive strength.

$$\frac{w}{s}(\%) = 100 \times \frac{\text{Weight of water}}{\text{Weight of binder} + \text{Weight of oven-dry aggregates}} \quad \text{Equation 2}$$

The aggregate volume in the concrete mixtures was determined based on the absolute volume method and was either 100% NA or 100% RA. Both NAC and RAC mixtures were prepared twice. Once with 100% PC as their binder (NAC-100PC, RAC-100PC), and once when a portion of PC (20 wt%) was replaced with pumice (NAC-80PC, RAC-80PC). Then, the water content was

adjusted to achieve a dry mixture with optimum compressive strength. At the end, selected concrete mixtures were prepared again by adding 1 wt% (of total binder content) X-Seed. The proportions for all the concretes are presented in Table 3.2. The label for each concrete mixture indicates the type of aggregate, amount of PC, and w/s. The concretes that contained X-Seed are also specified by the letter X at the end of their labels.

Table 3.2. Mixture proportions of concretes.

Mixture	w/b	w/s %	Binder content (PC-P) kg/m ³	Water content kg/m ³	Aggregate content kg/m ³	Aggregate type	Admixture
NAC-100PC-3.8	0.42	3.8	207 - 0	87	2075	Natural	-
NAC-100PC-5	0.35	5.0	320 - 0	112	1917	Natural	-
NAC-100PC-5.5	0.38	5.5	320 - 0	122	1891	Natural	-
NAC-100PC-6	0.41	6.0	320 - 0	132	1860	Natural	-
NAC-100PC-6.5	0.44	6.5	320 - 0	141	1841	Natural	-
NAC-100PC-7	0.47	7.0	320 - 0	150	1818	Natural	-
NAC-100PC-7.5	0.50	7.5	320 - 0	159	1795	Natural	-
NAC-100PC-7-X	0.47	7.0	320 - 0	150	1818	Natural	X
NAC-80PC-6.5	0.44	6.5	256 - 64	140	1828	Natural	-
NAC-80PC-7	0.47	7.0	256 - 64	149	1804	Natural	-
NAC-80PC-7.5	0.49	7.5	256 - 64	158	1781	Natural	-
NAC-80PC-7-X	0.47	7.0	256 - 64	149	1804	Natural	X
RAC-100PC-5	0.29	5.0	320 - 0	93	1534	Recycled	-
RAC-100PC-5.5	0.32	5.5	320 - 0	101	1517	Recycled	-
RAC-100PC-6	0.34	6.0	320 - 0	109	1500	Recycled	-
RAC-100PC-6.5	0.37	6.5	320 - 0	117	1484	Recycled	-
RAC-100PC-7	0.39	7.0	320 - 0	125	1468	Recycled	-
RAC-100PC-7.5	0.42	7.5	320 - 0	134	1454	Recycled	-
RAC-100PC-6.5-X	0.37	6.5	320 - 0	117	1484	Recycled	X
RAC-80PC-6	0.34	6.0	320 - 0	109	1489	Recycled	-
RAC-80PC-6.5	0.36	6.5	256 - 64	117	1473	Recycled	-
RAC-80PC-7	0.39	7.0	256 - 64	124	1457	Recycled	-
RAC-80PC-7-X	0.39	7.0	256 - 64	124	1457	Recycled	X

All the aggregates were pre-wetted for 24 hours with water to reach the moisture content to 1% above the SSD condition prior to mixing. This was an important and effective step especially for

the RAC mixtures as the water absorption of the RA was relatively high (8%). This method limited the tendency of RA to absorb water during mixing. This has been reported to be an important technique that enables RAC to have comparable mechanical properties with NAC [118]. The pre-wetted aggregates were weighed again right before mixing to measure the extra moisture content of aggregates and adjust the mixing water accordingly.

The aggregates were added to the mixer. Then, the binder (PC or dry mixture of PC and pumice) was added and mixed thoroughly with the aggregates for 1 min. At the end, the mixing water was added gradually and mixed for 3 min with 45 s rest after the first 1.5 min. For the concretes containing X-Seed, the admixture was well mixed with the mixing water and added to the mix.

A dry concrete mixture was sought and two methods were used to check if the consistency of the mixture was desirable. In the first method, which is also used in industry, some of the mixed material was squeezed in the palm and was supposed to keep its shape. The second method involved simulating the conditions in actual concrete masonry block production procedure in which the specimens were demolded immediately after compaction. The desired consistency was achieved if the specimen could retain its shape. Both of these methods are shown in Figure 3.4.

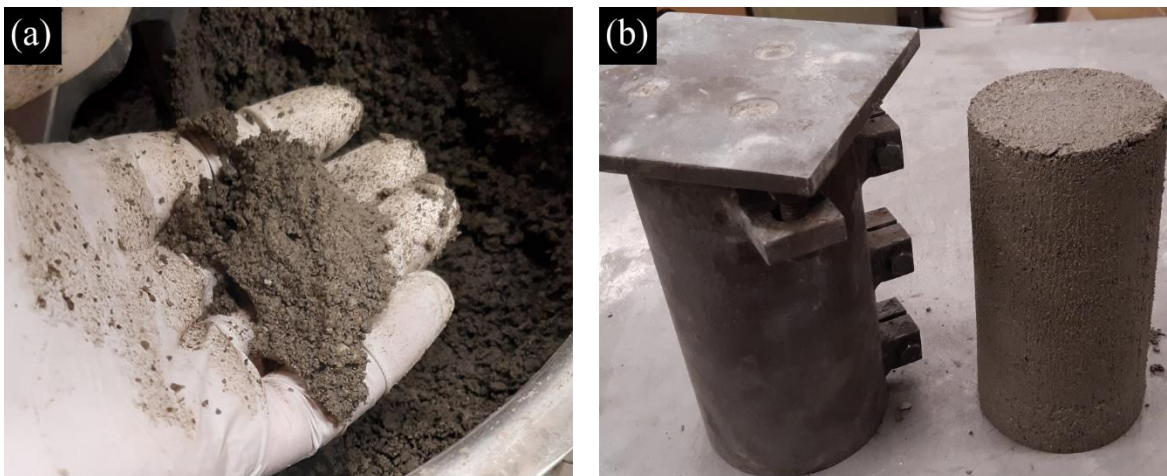


Figure 3.4. Assessing the consistency of the concretes using (a) the conventional method of squeezing the concrete in the palm and (b) demolding immediately after compaction.

For the compaction of dry mixtures for concrete masonry block production, a vibro-compaction process is used in manufacturing plants. Such compaction is not practical to use in the laboratory. Various methods have been recommended in the literature to simulate the compaction process for dry mixtures in the laboratory conditions including compaction by an electric hammer drill, compaction under static loading, and compaction by a proctor hammer [117,119–122]. In this study, the standard proctor hammer was used for the compaction (Figure 3.5). Cylindrical molds (100×200 mm) were filled with concrete in four layers with approximately equal volumes. Each layer was compacted by having 25 uniformly distributed drops of the standard proctor hammer. Therefore, the compactive effort for each cylinder was about $475 \text{ kN} \cdot \text{m}/\text{m}^3$.



Figure 3.5. Using standard proctor hammer for the compaction of concrete mixtures.

To ensure a proper bonding forms between the layers, the top surface of each layer was scratched before the addition and compaction of the next layer. This is shown in Figure 3.6. Although the concretes were tested to be able to retain their shape by demolding instantly after compaction, they were kept in the molds for 24 hours to ensure they have gained enough strength to be transferred into the fog room. The specimens were kept in the fog room until the testing age.



Figure 3.6. Scratching the top surface of each layer to create better bonding between the layers.

3.2.2.1 Compressive strength of concrete cylinders

The compressive strength of concrete was determined according to ASTM C39/C39M [123]. Cylindrical molds (100 mm × 200 mm) were used for casting the specimens. Cylindrical specimens were chosen rather than hollow rectangular specimens (shape of actual concrete masonry blocks) for faster and easier casting. The compressive strength of the cylinders was tested after 7 and 28 days of curing using a standard compression testing machine (ELE international) with a 2000 kN load capacity. The rate of loading was constant at 0.3 MPa/s. An average of three specimens was considered as the compressive strength of each concrete mixture. In masonry design codes, the specified (characteristic) compressive strength of blocks is generally used rather than the average compressive strength. According to CSA A165.1-14 [124], the specified compressive strength of concrete masonry units (including blocks) should be calculated based on testing of at least 5 units using Equation 3:

$$f'_{bi} = f_{av}(1 - 1.64v)$$

Equation 3

Where:

f'_{bi} = specified compressive strength, MPa

f_{av} = mean compressive strength of the specimens, MPa

v = coefficient of variation

In case less than 10 concrete masonry units are tested, the greater of the calculated value or 10% should be used in the calculations as the coefficient of variation. If the calculated value for coefficient of variation is more than 15%, at least 10 units should be tested [124].

In this study, since the specimens are in cylindrical shape and only three specimens were cast and tested for each age, the specified compressive strength is not reported and the results are based on the average compressive strength of three concrete cylinders according to ASTM C39/C39M-21 [123]. The difference in the shape of the specimens cast in this study and the actual shape of concrete masonry blocks may cause errors when scaling up the work for producing real-scale masonry blocks. However, a better compaction is typically achieved in concrete block manufacturing plants than that in the laboratory. It is, therefore, possible that a higher compressive strength is reached in the plant [103].

3.2.2.2 Density of hardened concrete

According to CSA A23.1/A23.2 [125], to calculate the density of hardened concrete, the diameter of the concrete cylinders (100 mm × 200 mm) was measured twice at around mid-height of the specimen. The length of the cylinders was also measured at three different locations around the circumference. The measurements were performed by using a digital caliper with 0.01 mm precision. By having the average diameter and length of each specimen, the volume of the cylinder

was calculated. Then, the specimens were weighed individually using a digital balance with 1 g precision. At the end, the density of hardened concrete cylinders was calculated by dividing the weight of each specimen to its volume.

3.2.2.3 Absorption of hardened concrete

The absorption of selected concrete mixtures was measured based on the method adapted from ASTM C140/C140M [126]. According to this standard, the specimens should be dried in a ventilated oven at 110 ± 5 °C for not less than 24 hours. Yet, as it was discussed before, drying samples at such a high temperature overestimates the absorption of the specimens. Therefore, the test was firstly done at 40 °C and then at 110 °C for both NAC and RAC selected mixtures. It is also worth noting that the standard specifies that the test should be done on full-sized masonry units or on specimens that are saw-cut from the full-sized units with at least 20% of the full-sized unit. However, in this study, the test was done on concrete cylinders.

Three concrete cylinders were prepared for each mixture and the average of these three measurements was considered as the absorption of the hardened concrete. After 28 days of curing, the specimens were immersed in water with a temperature of 25 °C for 24 hours. They were kept in an immersion tank with at least 150 mm distance between the top surface of the specimen to the surface of the water. Specimens were also separated from each other and from the bottom of the tank by 5 mm. After 24 hours, the specimens were removed from the immersion tank and their visible surface water was dried by a cloth. The weight of specimens at this stage is called saturated weight (W_s). Then, the specimens were dried in a ventilated and preheated oven at 40 °C. When a constant mass was attained (the mass measurements in a 2-hour interval did not differ more than 0.2% from each other), the weight of specimens was recorded as the oven-dry weight (W_d). After

measuring the W_d at 40 °C, the specimens were moved back to the oven with a temperature of 110 °C for at least 24 hours. The oven-dry weight of the samples was measured again. The absorption of the specimens was calculated using Equation 4:

$$Absorption, \% = \frac{W_s - W_d}{W_d} \times 100$$

Equation 4

Chapter 4 Results and Discussion

4.1 Part I – Cementitious matrix

4.1.1 Reactivity of SCMs

Figure 4.1 shows the normalized cumulative heat release of both samples containing pumice and fly ash obtained by the isothermal calorimetry test according to the ASTM C1897 [59]. It is noticeable from Figure 4.1 that more heat was released from the sample made with pumice in the first 30 hours. However, in the longer term, the sample containing fly ash released more amount of heat. The cumulative heat released after 3 and 7 days of reaction at 40 °C were 145 and 219 J/g for the samples made with pumice and 187 and 335 J/g for the samples made fly ash, respectively. The RILEM TC 267-TRM phase 3 [62] considers a material as chemically reactive (with a 90% confidence level) if its cumulative heat release after 7 days of reaction in the reactivity measurement test exceeds 160 J/g. Therefore, both pumice and fly ash tested in this study are considered to be chemically reactive although fly ash was generally more reactive than pumice.

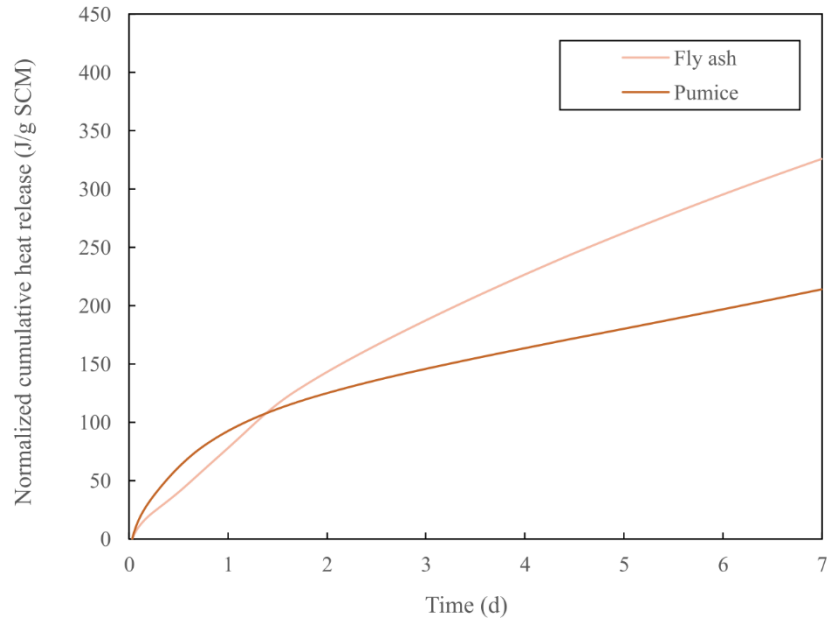
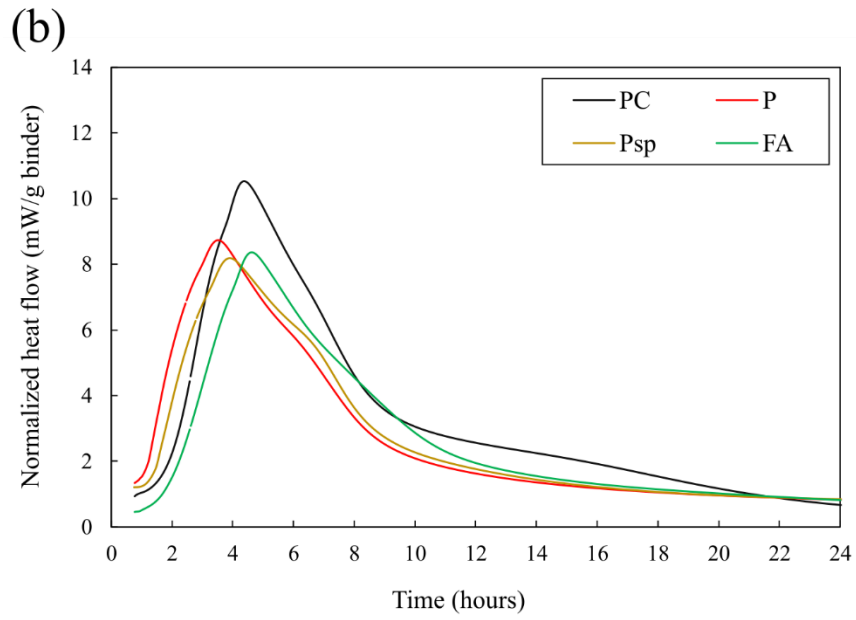
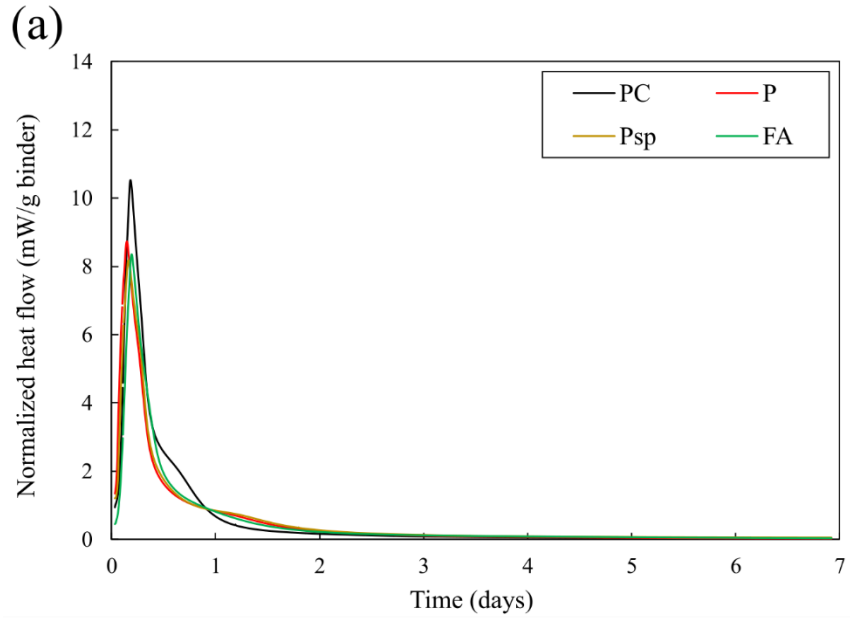


Figure 4.1. Normalized cumulative heat release (at 40 °C) for reactivity measurement of pumice and fly ash based on ASTM C1897.

4.1.2 Heat of hydration of cement pastes

The normalized heat flow of the paste samples is presented in Figure 4.2. The heat flow is normalized to the total weight of binder in each sample. The important points of the Figure 4.2 are also presented in Table 4.1.



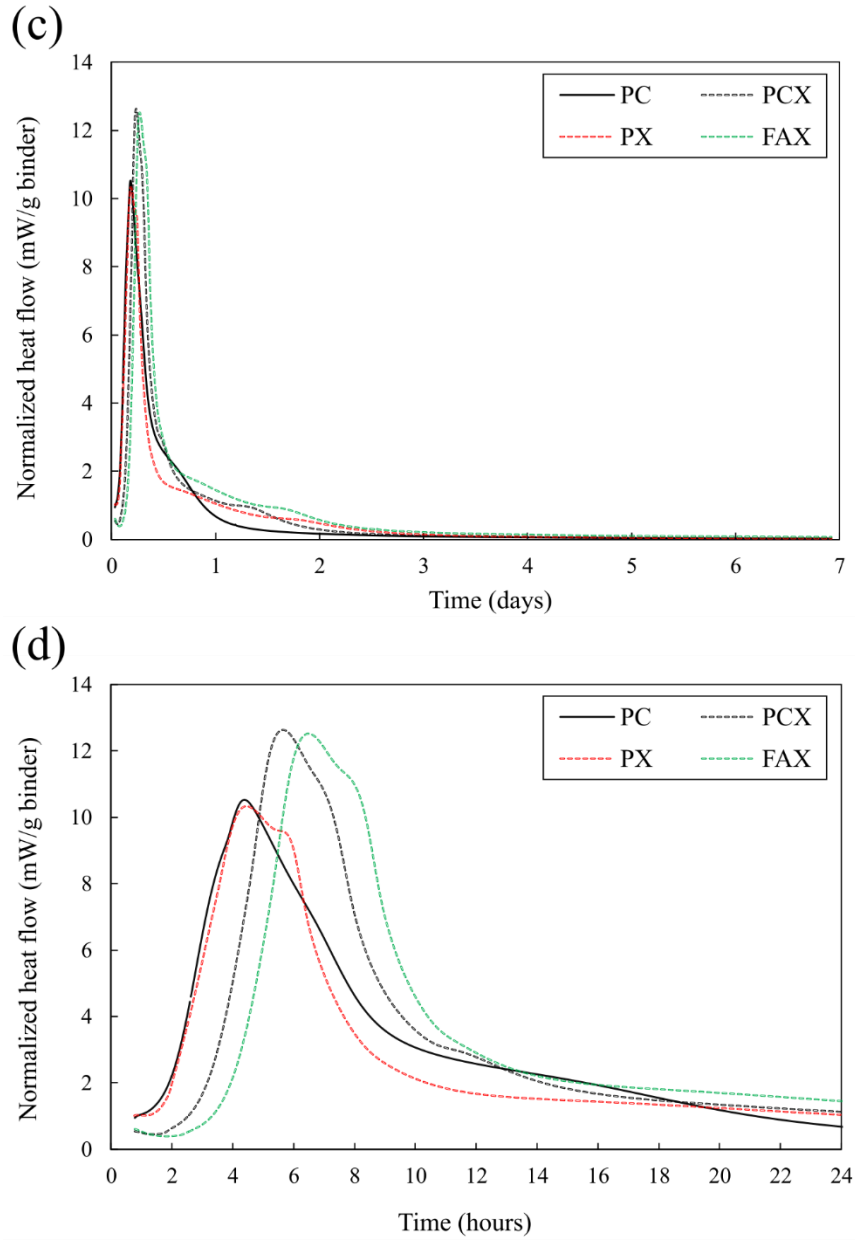


Figure 4.2. Normalized heat flow of the pastes (w/b=0.42) at 40 °C (a) for 7 days without any admixture (b) for 24 hours without any admixtures (c) for 7 days after addition of X-Seed (d) for 24 hours after addition of X-Seed.

Table 4.1. Important points from the normalized heat flow curve of the paste samples.

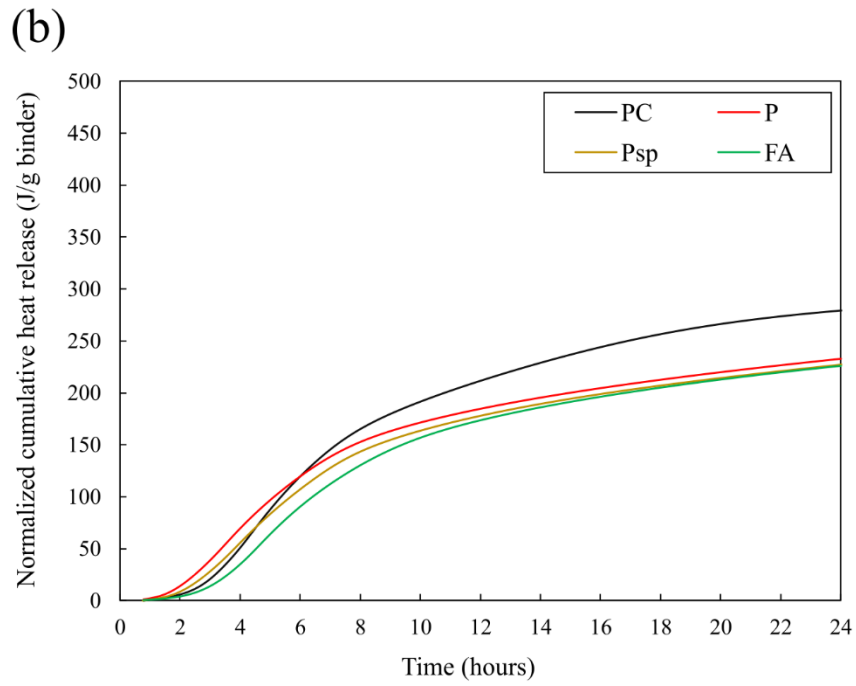
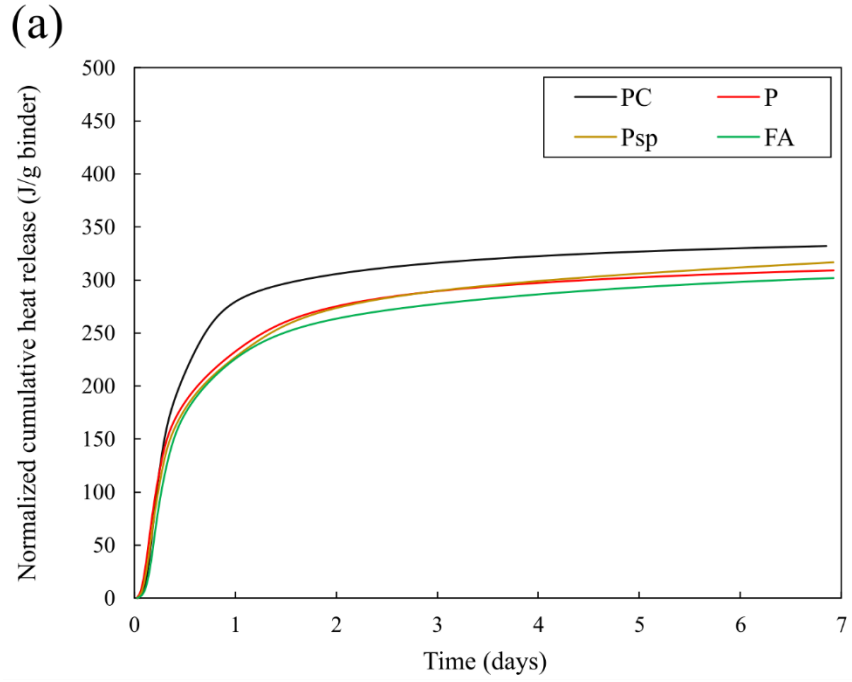
	PC	PCX	P	Psp	PX	FA	FAX
Main peak of Norm. heat flow (mW/g)	10.5	12.6	8.7	8.2	10.4	8.4	12.5
Time, main peak of Norm. heat flow (h)	4.39	5.65	3.52	3.92	4.46	4.62	6.50

As expected, the main peak of the heat flow for the reference paste (10.5 mW/g) was higher than that of the paste incorporating pumice (8.7 mW/g) and fly ash (8.4 mW/g). The peak, however, occurred at earlier time for the paste with pumice (3.52 h) compared to both the reference paste (4.39 h) and paste incorporating fly ash (4.62 h). This acceleration in the reactions could be an evidence of the filler effect of pumice. The filler effect promotes the hydration of the PC particles and causes more amount of heat to be released. The smaller particle size of pumice compared to fly ash further strengthens this observation.

The addition of X-Seed increased the main peak of the normalized heat flow graph of all the pastes. More specifically, the peak for the paste incorporating pumice with X-Seed increased up to a comparable level to that of the reference paste without the admixture. The effect of X-Seed on the reaction kinetics of the paste incorporating fly ash was more significant compared to pumice. The reason for this observation requires further investigation on the microstructure of the paste. It is worth pointing out that X-Seed also affected the reference paste significantly. The main purpose of using this admixture in this study, however, was to enhance the performance of the mixtures incorporating SCMs. It is also notable that the addition of X-Seed prolonged the dormant period in the normalized heat flow curve which can be due to the presence of organic polymers in this admixture.

It should be noted that the addition of SP to the paste incorporating pumice did not have any considerable effect other than a small retardation in the reactions which is in line with the literature [127,128].

The normalized cumulative heat release of the pastes is presented in Figure 4.3. The cumulative heat is normalized to the total weight of binder in each mixture. The important points of the Figure 4.3 are also presented in Table 4.2.



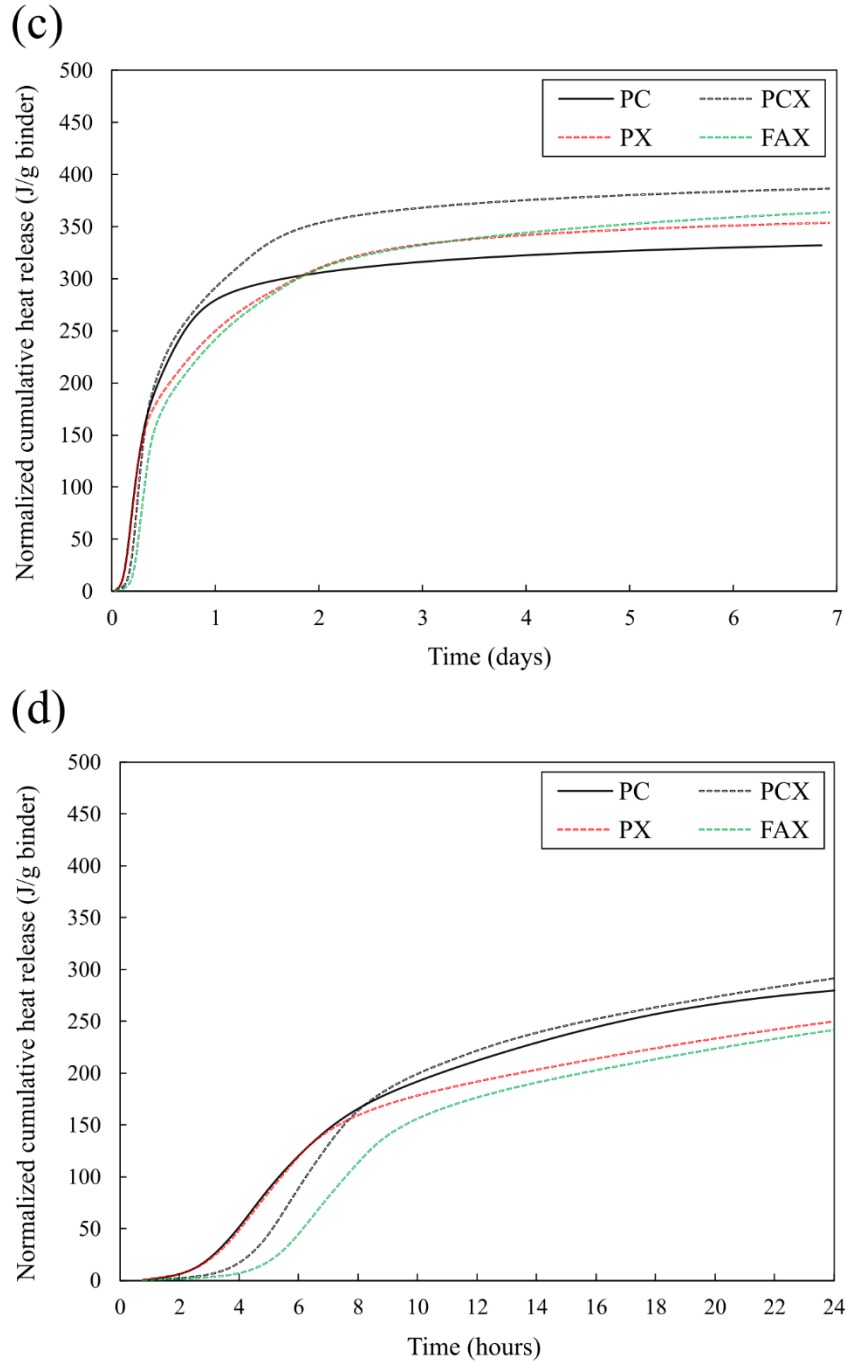


Figure 4.3. Normalized cumulative heat release of the pastes ($w/b=0.42$) at $40\text{ }^{\circ}\text{C}$ (a) for 7 days without X-Seed (b) for 24 hours without X-Seed (c) for 7 days after addition of X-Seed (d) for 24 hours after addition of X-Seed.

The cumulative heat that is released from reference paste is significantly higher than paste samples incorporating SCMs. This was expected as PC starts to react with water as soon as they are mixed

while pumice and fly ash are pozzolans that would react with the products of hydration of PC. This is evident as the difference in the cumulative heat released from the reference paste and paste samples incorporating SCMs at 1 day decreased at 3 and 7 days.

Table 4.2. Important points from the normalized cumulative heat release curves of the paste samples.

	PC	PCX	P	Psp	PX	FA	FAX
Norm. Cum. Heat 1 d (J/g)	279.5	291.6	232.6	227.3	250.0	225.8	241.8
Norm. Cum. Heat 3 d (J/g)	316.2	368.2	289.5	289.7	333.1	277.5	332.5
Norm. Cum. Heat 7 d (J/g)	332.2	386.6	309.1	316.7	353.7	301.8	363.8

As observed in Table 4.2, the amount of cumulative heat released from the paste samples incorporating pumice and fly ash showed only a small difference with each other at the age of 1, 3, and 7 days. This is not in line with the results of the reactivity measurement test that showed fly ash is generally more reactive than pumice. This is likely due to the filler effect of the pumice particles and promoting hydration of PC particles which was discussed earlier. The difference in the cumulative heat released from the pastes incorporating pumice and fly ash became negligible after 7 days. This could show that the filler effect of pumice was not the dominant factor anymore. Instead, the pozzolanic reactivity became the most influential factor. The cumulative heat released from the paste incorporating fly ash could potentially become higher than that of released from the paste incorporating pumice if the test had been continued for a longer time.

The addition of X-Seed, as expected, increased the cumulative heat of all the pastes. The main purpose of using X-Seed was to increase the rate of reactions in the pastes incorporating SCMs up to a comparable level to the reference paste without the admixture at earlier ages. The results showed that the goal could be achieved as the amount of heat released from pastes incorporating pumice and fly ash with X-Seed became comparable to reference paste at the age of 1 day, and surpassed the reference paste as early as about 2 days. It should also be noted that addition of X-

Seed to the reference paste increased its cumulative heat at all the 1, 3, and 7-day ages. The primary objective for utilization of this admixture, however, was to improve the performance of mixtures incorporating SCMs. For that objective, despite the retarding effect due to addition of X-Seed in the first hours, overall the admixture clearly increased the amount of heat that is released from the pastes.

It is also noteworthy to mention that the addition of SP to the paste incorporating pumice did not have any considerable effect on the amount of cumulative heat released, although it showed a retarding effect in the first few hours.

4.1.3 Compressive strength of mortar cubes

Figure 4.4 (a) shows the compressive strength of all the mortars at different ages. The results are normalized with respect to the compressive strength of the reference mortar at each specific age and presented in Figure 4.4 (b). The error bars indicate the standard deviation of the results of three samples for each mortar at any specific age. The location of the 75% of the compressive strength of reference mortar as the SAI requirement specified in ASTM C618 [35] is shown in Figure 4.4 (b) by a dash line. The analysis of variance (ANOVA) was used to determine whether there is a significant difference between the means of compressive strength of mortars with a significance level of 0.05. A Tukey pairwise comparison was also used to show which specific groups are different from one another. The results for the ANOVA are presented in Appendix I.

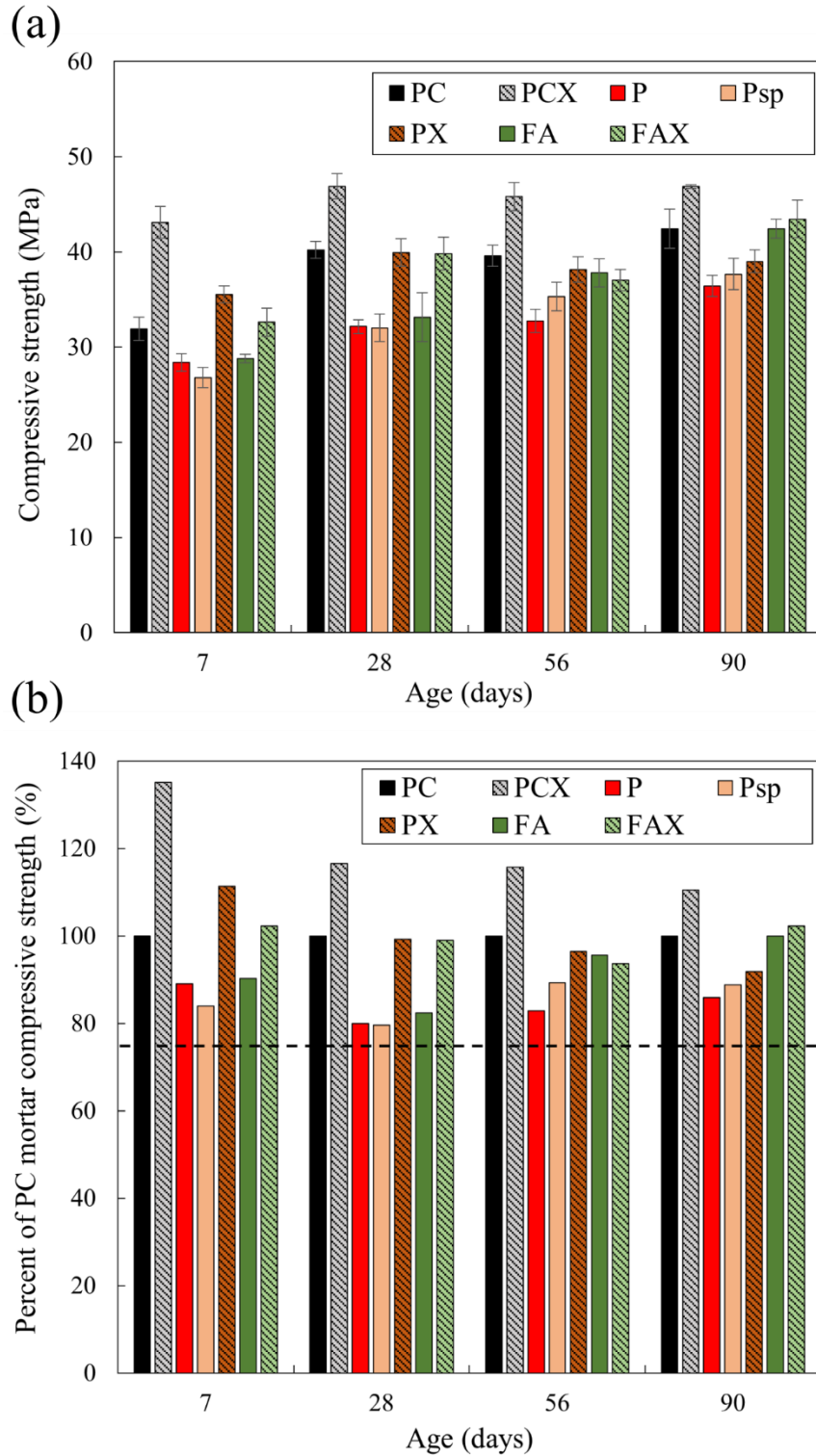


Figure 4.4. (a) Compressive strength of mortars containing 20 wt% pumice or fly ash as replacement of PC, with and without presence of X-Seed (w/b=0.485); (b) compressive strength of mortars normalized to the compressive strength of the reference mortar (w/b=0.485).

As can be seen in Figure 4.4 (a), at 7 and 28-day ages, the compressive strength of the mortar incorporating pumice was comparable to that of incorporating fly ash. Similar finding was observed in the heat of hydration test as the amount of cumulative heat released from pastes incorporating pumice and fly ash was almost identical (Figure 4.3 (a)). The compressive strength at later ages (56 and 90 days), however, was lower for the mortar incorporating pumice than fly ash. This was also expected as the reactivity measurement test showed that pumice has less pozzolanic reactivity compared to than fly ash. The results of Figure 4.4 (b) also show that the compressive strength of both pastes incorporating pumice and fly ash surpassed the 75% SAI requirement of the ASTM C618 [35] at all the testing ages.

The ANOVA showed that the compressive strength results of the mortars incorporating pumice with and without SP were not significantly different. The amount of heat released from pastes incorporating pumice with and without SP was also almost identical in the heat of hydration test (Figure 4.3).

Addition of X-Seed to the mortars significantly increased their compressive strength at all the ages. The enhancing effect, however, was more pronounced at the earlier ages. The compressive strength of the mortar incorporating pumice at 7 days (28.4 MPa), for instance, was slightly lower than the reference mortar prior to adding X-Seed (31.9 MPa). It, however, surpassed the reference mortar at this age after the addition of X-Seed (35.5 MPa). In addition, at 28 days, while the reference mortar had a higher compressive strength than that of the mortar incorporating pumice, its compressive strength was not significantly different than that of the mortar incorporating pumice and X-Seed. Moreover, although the compressive strength of the mortar incorporating fly ash was less than that of the reference mortar at both 7 and 28 days, after addition of X-Seed to this mixture, it showed a comparable strength with the reference mortar at both of these ages. These results

showed that addition of X-Seed had a very significant effect on the compensation of the lower strength gain of the mortars incorporating SCMs at early ages. This is in line with the effect of X-Seed on the results of the normalized cumulative heat released from the pastes incorporating SCMs.

The addition of X-Seed also had a significant effect on the compressive strength of the reference mortar. The effect was more substantial at 7 days similar to the other mortars with X-Seed, and it started to get insignificant afterwards. The compressive strength of the reference mortar with and without the admixture showed a converging trend after 90 days.

The Tukey pairwise comparison results showed that the 28, 56, and 90-day compressive strength of the reference mortar after addition of X-Seed were not significantly different from each other. This would mean that X-Seed accelerated the reactions to such a degree that compressive strength development became insignificant after 28 days. Similar trend was evident for the mortar incorporating pumice and X-Seed as well.

It should be noted that the replacement of PC with pumice by 20 wt% can reduce the flow of the mortar. This can be attributed to the higher water absorption of pumice (as reported in the literature [129]). SP, therefore, was added to the mortar incorporating pumice to adjust its flow. The compressive strength of the mortar incorporating pumice, however, was not affected by the lower flow as discussed earlier. The results of the flow table test of mortars are presented in Table 4.3. The mortar incorporating fly ash, on the other hand, increased the flow which is also in line with the literature [130,131]. It is also notable that the addition of X-Seed increased the flow of the mortars.

Table 4.3. Flow table test results for the mortars.

	PC	PCX	P	Psp	PX	FA	FAX
Flow (%)	90.0	95.5	74.5	93.5	85.0	96.5	101.0

4.2 Part II – Granular skeleton

The suitability of pumice and X-Seed was demonstrated in Part I. The results of the tests on concretes prepared with natural and recycled aggregates, with and without pumice and X-Seed are presented in Part II.

4.2.1 Compressive strength of concrete cylinders

The average compressive strength of the baseline concrete mixture (NAC-100PC-3.8) after 28 days of curing was 12.6 MPa. The lower achieved compressive strength compared to the target compressive strength for the mixtures cast in the laboratory was previously reported in the literature [103]. It can be due to the differences in compaction method used in the laboratory compared to that of used in block manufacturing plants. With better compaction, similar mixture is anticipated to achieve the target compressive strength of 15 MPa in a manufacturing plant.

All other concrete mixtures made in this study had a binder content of 320 kg/m³ for achieving higher compressive strengths. Figure 4.5 presents the average compressive strength of the reference NAC-100PC and RAC-100PC mixtures at various w/s ratios after 7 and 28 days of curing.

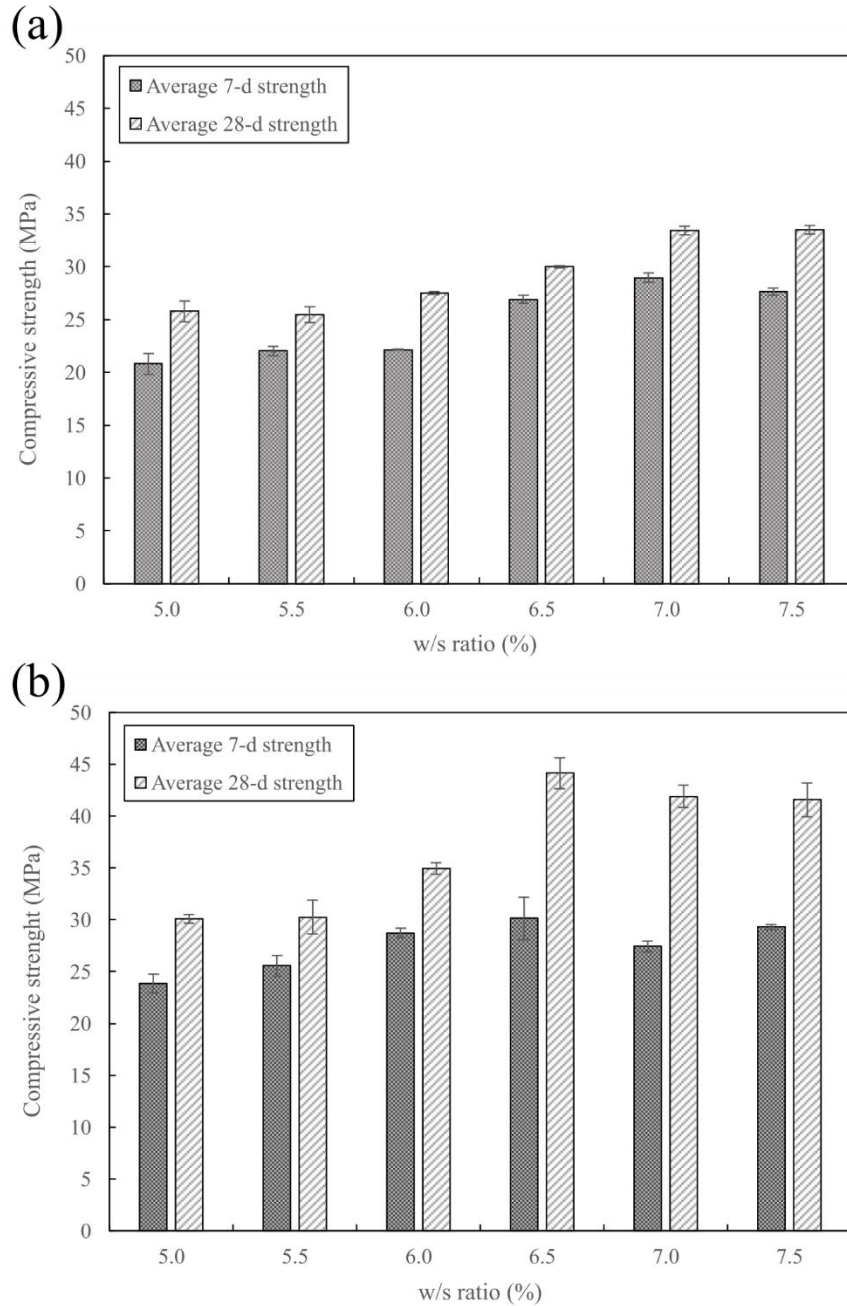


Figure 4.5. Average compressive strength of (a) NAC mixtures and (b) RAC mixtures made with 100% PC at different w/s ratios.

Both series of mixtures were cast and tested at different w/s ratios ranging from 5% to 7.5%. The w/s ratio was increased until the mixture failed the consistency tests. RAC-100PC-7.5 failed the consistency tests. The results of this mixture, however, are presented for easier comparison.

ANOVA was used to determine whether there is a significant difference between the means of

compressive strength of concrete mixtures with different w/s ratios with a significance level of 0.05. The results for the ANOVA are presented in Appendix II.

As can be seen in the Figure 4.5, there is a w/s ratio at which the compressive strength was maximum. In this study, this is called the optimum w/s. The optimum w/s was 7% for NAC-100PC (Figure 4.5 (a)) and 6.5% for RAC-100PC (Figure 4.5 (b)). The Tukey pairwise comparison did not show any significant difference between the average compressive strength of NAC-100PC mixtures with w/s ratios of 7 and 7.5%. Similarly, the RAC-100PC mixtures with w/s ratios of 6.5, 7, and 7.5% were not significantly different. The lowest w/s ratio among these mixtures, however, was considered as the optimum w/s since it has smaller amount of water leading to a drier mixture. Although the mixtures with w/s ratios lower than the optimum had lower w/c ratios, their compressive strength was lower. This is mainly due to the entrapped air voids in those concrete mixtures. In fact, lack of sufficient amount of cement paste to fill the gaps between the aggregates leads to entrapped air voids that decreases the compressive strength.

An important concept affecting the properties of concrete mixtures is packing density. It is defined as the ratio of the solid volume of the particles to the bulk volume occupied by the particles. In concrete, it is the cement paste that fills the interstitial space (gaps) between the aggregate particles. The higher the packing density of the aggregates, the lower cement paste is required to fill the gaps. At a constant PC content, a higher packing density will result in a paste with lower w/c ratio. A lower w/c ratio typically leads to a higher compressive strength. Comparison of the results of Figure 4.5 (a) and (b) show that the average compressive strength of RAC mixtures was higher than those obtained for NAC mixtures at all the w/s ratios. This is likely due to a better packing density of the RA compared to NA.

The dry mixture of concrete masonry blocks typically contains a relatively low paste volume. There is, therefore, a higher possibility that not all the gaps between the aggregates are filled with the paste. In this case, there will be entrapped air voids inside the mixture affecting the properties of the concrete especially its compressive strength. Voids are a common factor for compressive fracture. The material expands laterally under the uniaxial compression due to Poisson's effect. This results in development of tension perpendicular to the compression load, causing crack propagation and ultimately fracture [132]. Therefore, reducing the entrapped air void content is important for achieving higher compressive strengths of concrete mixtures. For that purpose, there will be a minimum amount of paste required to fill the interstitial space between the aggregate particles. It should be noted, however, it is assumed that extra paste volume in the mixture lubricates the concrete [133], which is not a desired property for concrete masonry block production. Therefore, the paste volume is of the utmost importance for this application.

Figure 4.6 presents the average compressive strength of the NAC-80PC and RAC-80PC mixtures which both contained 256 kg/m^3 of PC and 64 kg/m^3 of pumice. Both NAC-80PC and RAC-80PC mixtures were cast and tested at different w/s ratios ranging from 6.5% to 7.5% and 6% to 7%, respectively. The w/s ratio was increased until the mixture failed the consistency tests. It was expected that the optimum w/s for the mixtures incorporating 20 wt% pumice not to be very different from that of the mixtures made with 100% PC. Only a slightly higher range of w/s ratios compared to the 100PC mixtures was selected due to the high water absorption of pumice reported in the literature [129]. Based on the results, the optimum w/s ratio for both NAC-80PC and RAC-80PC mixtures was 7%.

The results show replacing PC with pumice by 20 wt% reduced the compressive strength of the mixtures both at 7 and 28 days. The inferior performance of the concrete mixtures incorporating pumice at early ages was in agreement with the results observed for mortar and paste mixtures.

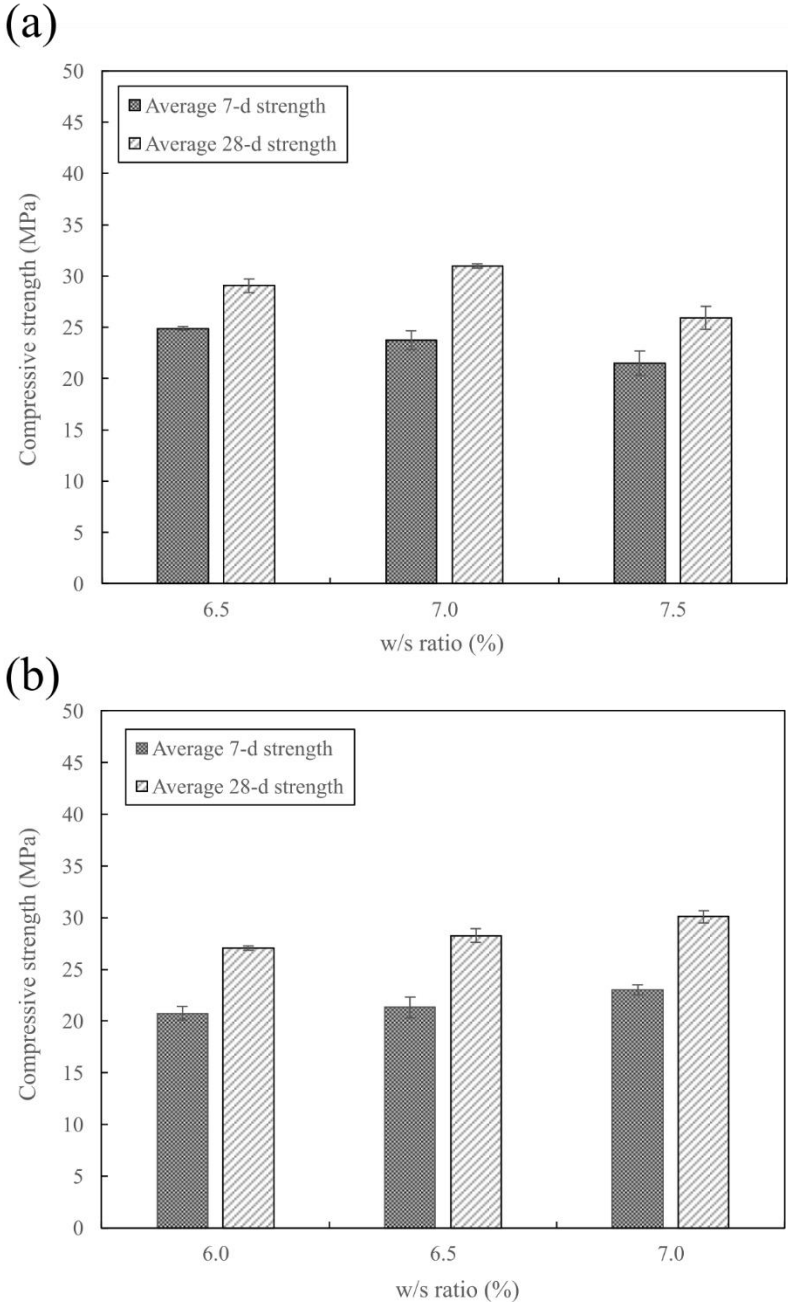


Figure 4.6. Average compressive strength of (a) NAC and (b) RAC mixtures incorporating 20% pumice at different w/s ratios.

4.2.2 Density of hardened concrete

The hardened density of all the mixtures was measured prior to the compressive strength test. The density of the baseline mixture (NAC-100PC-3.8) was 2009.5 kg/m³. Figure 4.7 presents the density alongside with the average compressive strength of the NAC-100PC and RAC-100PC mixtures which both contain 320 kg/m³ of PC. As can be seen in the Figure 4.7, there is a w/s ratio at which the density was maximum. As expected, the mixture with the highest compressive strength showed the highest density as well. The results presented in Figure 4.7 show that the density curve followed an increasing trend up to a certain w/s ratio and then started to decrease. This confirms the presence of entrapped air voids in the mixtures with w/s ratios lower than the optimum which decreases the density of these mixtures. By increasing the w/s ratio up to the optimum w/s, the paste content will also increase, resulting in less voids and higher density of the mixtures.

Comparison of the results of Figure 4.7 (a) and (b) shows that the density of NAC mixtures was higher than those of RAC mixtures at all the w/s ratios. This is due to the difference in the density of the NA and RA. The relative density of NA and RA used in this study were 2.61 and 2.04, respectively, as presented in section 3.1.3.

The effect of pumice replacement on the density is also shown in Figure 4.8. As it can be seen, the maximum density was achieved at the optimum w/s ratio found in the compressive strength results for NAC-80PC and RAC-80PC mixtures as well. The hardened density of concrete mixtures incorporating 20 wt% pumice was slightly smaller than that of the mixtures with 100% PC.

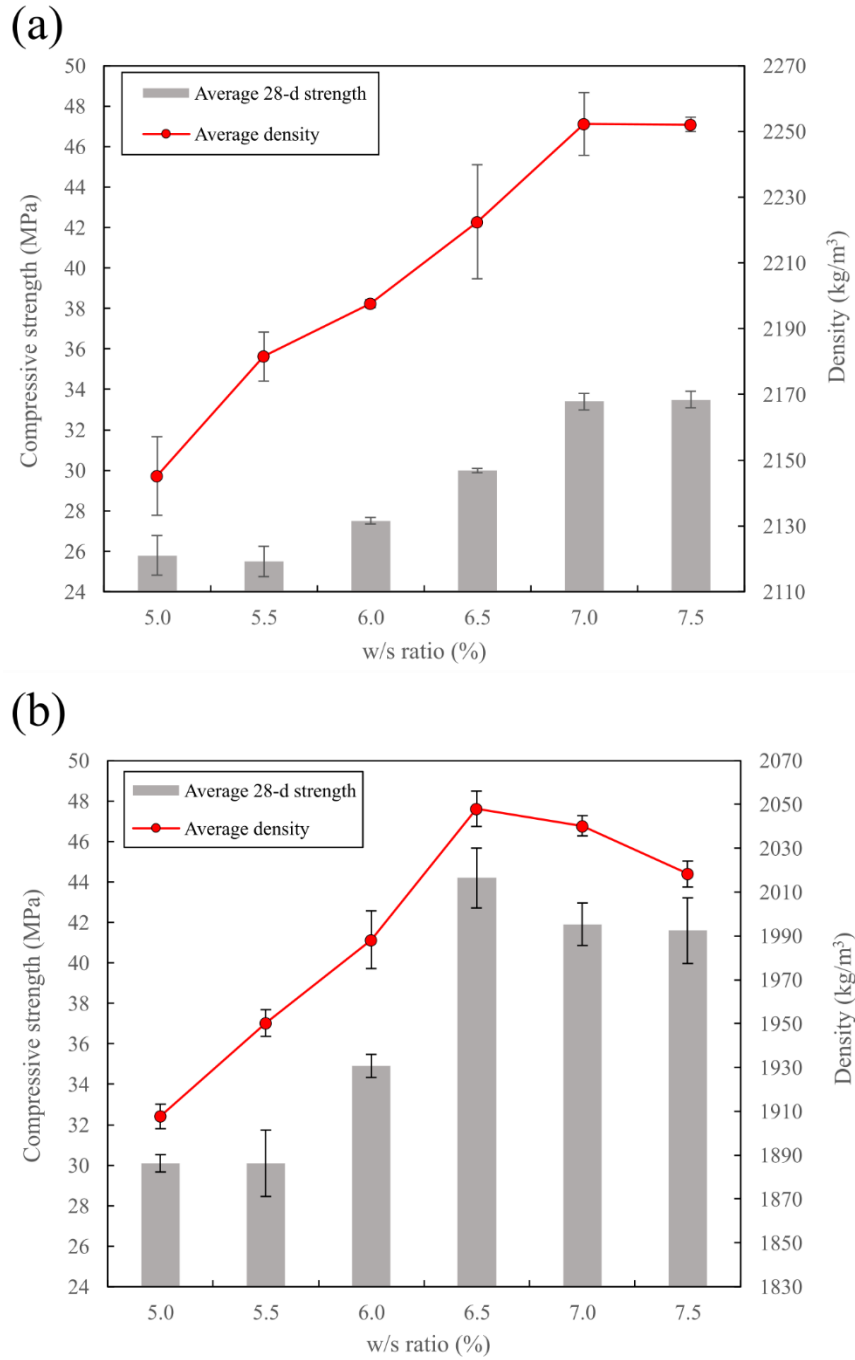


Figure 4.7. Average 28-d compressive strength and density of (a) NAC and (b) RAC mixtures with 100% PC as binder and without any admixtures at different w/s ratios.

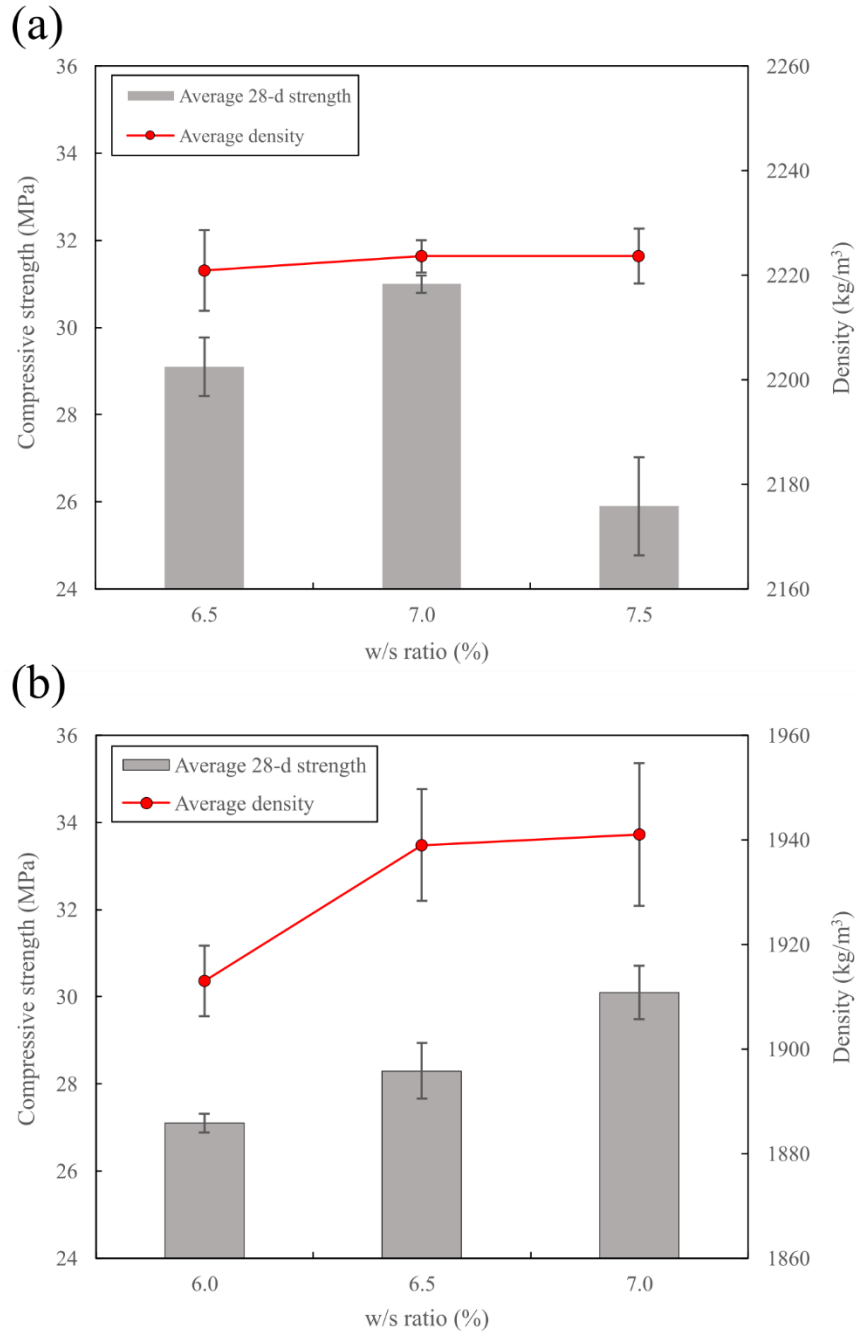


Figure 4.8. Average 28-d compressive strength and density of (a) NAC and (b) RAC mixtures with 80% PC and 20% pumice as binder and without any admixtures at different w/s ratios.

4.2.3 Enhancing effect of X-Seed

The effect of performance enhancing admixture, in this study X-Seed, on the heat of hydration of pastes and compressive strength of mortars was presented in sections 4.1.2 and 4.1.3, respectively.

The results show that X-Seed could effectively increase the rate of hydration reactions and compensate for the lower rate of compressive strength gain in mortars containing SCMs at early ages. Therefore, this admixture was also used for producing concrete mixtures with the optimum w/s ratios. It should be noted that the optimum w/s ratio of concrete mixtures may slightly change as a result of addition of X-Seed. Due to the challenging nature of casting dry mixture specimens in the laboratory, however, the mixtures incorporating X-Seed were not cast at different w/s ratios. The admixture was only used for producing concrete mixtures with the optimum w/s ratios obtained for the concrete mixtures without the admixture. The average compressive strength and density of each concrete mixture with and without X-Seed are summarized in Table 4.4.

Table 4.4. Average compressive strength and density of the concrete mixtures with optimum w/s ratio.

	Compressive strength (MPa)		Density (kg/m³)
	Average 7-d	Average 28-d	
NAC-100PC-7	29.0 (0.64)	33.4 (0.51)	2252 (9.57)
NAC-100PC-7-X	32.6 (0.19)	37.9 (0.79)	2253 (5.94)
RAC-100PC-6.5	30.2 (2.05)	44.2 (1.48)	2048 (8.01)
RAC-100PC-6.5-X	39.8 (1.73)	54.5 (0.99)	2047 (11.44)
NAC-80PC-7	23.7 (0.93)	31.0 (0.20)	2221 (3.05)
NAC-80PC-7-X	26.2 (0.03)	35.7 (1.76)	2211 (15.10)
RAC-80PC-7	23.0 (0.49)	30.1 (0.61)	1941 (13.66)
RAC-80PC-7-X	28.6 (0.48)	39.2 (1.92)	2008 (11.60)

Numbers in parenthesis indicate the standard deviation.

The results show that the addition of X-Seed increased the compressive strength of all the concrete mixtures at both 7 and 28 days. Over 95% of the 28-day compressive strength of the concretes without X-Seed was achieved at 7 days with the presence of X-Seed in the similar mixture. The only exception was NAC-80PC-7 that achieved 85%.

Addition of X-Seed clearly compensated for the lower compressive strength gain of the concrete mixtures incorporating pumice to such a degree that they reached a comparable compressive strength to their corresponding 100PC concrete mixtures without X-Seed at both 7 and 28 days.

The effect of X-Seed on the RAC mixtures was notable. The increment in the compressive strength due to the addition of X-Seed to the RAC mixtures was more significant compared to NAC ones. For instance, the compressive strength of RAC-100PC-6.5 mixtures was increased by 36% at 7 days after the addition of X-Seed while the similar figure for NAC-100PC-7 was 12%. Further investigation is required to clearly understand the mechanism underlying this effect.

4.2.4 Absorption of hardened concrete

The absorption of the hardened concrete was measured after 28 days of hydration. The results are presented in Table 4.5.

Table 4.5. Absorption of hardened concrete based on drying at 40 °C and 110 °C.

	Absorption, dried at 40 °C (%)	Absorption, dried at 110 °C (%)
NAC-100PC-7	2.7 (0.04)	5.0 (0.12)
NAC-100PC-7-X	2.3 (0.01)	4.4 (0.03)
RAC-100PC-6.5	3.1 (0.15)	6.7 (0.37)
RAC-100PC-6.5-X	2.9 (0.17)	6.6 (0.44)
NAC-80PC-7	4.0 (0.05)	6.2 (0.03)
NAC-80PC-7-X	3.6 (0.20)	5.6 (0.21)
RAC-80PC-7	3.4 (0.24)	7.1 (0.36)
RAC-80PC-7-X	3.1 (0.19)	6.6 (0.10)

Numbers in parenthesis indicate the standard deviation.

As it can be seen in Table 4.5, the absorption measurements obtained based on drying at 110 °C were higher than those obtained at 40 °C. This is likely due to the loss of some bound water of the

cement paste at 110 °C temperature. Similar observations have been reported in the literature for measuring the water absorption of RA [84].

The results show that the addition of X-Seed to the concrete mixtures slightly reduced their absorption. This can be attributed to the effect of X-Seed on the rate of hydration reactions and the accelerated formation of hydration products.

4.2.5 Cement intensity index

The cement intensity (CI) index is defined in Equation 5. It shows the mass of PC required to develop one unit of compressive strength at 28 days. The lower the CI index for a mixture, the higher the efficiency of PC in that mixture.

$$CI\ index = \frac{\text{Mass of Portland cement in } 1\ m^3\ \text{of concrete}}{\text{Compressive strength of the mixture at 28 days}} \quad \text{Equation 5}$$

The CI index of the baseline mixture and the high-strength mixtures with the optimum w/s ratios are presented in Figure 4.9.

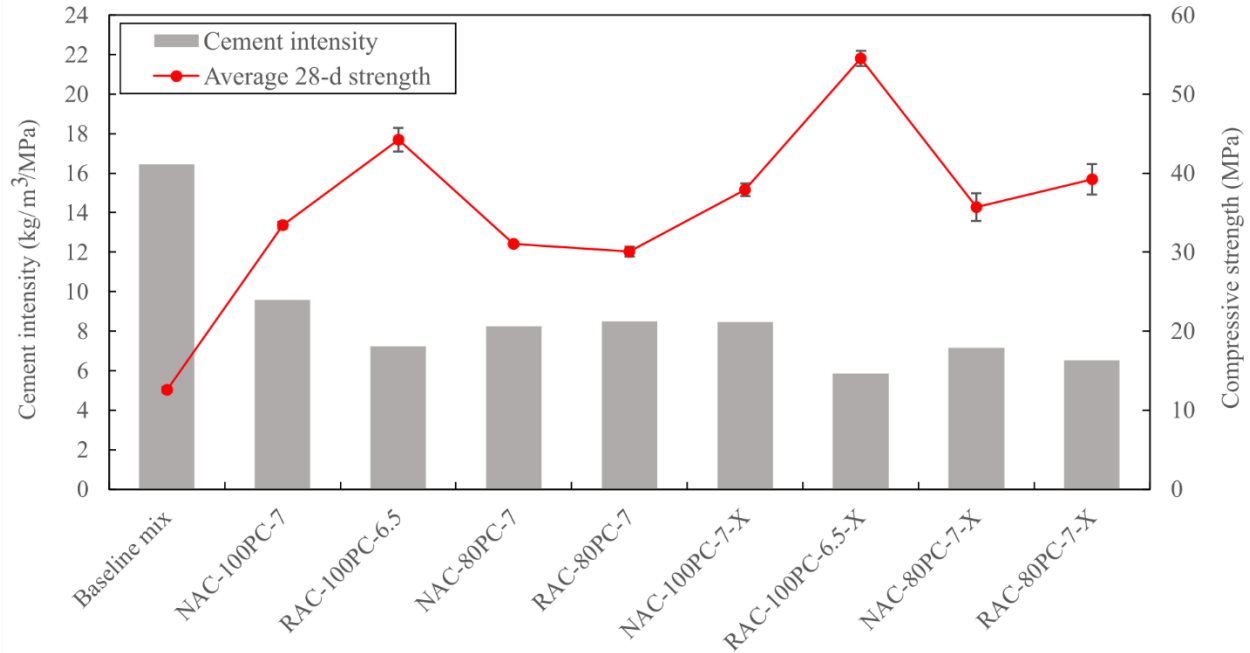


Figure 4.9. The CI index and the average compressive strength at 28 days of the baseline mix and the mixtures with optimum w/s ratios.

As expected, the baseline mix had the highest CI index since PC may not be used to its full potential. However, the baseline mixture should not be compared with the high-strength mixtures as these concrete blocks would have different applications. For instance, for a nonloadbearing application, the baseline mix can be suitable while the high-strength mixtures are likely to be oversized for the same application. On the other hand, high-strength concrete blocks will be important for many loadbearing applications. To be able to compare the mixtures with the same application, the high-strength mixtures were categorized into four groups namely 30, 35, 40, and 50 MPa, based on their average compressive strength at 28 days.

As observed in Table 4.6, in the 30 MPa group, the mixtures incorporating pumice without the performance enhancing admixture had lower CI indexes compared to that of NAC-100PC-7. This shows that for a mixture with 30 MPa compressive strength, replacing 20 wt% of PC with pumice can be an effective method towards reducing the carbon footprint of the mixture. In this group,

RAC-80PC-7 has a slightly higher CI index compared to NAC-80PC-7, however, the RAC mixture contains RA that can have costs and environmental benefits. In some regions, accessibility to the NA is limited and it has to be transported from long distances. Thus, utilization of RA produced from crushed blocks in a plant, has the potential to reduce costs. In addition, use of RA provides the advantage of waste utilization and natural resources conservation. The mixtures in the 30 MPa group, formed the 35 MPa group when X-Seed was added to these mixtures. In this group, RAC-80PC-7-X performed the best with the highest compressive strength (39.2 MPa) and the lowest CI index (6.53) compared to the other mixtures in the group. The only mixtures in the 40 and 50 MPa groups were RAC-100PC-6.5 and RAC-100PC-6.5-X, respectively. Although these mixtures contained 320 kg/m³ of cement, their CI indexes were relatively small compared to other groups. These suggest that the use of RA, pumice, and X-Seed has great potentials for producing low-carbon and high-strength concrete masonry mixtures.

Table 4.6. Summary of the average strength at 28 days and the CI index of the high-strength mixtures categorized into four groups.

Category	Mix	Average 28-d strength (MPa)	CI index (kg/m³/MPa)
30	NAC-100PC-7	33.4 (0.51)	9.58
	RAC-80PC-7	30.1 (0.61)	8.50
	NAC-80PC-7	31.0 (0.20)	8.25
35	NAC-100PC-7-X	37.9 (0.79)	8.44
	NAC-80PC-7-X	35.7 (1.76)	7.17
	RAC-80PC-7-X	39.2 (1.92)	6.53
40	RAC-100PC-6.5	44.2 (1.48)	7.23
50	RAC-100PC-6.5-X	54.5 (0.99)	5.87

Numbers in parenthesis indicate the standard deviation.

Chapter 5 Conclusions and Recommendations for Future Research

5.1 Conclusions

High-strength and low-carbon concrete masonry mixtures were produced by using pumice, as a locally available natural pozzolan, RA, and X-Seed as a performance enhancing chemical admixture. The experiments were conducted in two parts. Part I focused on the cementitious matrix, and Part II mainly involved the granular skeleton. The main concluding remarks are as follows:

- The reactivity measurements showed that pumice can be considered as a pozzolan although it has less pozzolanic reactivity compared to fly ash. Considering the decline in the supply of fly ash, pumice can serve as an alternative option for concrete block production.
- Addition of X-Seed increased the rate of hydration reactions and strength development in the cementitious mixtures. As a result, the mixtures incorporating SCMs achieved comparable early-age properties to the reference mixture with no X-Seed.
- Pumice decreased the flow of cementitious mixtures. It was still suitable for producing the dry concrete mixtures of this study. However, for applications where higher flow properties are required, the use of SP would be necessary. The results of this study showed that the addition of SP to the pastes incorporating pumice did not play a major role in the heat of hydration measurements other than a retarding effect in the early age. The compressive strength of the mortar incorporating pumice did not significantly change either as a result of adding SP.

- The compressive strength measurements on mortars showed that the filler effect of pumice could compensate for its lower pozzolanic reactivity compared to fly ash at ages up to 28 days. At later ages, however, the filler effect became inconsiderable and the pozzolanic reactivity was the dominant factor.
- RA produced from previously used concrete masonry blocks for structural tests in the laboratory was successfully utilized to achieve high-strength concrete mixtures. The water absorption and packing density of the RA are important factors that need to be taken into account for the successful design of RAC masonry mixtures.
- Dry concrete mixtures typically contain low paste content. They are, therefore, more susceptible to entrapped air voids which significantly affect their mechanical properties especially compressive strength. It is suggested that the gaps between the aggregates be filled with paste to reduce the volume of the entrapped air voids in the concrete mixture. On the other hand, extra paste content in the concrete mixture would lubricate the concrete which is not desired in a dry mixture. Selecting the appropriate paste content is, therefore, of significant importance in achieving dry concrete mixtures with high compressive strengths.
- The high-strength concrete mixtures of this study were categorized into four categories of 30, 35, 40, and 50 MPa based on their average 28-day compressive strength. The concrete within the highest strength category included X-Seed and RA, and with 320 kg/m³ of PC. Concretes incorporating 20 wt% pumice also fell within the 35 MPa category (with the average compressive strengths of 35 and 39 MPa) with the use of X-Seed.

5.2 Recommendations for future research

Although this thesis included a comprehensive investigation on the production of high-strength and low-carbon concrete masonry blocks using pumice and RA, there are still research areas that can be explored. Some recommendations for future research are listed below:

- In this study pumice was used as a partial replacement for PC; however, the feasibility of using other SCMs, including industrial by products and other sources of locally available natural pozzolans, in the form of binary and ternary combinations for higher levels of PC replacements with the help of X-Seed can be further explored.
- The replacement level of pumice and dosage of X-Seed were chosen based on the literature. It is recommended to test other levels to find an optimum that satisfies both the desired mechanical properties and goals for reduction of the carbon footprint of the final concrete mix. In addition, other materials are recommended to be explored as performance enhancer allowing for higher levels of PC substitution.
- Due to the important effect of the void content of concrete masonry blocks on their compressive strength, it is suggested that a more detailed analysis be conducted to determine the size and content of various voids in the masonry mixtures.
- The concept of packing density is not limited to the aggregates only and is extended to all the solid particles including the cementitious materials. A combination of improving the packing density of both the cementitious materials and the aggregates to improve the compressive strength of the final product can be investigated.
- The compaction effort was held constant for all the concrete cylinders of this study. It is recommended to test the effect of compaction level on the results.

- X-Seed had a more significant effect on the compressive strength of RAC compared to NAC mixtures. Therefore, the effect of X-Seed on RA is recommended to be further explored.
- CI index was presented as an indicator of the PC efficiency in this study. A life cycle assessment (LCA) is suggested to be conducted for thorough understanding of the carbon footprint and other environmental impacts of different concrete masonry mixtures. It is very important that the differences in the performance and application of the concrete masonry blocks produced by these dry mixtures is taken into account in such LCA.

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Appendix I

ANOVA test results for the compressive strength of mortars

The analysis of variances (ANOVA) was used in order to determine if there is significant difference between the means of the compressive strength of different mortar samples (Figure 4.4), the means of the compressive strength of concrete samples (Figure 4.5, Figure 4.6, and Table 4.4), and the means of the density of the concrete mixtures with the optimum w/s ratios with and without X-Seed 55 (Table 4.4). The null and alternative hypothesis were:

H₀: All means are equal.

H₁: Not all means are equal.

(Equal variances were assumed for the analysis).

The one-way ANOVA showed that the means of the testing groups are different. Therefore, a Tukey pairwise comparison was used to show which specific groups differed. In the following the results of these tests are presented. The significance level was set at 0.05.

Comparison of 7-d compressive strength of mortar samples

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	6	540.73	90.122	62.88	0.000	PC 7-d	3	31.9	1.22	(30.407, 33.393)
						PCX 7-d	3	43.1	1.68	(41.607, 44.593)
						P 7-d	3	28.4	0.92	(26.907, 29.893)
Error	13	18.63	1.433			Psp 7-d	3	26.8	1.04	(25.307, 28.293)
Total	19	559.37				PX 7-d	3	35.5	0.90	(34.040, 37.027)
						FA 7-d	2	28.8	0.42	(26.971, 30.629)
						FAX 7-d	3	32.6	1.47	(31.140, 34.127)

Pooled StDev = 1.19722

Factor	N	Mean	Grouping
PCX 7-d	3	43.1	A
PX 7-d	3	35.5	B
FAX 7-d	3	32.6	B C
PC 7-d	3	31.9	C D
FA 7-d	2	28.8	D E
P 7-d	3	28.4	E
Psp 7-d	3	26.8	E

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
PCX 7-d - PC 7-d	0.000
P 7-d - PC 7-d	0.040
Psp 7-d - PC 7-d	0.002
PX 7-d - PC 7-d	0.032
FA 7-d - PC 7-d	0.140
FAX 7-d - PC 7-d	0.986
P 7-d - PCX 7-d	0.000
Psp 7-d - PCX 7-d	0.000
PX 7-d - PCX 7-d	0.000
FA 7-d - PCX 7-d	0.000
FAX 7-d - PCX 7-d	0.000
Psp 7-d - P 7-d	0.664
PX 7-d - P 7-d	0.000
FA 7-d - P 7-d	0.999
FAX 7-d - P 7-d	0.011
PX 7-d - Psp 7-d	0.000
FA 7-d - Psp 7-d	0.553
FAX 7-d - Psp 7-d	0.001
FA 7-d - PX 7-d	0.000
FAX 7-d - PX 7-d	0.114
FAX 7-d - FA 7-d	0.046

Comparison of 28-d compressive strength of mortar samples

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	6	510.93	85.155	70.07	0.000	PC 28-d	3	39.9	0.32	(38.492, 41.242)
Error	13	15.80	1.215			PCX 28-d	3	46.9	1.35	(45.525, 48.275)
Total	19	526.73				P 28-d	3	32.2	0.72	(30.792, 33.542)
						Psp 28-d	3	32.0	1.46	(30.658, 33.408)
						PX 28-d	3	39.0	0.76	(37.658, 40.408)
						FA 28-d	2	33.2	1.48	(31.47, 34.83)
						FAX 28-d	3	39.3	1.29	(37.958, 40.708)

Pooled StDev = 1.10239

Factor	N	Mean	Grouping
PCX 28-d	3	46.9	A
PC 28-d	3	39.9	B
FAX 28-d	3	39.3	B
PX 28-d	3	39.0	B
FA 28-d	2	33.2	C
P 28-d	3	32.2	C
Psp 28-d	3	32.0	C

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
PCX 28-d - PC 28-d	0.000
P 28-d - PC 28-d	0.000
Psp 28-d - PC 28-d	0.000
PX 28-d - PC 28-d	0.961
FA 28-d - PC 28-d	0.000
FAX 28-d - PC 28-d	0.996
P 28-d - PCX 28-d	0.000
Psp 28-d - PCX 28-d	0.000
PX 28-d - PCX 28-d	0.000
FA 28-d - PCX 28-d	0.000
FAX 28-d - PCX 28-d	0.000
Psp 28-d - P 28-d	1.000
PX 28-d - P 28-d	0.000
FA 28-d - P 28-d	0.951
FAX 28-d - P 28-d	0.000
PX 28-d - Psp 28-d	0.000
FA 28-d - Psp 28-d	0.914
FAX 28-d - Psp 28-d	0.000
FA 28-d - PX 28-d	0.001
FAX 28-d - PX 28-d	0.999
FAX 28-d - FA 28-d	0.000

Comparison of 56-d compressive strength of mortar samples

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	6	306.68	51.113	30.58	0.000	PC 56-d	3	39.6	1.10	(37.954, 41.179)
Error	13	21.73	1.672			PCX 56-d	3	46.1	1.06	(44.487, 47.713)
Total	19	328.41				P 56-d	3	32.8	1.23	(31.154, 34.379)
						Psp 56-d	3	35.3	1.52	(33.721, 36.946)
						PX 56-d	2	38.8	0.50	(36.775, 40.725)
						FA 56-d	3	37.8	1.48	(36.187, 39.413)
						FAX 56-d	3	38.3	1.55	(36.721, 39.946)

Pooled StDev = 1.29293

Factor	N	Mean	Grouping
PCX 56-d	3	46.1	A
PC 56-d	3	39.6	B
PX 56-d	2	38.8	B C
FAX 56-d	3	38.3	B C
FA 56-d	3	37.8	B C
Psp 56-d	3	35.3	C D
P 56-d	3	32.8	D

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
PCX 56-d - PC 56-d	0.000
P 56-d - PC 56-d	0.000
Psp 56-d - PC 56-d	0.019
PX 56-d - PC 56-d	0.991
FA 56-d - PC 56-d	0.643
FAX 56-d - PC 56-d	0.894
P 56-d - PCX 56-d	0.000
Psp 56-d - PCX 56-d	0.000
PX 56-d - PCX 56-d	0.001
FA 56-d - PCX 56-d	0.000
FAX 56-d - PCX 56-d	0.000
Psp 56-d - P 56-d	0.260
PX 56-d - P 56-d	0.003
FA 56-d - P 56-d	0.005
FAX 56-d - P 56-d	0.002
PX 56-d - Psp 56-d	0.128
FA 56-d - Psp 56-d	0.297
FAX 56-d - Psp 56-d	0.139
FA 56-d - PX 56-d	0.980
FAX 56-d - PX 56-d	0.999
FAX 56-d - FA 56-d	0.998

Comparison of 90-d compressive strength of mortar samples

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	6	241.19	40.198	24.17	0.000	PC 90-d	3	43.0	1.57	(41.425, 44.642)
Error	13	21.62	1.663			PCX 90-d	3	46.9	0.21	(45.258, 48.475)
Total	19	262.81				P 90-d	3	36.4	1.10	(34.825, 38.042)
						Psp 90-d	3	37.7	1.63	(36.058, 39.275)
						PX 90-d	3	39.0	1.21	(37.358, 40.575)
						FA 90-d	3	42.4	1.01	(40.825, 44.042)
						FAX 90-d	2	43.4	1.98	(41.43, 45.37)

Pooled StDev = 1.28960

Factor	N	Mean	Grouping			
PCX 90-d	3	46.9	A			
FAX 90-d	2	43.4	A	B		
PC 90-d	3	43.0		B		
FA 90-d	3	42.4		B	C	
PX 90-d	3	39.0			C	D
Psp 90-d	3	37.7				D
P 90-d	3	36.4				D

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
PCX 90-d - PC 90-d	0.036
P 90-d - PC 90-d	0.000
Psp 90-d - PC 90-d	0.003
PX 90-d - PC 90-d	0.025
FA 90-d - PC 90-d	1.000
FAX 90-d - PC 90-d	1.000
P 90-d - PCX 90-d	0.000
Psp 90-d - PCX 90-d	0.000
PX 90-d - PCX 90-d	0.000
FA 90-d - PCX 90-d	0.013
FAX 90-d - PCX 90-d	0.118
Psp 90-d - P 90-d	0.893
PX 90-d - P 90-d	0.270
FA 90-d - P 90-d	0.001
FAX 90-d - P 90-d	0.001
PX 90-d - Psp 90-d	0.869
FA 90-d - Psp 90-d	0.008
FAX 90-d - Psp 90-d	0.004
FA 90-d - PX 90-d	0.066
FAX 90-d - PX 90-d	0.029
FAX 90-d - FA 90-d	0.978

Comparison compressive strength of PC mortar samples at different ages

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	3	201.25	67.083	51.11	0.000	PC 7-d	3	31.9	1.22	(30.375, 33.425)
Error	8	10.50	1.313			PC 28-d	3	39.9	0.32	(38.341, 41.392)
Total	11	211.75				PC 56-d	3	39.6	1.10	(38.041, 41.092)
						PC 90-d	3	43.0	1.57	(41.508, 44.559)

Pooled StDev = 1.14564

Factor	N	Mean	Grouping
PC 90-d	3	43.0	A
PC 28-d	3	39.9	B
PC 56-d	3	39.6	B
PC 7-d	3	31.9	C

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
PC 28-d - PC 7-d	0.000
PC 56-d - PC 7-d	0.000
PC 90-d - PC 7-d	0.000
PC 56-d - PC 28-d	0.988
PC 90-d - PC 28-d	0.039
PC 90-d - PC 56-d	0.025

Comparison compressive strength of PCX mortar samples at different ages

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	3	29.14	9.714	6.70	0.014	PCX 7-d	3	43.1	1.68	(41.496, 44.704)
Error	8	11.61	1.451			PCX 28-d	3	46.9	1.35	(45.296, 48.504)
Total	11	40.75				PCX 56-d	3	46.1	1.06	(44.496, 47.704)
						PCX 90-d	3	46.9	0.21	(45.263, 48.470)

Pooled StDev = 1.20451

Factor	N	Mean	Grouping
PCX 28-d	3	46.9	A
PCX 90-d	3	46.9	A
PCX 56-d	3	46.1	A
PCX 7-d	3	43.1	B

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
PCX 28-d - PCX 7-d	0.020
PCX 56-d - PCX 7-d	0.062
PCX 90-d - PCX 7-d	0.021
PCX 56-d - PCX 28-d	0.847
PCX 90-d - PCX 28-d	1.000
PCX 90-d - PCX 56-d	0.862

Comparison compressive strength of P mortar samples at different ages

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	3	97.349	32.450	31.66	0.000	P 7-d	3	28.4	0.92	(27.052, 29.748)
Error	8	8.200	1.025			P 28-d	3	32.2	0.72	(30.819, 33.515)
Total	11	105.549				P 56-d	3	32.8	1.23	(31.419, 34.115)
						P 90-d	3	36.4	1.10	(35.085, 37.781)

Pooled StDev = 1.01242

Factor	N	Mean	Grouping
P 90-d	3	36.4	A
P 56-d	3	32.8	B
P 28-d	3	32.2	B
P 7-d	3	28.4	C

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
P 28-d - P 7-d	0.008
P 56-d - P 7-d	0.003
P 90-d - P 7-d	0.000
P 56-d - P 28-d	0.884
P 90-d - P 28-d	0.004
P 90-d - P 56-d	0.009

Comparison compressive strength of Psp mortar samples at different ages

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	3	199.77	66.590	32.60	0.000	Psp 7-d	3	26.8	1.04	(24.897, 28.703)
Error	8	16.34	2.043			Psp 28-d	3	32.0	1.46	(30.131, 33.936)
Total	11	216.11				Psp 56-d	3	35.3	1.52	(33.431, 37.236)
						Psp 90-d	3	37.7	1.63	(35.764, 39.569)

Pooled StDev = 1.42916

Factor	N	Mean	Grouping
Psp 90-d	3	37.7	A
Psp 56-d	3	35.3	A B
Psp 28-d	3	32.0	B
Psp 7-d	3	26.8	C

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
Psp 28-d - Psp 7-d	0.009
Psp 56-d - Psp 7-d	0.000
Psp 90-d - Psp 7-d	0.000
Psp 56-d - Psp 28-d	0.085
Psp 90-d - Psp 28-d	0.006
Psp 90-d - Psp 56-d	0.264

Comparison compressive strength of PX mortar samples at different ages

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	3	25.384	8.4614	9.96	0.006	PX 7-d	3	35.5	0.90	(34.275, 36.791)
Error	7	5.945	0.8493			PX 28-d	3	39.0	0.76	(37.775, 40.291)
Total	10	31.329				PX 56-d	2	38.8	0.50	(37.209, 40.291)
						PX 90-d	3	39.0	1.21	(37.709, 40.225)

Pooled StDev = 0.921567

Factor	N	Mean	Grouping
PX 28-d	3	39.0	A
PX 90-d	3	39.0	A
PX 56-d	2	38.8	A
PX 7-d	3	35.5	B

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
PX 28-d - PX 7-d	0.010
PX 56-d - PX 7-d	0.026
PX 90-d - PX 7-d	0.011
PX 56-d - PX 28-d	0.986
PX 90-d - PX 28-d	0.999
PX 90-d - PX 56-d	0.994

Comparison compressive strength of FA mortar samples at different ages

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	3	251.692	83.897	57.26	0.000	FA 7-d	2	28.8	0.42	(26.706, 30.894)
						FA 28-d	2	33.2	1.48	(31.06, 35.24)
Error	6	8.792	1.465			FA 56-d	3	37.8	1.48	(36.090, 39.510)
Total	9	260.484				FA 90-d	3	42.4	1.01	(40.723, 44.143)

Pooled StDev = 1.21049

Factor	N	Mean	Grouping
FA 90-d	3	42.433	A
FA 56-d	3	37.800	B
FA 28-d	2	33.15	C
FA 7-d	2	28.800	D

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
FA 28-d - FA 7-d	0.043
FA 56-d - FA 7-d	0.001
FA 90-d - FA 7-d	0.000
FA 56-d - FA 28-d	0.022
FA 90-d - FA 28-d	0.001
FA 90-d - FA 56-d	0.013

Comparison compressive strength of FAX mortar samples at different ages

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	3	150.38	50.127	21.40	0.001	FAX 7-d	3	32.6	1.47	(30.544, 34.723)
Error	7	16.40	2.343			FAX 28-d	3	39.3	1.29	(37.244, 41.423)
Total	10	166.78				FAX 56-d	3	38.3	1.55	(36.244, 40.423)
						FAX 90-d	2	43.4	1.98	(40.84, 45.96)

Pooled StDev = 1.53064

Factor	N	Mean	Grouping
FAX 90-d	2	43.40	A
FAX 28-d	3	39.333	A B
FAX 56-d	3	38.333	B
FAX 7-d	3	32.633	C

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
FAX 28-d - FAX 7-d	0.005
FAX 56-d - FAX 7-d	0.011
FAX 90-d - FAX 7-d	0.001
FAX 56-d - FAX 28-d	0.852
FAX 90-d - FAX 28-d	0.084
FAX 90-d - FAX 56-d	0.033

Appendix II

ANOVA test results for the compressive strength of concretes

The analysis of variances (ANOVA) was used in order to determine if there is significant difference between the means of the compressive strength concretes (Figure 4.5, Figure 4.6, and Table 4.4). The null and alternative hypothesis were:

H₀: All means are equal.

H₁: Not all means are equal.

(Equal variances were assumed for the analysis).

The one-way ANOVA showed that the means of the testing groups are different. Therefore, a Tukey pairwise comparison was used to show which specific groups differed. In the following the results of these tests are presented. The significance level was set at 0.05.

Comparison of 28-d compressive strength NAC-100PC concrete mixtures with different w/s

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	5	164.182	32.8363	60.58	0.000	NAC-100PC-5	3	25.8	1.19	(24.805, 26.728)
						NAC-100PC-5.5	2	25.5	1.06	(24.272, 26.628)
Error	9	4.878	0.5420			NAC-100PC-6	3	27.5	0.20	(26.538, 28.462)
Total	14	169.060				NAC-100PC-6.5	2	30.0	0.14	(28.822, 31.178)
						NAC-100PC-7	3	33.4	0.51	(32.472, 34.395)
						NAC-100PC-7.5	2	33.5	0.57	(32.322, 34.678)

Pooled StDev = 0.736232

Factor	N	Mean	Grouping
NAC-100PC-7.5	2	33.5	A
NAC-100PC-7	3	33.4	A
NAC-100PC-6.5	2	30.0	B
NAC-100PC-6	3	27.5	C
NAC-100PC-5	3	25.8	C
NAC-100PC-5.5	2	25.5	C

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
NAC-100PC-5. - NAC-100PC-5	0.996
NAC-100PC-6 - NAC-100PC-5	0.130
NAC-100PC-6. - NAC-100PC-5	0.001
NAC-100PC-7 - NAC-100PC-5	0.000
NAC-100PC-7. - NAC-100PC-5	0.000
NAC-100PC-6 - NAC-100PC-5.	0.102
NAC-100PC-6. - NAC-100PC-5.	0.002
NAC-100PC-7 - NAC-100PC-5.	0.000
NAC-100PC-7. - NAC-100PC-5.	0.000
NAC-100PC-6. - NAC-100PC-6	0.039
NAC-100PC-7 - NAC-100PC-6	0.000
NAC-100PC-7. - NAC-100PC-6	0.000
NAC-100PC-7 - NAC-100PC-6.	0.006
NAC-100PC-7. - NAC-100PC-6.	0.009
NAC-100PC-7. - NAC-100PC-7	1.000

Comparison of 28-d compressive strength RAC-100PC concrete mixtures with different w/s

	Adj	Adj	F-	P-	Factor	N	Mean	StDev	95% CI	
Source	DF	SS	MS	Value	Value					
Factor	5	430.89	86.179	57.55	0.000	RAC-100PC-5	2	30.1	0.42	(28.143, 32.057)
Error	9	13.48	1.497			RAC-100PC-5.5	2	30.3	1.63	(28.29, 32.21)
Total	14	444.37				RAC-100PC-6	3	34.9	0.70	(33.302, 36.498)
						RAC-100PC-6.5	2	44.2	1.48	(42.19, 46.11)
						RAC-100PC-7	3	41.9	1.05	(40.302, 43.498)
						RAC-100PC-7.5	3	41.6	1.62	(39.968, 43.165)

Pooled StDev = 1.22369

Factor	N	Mean	Grouping
RAC-100PC-6.5	2	44.2	A
RAC-100PC-7	3	41.9	A
RAC-100PC-7.5	3	41.6	A
RAC-100PC-6	3	34.9	B
RAC-100PC-5.5	2	30.3	C
RAC-100PC-5	2	30.1	C

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
RAC-100PC-5. - RAC-100PC-5	1.000
RAC-100PC-6 - RAC-100PC-5	0.018
RAC-100PC-6. - RAC-100PC-5	0.000
RAC-100PC-7 - RAC-100PC-5	0.000
RAC-100PC-7. - RAC-100PC-5	0.000
RAC-100PC-6 - RAC-100PC-5.	0.021
RAC-100PC-6. - RAC-100PC-5.	0.000
RAC-100PC-7 - RAC-100PC-5.	0.000
RAC-100PC-7. - RAC-100PC-5.	0.000
RAC-100PC-6. - RAC-100PC-6	0.000
RAC-100PC-7 - RAC-100PC-6	0.001
RAC-100PC-7. - RAC-100PC-6	0.001
RAC-100PC-7 - RAC-100PC-6.	0.403
RAC-100PC-7. - RAC-100PC-6.	0.280
RAC-100PC-7. - RAC-100PC-7	0.999

Comparison of 28-d compressive strength NAC-80PC concrete mixtures with different w/s

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
						NAC-80PC-6.5	3	29.1	0.67	(27.989, 30.145)
Factor	2	39.227	19.6133	33.69	0.000	NAC-80PC-7	3	31.0	0.20	(29.922, 32.078)
Error	6	3.493	0.5822			NAC-80PC-7.5	3	25.9	1.12	(24.855, 27.011)
Total	8	42.720								

Pooled StDev = 0.763035

Factor	N	Mean	Grouping
NAC-80PC-7	3	31.0	A
NAC-80PC-6.5	3	29.1	B
NAC-80PC-7.5	3	25.9	C

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
NAC-80PC-7 - NAC-80PC-6.5	0.048
NAC-80PC-7.5 - NAC-80PC-6.5	0.006
NAC-80PC-7.5 - NAC-80PC-7	0.000

Comparison of 28-d compressive strength RAC-80PC concrete mixtures with different w/s

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
						RAC-80PC-6	2	27.1	0.21	(26.018, 28.082)
Factor	2	11.868	5.9342	18.41	0.005	RAC-80PC-6.5	3	28.3	0.64	(27.424, 29.109)
Error	5	1.612	0.3223			RAC-80PC-7	3	30.1	0.61	(29.257, 30.943)
Total	7	13.480								

Pooled StDev = 0.567744

Factor	N	Mean	Grouping
RAC-80PC-7	3	30.1	A
RAC-80PC-6.5	3	28.3	B
RAC-80PC-6	2	27.1	B

Means that do not share a letter are significantly different.

Difference of Levels	Adjusted P-Value
RAC-80PC-6.5 - RAC-80PC-6	0.138
RAC-80PC-7 - RAC-80PC-6	0.005
RAC-80PC-7 - RAC-80PC-6.5	0.024

Comparison of 28-d compressive strength of concrete mixtures with optimum w/s with and without X-Seed 55

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Factor	N	Mean	StDev	95% CI
Factor	21	2626.77	125.084	114.74	0.000	NAC-100PC-7	3	33.4	0.51	(31.978, 34.889)
						RAC-100PC-6.5	2	44.2	1.48	(42.37, 45.93)
Error	36	39.25	1.090			NAC-80PC-7	3	31.0	0.20	(29.545, 32.455)
Total	57	2666.02				RAC-80PC-7	3	30.1	0.61	(28.645, 31.555)
						NAC-100PC-7-X	3	37.9	0.79	(36.445, 39.355)
						RAC-100PC-6.5-X	2	54.5	0.99	(52.718, 56.282)
						NAC-80PC-7-X	3	35.7	1.76	(34.28, 37.19)
						RAC-80PC-7-X	3	39.2	1.92	(37.74, 40.66)

Pooled StDev = 1.17529

Factor	N	Mean	Grouping
RAC-100PC-6.5-X	2	54.5	A
RAC-100PC-6.5	2	44.2	B
RAC-80PC-7-X	3	39.2	C
NAC-100PC-7-X	3	37.9	C
NAC-80PC-7-X	3	35.7	D
NAC-100PC-7	3	33.4	E
NAC-80PC-7	3	31.0	F
RAC-80PC-7	3	30.1	F

Difference of Levels	Adjusted P-Value
RAC-100PC - NAC-100PC	0.000
NAC-80PC - NAC-100PC	0.257
RAC-80PC - NAC-100PC	0.055
NAC-100PC-X - NAC-100PC	0.007
RAC-100PC-X - NAC-100PC	0.000
NAC-80PC-X - NAC-100PC	0.313
RAC-80PC-X - NAC-100PC	0.001
NAC-80PC - RAC-100PC	0.000
RAC-80PC - RAC-100PC	0.000
NAC-100PC-X - RAC-100PC	0.001
RAC-100PC-X - RAC-100PC	0.000
NAC-80PC-X - RAC-100PC	0.000
RAC-80PC-X - RAC-100PC	0.007
RAC-80PC - NAC-80PC	0.976
NAC-100PC-X - NAC-80PC	0.000
RAC-100PC-X - NAC-80PC	0.000
NAC-80PC-X - NAC-80PC	0.004
RAC-80PC-X - NAC-80PC	0.000
NAC-100PC-X - RAC-80PC	0.000
RAC-100PC-X - RAC-80PC	0.000
NAC-80PC-X - RAC-80PC	0.001
RAC-80PC-X - RAC-80PC	0.000
RAC-100PC-X - NAC-100PC-X	0.000
NAC-80PC-X - NAC-100PC-X	0.377
RAC-80PC-X - NAC-100PC-X	0.863
NAC-80PC-X - RAC-100PC-X	0.000
RAC-80PC-X - RAC-100PC-X	0.000
RAC-80PC-X - NAC-80PC-X	0.043