Investigation of low-carbon concrete mixes for roading infrastructure

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Executive summary

Introduction

The road infrastructure of a country is critical and essential because it plays a pivotal role in fostering economic development and connectivity. While most roads in Aotearoa / New Zealand are bituminous, concrete is widely used in other aspects of our road infrastructure, such as bridges, tunnels and drainage systems.

Concrete is made of a binder, typically cement, and sand and gravel as fine and coarse aggregates respectively. Cement reacts with water through hydraulic reactions to form calcium silicate hydrate crystals that gives concrete its strength and durability, although at a considerable carbon footprint. The vast majority of these emissions come from the manufacturing of cement, being approximately evenly divided between the use of fossil fuels to produce the cement and the chemical reactions that occur during the hydraulic reactions when the cement hardens with the water.

Today, the concrete industry uses supplementary cementitious materials as partial replacement of cement to reduce the environmental impact of concrete, but most of these supplementary cementitious materials are the byproduct of heavy industries such as coal plants and steel smelters, which do not exist in Aotearoa and/or are being phased down or transformed in a way that limits the availability of these materials both nationally and overseas.

Another potential supplementary cementitious material is natural pozzolana, such as volcanic ashes (mainly pumice and tephra). These materials are inert by themselves, i.e. they do not possess hydraulic reactivity potential like cement. However, they possess pozzolanic reactivity when mixed with cement, in which the oxides from the ashes react with the hydroxides from the hydraulic reactions to form more calcium silicate hydrate crystals to contribute to the strength and durability of the concrete. These materials are suitable as partial replacements of cement, often in the 20% to 30% replacement ratio, due the availability of hydroxides from the hydraulic reactions. The pozzolanic reactions related to these natural pozzolana are different than the hydration reactions of typical Portland cement in terms of for example heat exchange and duration, but both contribute to the strength of the concrete through the formation of calcium silicate hydrate crystals.

New Zealand has a long history of volcanic activity, and an abundance of volcanic material, but very little research has been published on the use of these local materials in concrete, as opposed to overseas where research is plentiful.

Objective of the research

This research was performed as a pilot study, or a proof of concept, to understand whether pumice and tephra from local deposits could be used in concrete to reduce its environmental impact while still meeting design requirements and national specifications.

Methodology

Pumice originating from the Taupo volcanic zone (Hatepe eruption) and tephra from the Rotorua volcanic zone (Rotorua eruption) were used for this study. Following chemical and mineralogical testing, it was determined that these materials meet the requirements of the widely recognised international standard ASTM C618, which sets out the properties that a natural pozzolana must meet to be used in concrete. Temperature, pH, density and slump were measured as fresh concrete properties, and compressive strength and flexural strength were measured as hardened concrete properties. The carbonation potential, or the susceptibility of the concrete to expose the steel to corrosion, was evaluated as a durability property. Life cycle assessment was conducted for all concrete mixes based on three main concrete batching plants in New Zealand.

Key findings

The main findings of this pilot study are:

- The slump of concrete mixes reduced with increasing the pumice and tephra content, but the mixes with up to 20% replacement still met the design specifications. The workability can be improved using off-the-shelf admixtures.
- The heat of reaction decreased as the replacement content increased, reducing the potential for thermal cracking of concrete while setting.
- The pH of concrete mixes reduced with increasing the pumice and tephra content, but the decrease was not enough to compromise the protection to steel corrosion that the concrete provides.
- The target compressive strength was 20 MPa after 28 days of curing. The compressive strength decreased with increasing the pumice and tephra content, and only the mixes with 10% replacement level could achieve this design requirement. However, this study and the comparison with international benchmark materials revealed that the natural pozzolana needs to be ground more finely than typical cement. The pumice and tephra used in this study were ground down to 95% passing 45 microns, following international standards for

cementitious materials. However, the international benchmark materials that have been used by our collaborators in the USA had a typical size of 10-15 micron.

- Flexural strength decreased with increasing the pumice and tephra, but this property is not part of the design specifications.
- The hardened density decreased with increasing the pumice and tephra content.
- The potential for carbonation is a key measure of concrete durability as it relates to steel corrosion, and it was reduced as the replacement ratio increased.
- The reduction in global warming potential (GWP) closely aligned with the percentages of cement replacement, such as 10%, 20% and 30%.

Next steps

The results show that pumice and tephra from the Taupo Volcanic Zone can be used for concrete mixes, but the study, being a pilot study, has significant limitations:

1) the materials were not ground finely enough, compromising the strength,
2) the water demand has not been investigated, which influences the workability during construction, and
3) only two materials were considered for one concrete mix.

These limitations, along with the critical aspect of durability, will be investigated under a PhD project scheduled to be completed in 2026-2027.

Acknowledgements

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Our heartfelt appreciation goes to NZTA's Shauna O'Malley for efficiently managing the administrative aspects of this research project. Her meticulous attention to detail has been crucial to the smooth execution and success of our study.

We express our sincere gratitude to Chaya Kumari, a masters student, and Osama Mughrabi, a PhD student for their valuable contributions to experiments conducted in this study. Additionally, our sincere gratitude goes to the laboratory staff at the University of Auckland. Their collective efforts and unwavering commitment to maintaining high standards in the laboratory have played a crucial role in the success of our research project.

This acknowledgement is a tribute to all those mentioned and the countless others whose contributions, whether financial, advisory, or operational, have been essential to the positive outcomes of our research endeavours.

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1.0 Introduction

1.1 The road network of a country

The road network of a country is vital infrastructure. A well-developed road network provides various benefits, such as enhancing connectivity and accessibility, fostering economic growth, generating employment opportunities, improving safety standards, promoting regional development, facilitating tourism and recreation, fostering social integration, and expediting emergency response. New Zealand has a comprehensive network of roads across its north and south islands, catering to a range of transportation needs. They connect cities, towns, remote regions, and popular tourist destinations from urban highways to rural roads. The road network in New Zealand accommodates various types of vehicles, including trucks, cars, motorcycles, and bicycles, facilitating convenient and efficient travel for more than 5 million people, road freight and the tourism industry.

1.2 Importance and environmental impact of concrete

Concrete is a strong, durable and versatile material used not only in the construction of roads but also for non-road uses within the roading network such as bridges, kerbs, retaining walls, etc. Concrete has become the second most consumed material in the world[1]. Concrete is a composite material made with cement, sand, crushed stones and water. The manufacture of ement, the binding ingredient in concrete, is a primary source of greenhouse gas emissions contributing to climate change. Cement production releases greenhouse gases while mining raw materials and manufacturing, mainly through the combustion of fossil fuels and chemical reactions. As a result, the concrete industry is responsible for 8% of global greenhouse gas emissions [2]. According to the Paris Agreement, limiting the global temperature rise below 1.5 to 2 degrees above the pre-industrial level is essential to prevent catastrophic climate change effects. Today, the concrete industry uses supplementary cementitious materials (SCMs) to replace cement partially to reduce greenhouse gas emissions. SCMs contribute to the properties of concrete through hydraulic activity, pozzolanic activity or both. Therefore, they give several benefits, such as increasing long-term strength, increasing durability, reducing the risk of thermal cracking etc. Fly ash, silica fume and slag are by-products from heavy industries commonly used as SCMs in concrete. These heavy industries such as coal thermal plants and steel smelters are shutting down or altering their processes due to government regulations to reduce greenhouse gas emissions, which is leading a shortage of these materials for SCM use. In addition to that, Aotearoa New Zealand never had these industries in any significant proportion and/or are being phased down or transformed, so alternative materials need to be found to replace the cement. Overseas, the concrete industry is starting to use natural pozzolans from volcanic origins to replace cement, but very little recent research has been published where New Zealand materials were evaluated, and key research questions remain.

1.3 Volcanic materials in New Zealand

New Zealand is a very geothermally, volcanic and seismic active area, being located on the boundary between the Pacific Plate and the Indo-Australian Plate known as the Ring of Fire. Whakaari, Tongariro, Ngauruhoe, and Tarawera are examples of active volcanoes, and Rotorua, Taupo and the Auckland Volcanic Fields are examples of dormant volcanoes.

During a volcanic eruption, lava, volcanic ash and tephra are ejected, and after reaching the earth's surface, the lava begins to cool and solidify, forming volcanic rock. There are various volcanic rocks such as pumice, scoria, rhyolite, andesite, basalt, etc. Pumice is a light and porous rock generally made from felsic magma, so it is more capable of holding water and air, and the colour varies from white to light grey. Scoria is a dense and less porous volcanic rock. It forms when mafic magma cools rapidly, and the colour varies from dark red to black based on its mineral composition. Because of the rapid escape of gases from the molten lava, both pumice and scoria have a vesicular texture. Rhyolite is formed from felsic magma, and it has a fine-grained texture. Andesite is usually a grey volcanic rock with a fine-grained texture. The largest active andesite volcano in New Zealand is Ruapehu [3]. Basalt is formed with mafic lava and varies from dark grey to black. It is rich in magnesium and iron but poor in silica. Tephra is a fragmental material that escapes from a volcano and appears darker in colour during an eruption.

1.4 Use of volcanic materials for making concrete

In Aotearoa, volcanic materials are ideal as a partial replacement of cement because of their abundant supply and ease of sourcing and transport. The incorporation of volcanic materials in concrete can reduce the environmental impact in several ways. First and foremost, the processing required to prepare these materials is significantly less-energy intensive than manufacturing cement, and it can be achieved with renewable energy. While New Zealand currently imports approximately half of the cement locally consumed, volcanic materials are locally available and reduce the need for long- distance transport, subsequently reducing transportation related energy consumption and environmental impact. The Taupo volcanic zone is in the central north island and is 300 km long and up to 60 km wide. Both pumice and tephra are present, among other volcanic materials [4]. Many studies claim that both pumice and tephra are pozzolanic[5,6], so both have been used as cement replacements in this study to investigate the performance of concrete, but not all pumices and tephra are pozzolanic by default. These are geology/volcanology terms that describe volcanic eruption types, not engineering terms that can be used in the concrete industry. Further characterisation of the particular material in engineering terms is necessary to fully evaluate its pozzolanity.

1.5 Project team

This research was conducted at the University of Auckland and funded by the New Zealand Transport Agency Waka Kotahi (NZTA)'s Innovation Fund. Dr Enrique del Rey Castillo, Senior Lecturer, was the principal investigator and Kavishan Ranatunga, PhD student, worked as the research assistant in this project.

2.0 Aim and Objectives

This report summarizes the results of a pilot study aimed at investigating the fundamental properties of concrete with partial replacement of cement by pumice and tephra, using one commonly used mix for low-demand applications such as footpaths. Target average compressive strength at 28 days of curing was 20 MPa. There were three main objectives in this study:

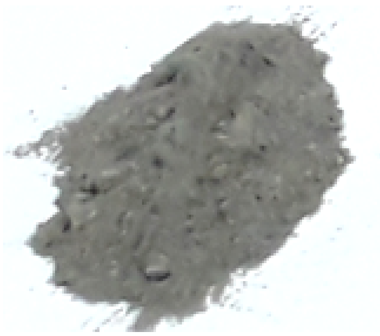
1. To identify the properties of the raw feedstock materials to benchmark them against international materials and standards,
2. To study the properties of concrete mixes using various replacement levels, mainly fresh workability, and concrete strength, and
3. To adequately quantify the environmental impacts according to the BS EN 15804:2012+A1:2013[7]. The mix design has been carried out as per the ACI standard[8] and is currently used in the concrete industry.

3.0 Methodology

The material properties and procedure used to succeed in this study are described in this chapter.

3.1 Materials

The Materials used for this study are shown in **Figure 3.1**, and their properties are described below.



Cement

Fine aggregate

Coarse aggregate

Pumice

Tephra unit 1

Tephra unit 2

Tephra unit 3

Figure 3. 1: Materials

- Cement

General-purpose cement was used as the binding material in this study. The carbon footprint of the cement was 0.70 kg of CO_2 /kg and, the initial and final setting time were 45 minutes and 300 minutes respectively as per the cement manufacturer[9]

- Water

Tap water of drinking quality and free from organic matter was used.

- Fine aggregate

Washed sea sand was used as fine aggregate to produce concrete. Sieve analysis was performed to determine the particle size distribution as per the ASTM C136 [10] and it is shown in **Figure 3.2** according to the sieve analysis test. The water absorption test was conducted to determine the ability of aggregate to absorb water as per the ASTM C127 [11,12]. The water absorption of the sand was 0.62% as per the water absorption test.

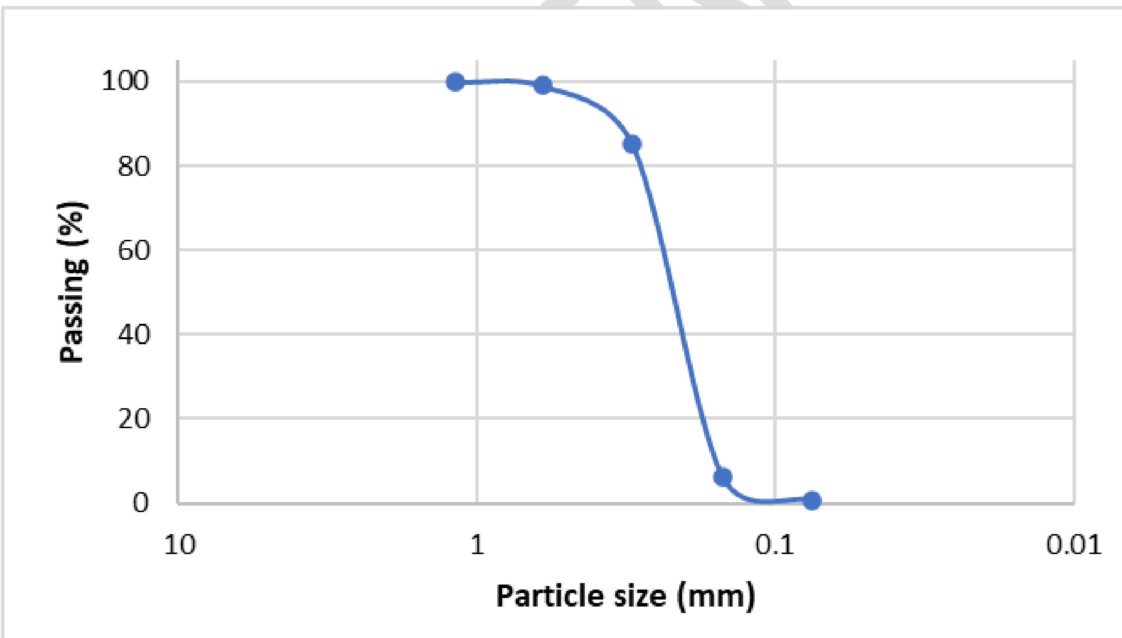


Figure 3. 2: Particle size distribution of sand

- Coarse aggregate

Graded crushed aggregates of 19 mm, 13 mm, and 7 mm were used as coarse aggregates to produce concrete mixes. The particle size distribution curves of crushed stones are shown in **Figure 3.3**.

The water absorption values of the 19 mm, 13 mm and 7 mm aggregate were 1.8%, 0.85% and 0.85% as per the ASTM C128[14].

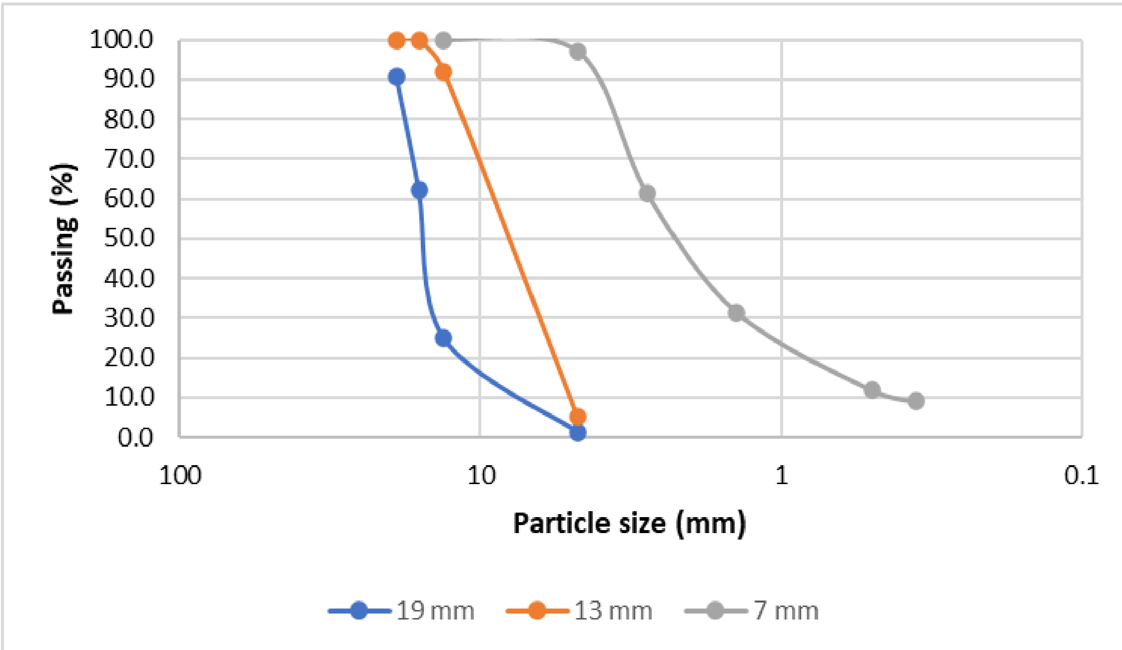


Figure 3. 3: Particle size distribution of stones

- Pumice

Pumice was used as a cement-replacing material in this study to investigate the performance of concrete. Pumice was brought from the Taupo volcanic zone originating from the Hatepe volcanic eruption, and ground before being used as a partial cement replacement. Initial moisture content was measured as per the ASTM D2216 [12], and it was 0.5%. **Figure 3.4** shows particle size distribution curves of pumice before and after grinding. X-ray fluorescence analysis was performed to determine the chemical composition in compliance with the ASTM C114[13]. **Table 3.1** shows the chemical composition of pumice. The sum of SiO_2, Al2O3 and Fe2O3 in pumice was higher than 70%, and the loss on ignition was less than 10%. Therefore, pumice can be used as natural pozzolans in concrete as per the ASTM C618.

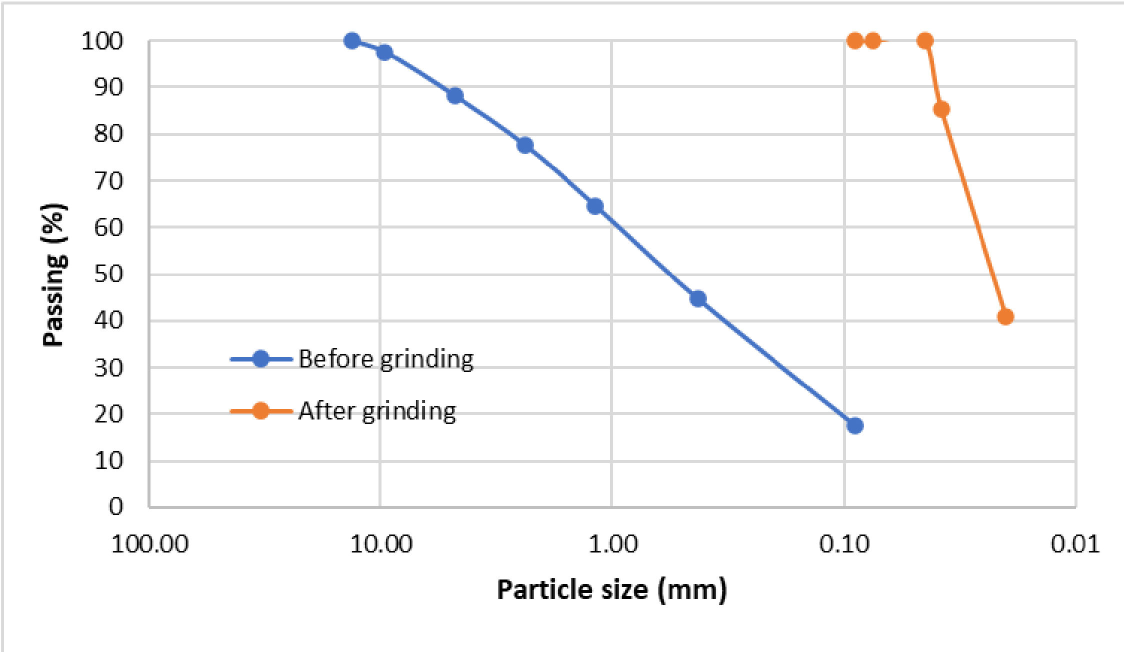


Figure 3. 4: Particle size distribution of the pumice used in this study

Table 3. 1: Chemical composition of the pumice used in this study

Oxide	**Percentages in pumice**
SiO_2	57.6
Al_2O_3	12.6
Fe_2O_3	2.3
CaO	1.7
MgO	0.3
LOI	2.8

- Tephra

Tephra was also used as a partial cement replacement in this study to investigate the performance of concrete. Tephra was brought from the Rotorua volcanic zone, where it had been deposited in three layers following the Rotorua volcanic eruption, and named unit 1, unit 2, and unit 3. The moisture content test was done to determine the initial moisture content and they were 35.2%, 40.1%, and 36.2%, respectively. Particle size distribution curves of tephra unit 1, unit 2, and 3 are illustrated by **Figure 3.5**, **Figure 3.6**, and **Figure 3.7**. **Table 3.2** shows the chemical composition of tephra units 1, 2, and 3.

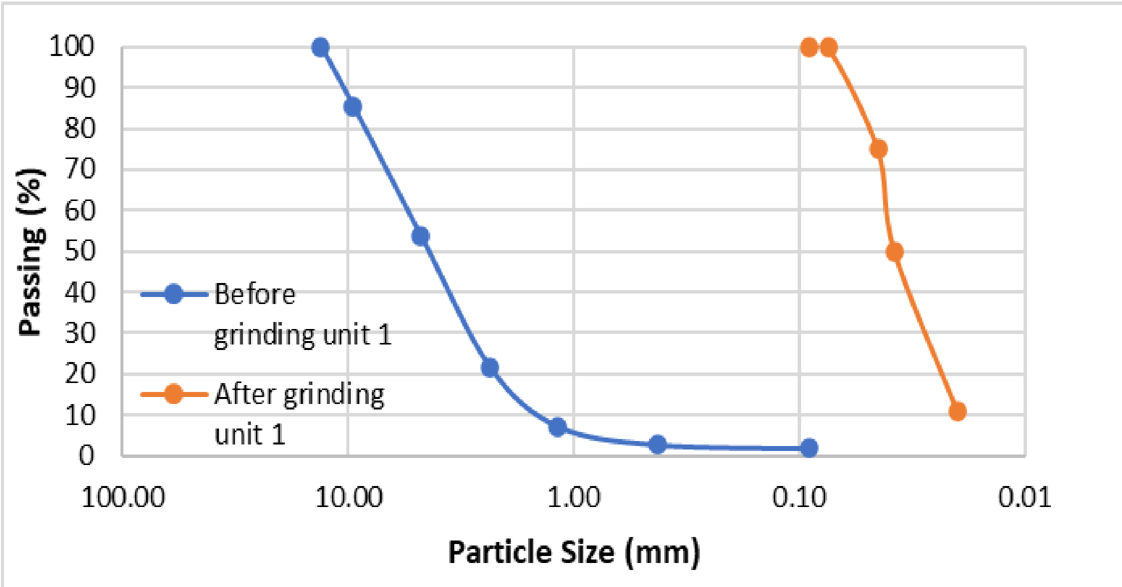


Figure 3. 5: Particle size distribution of tephra unit 1

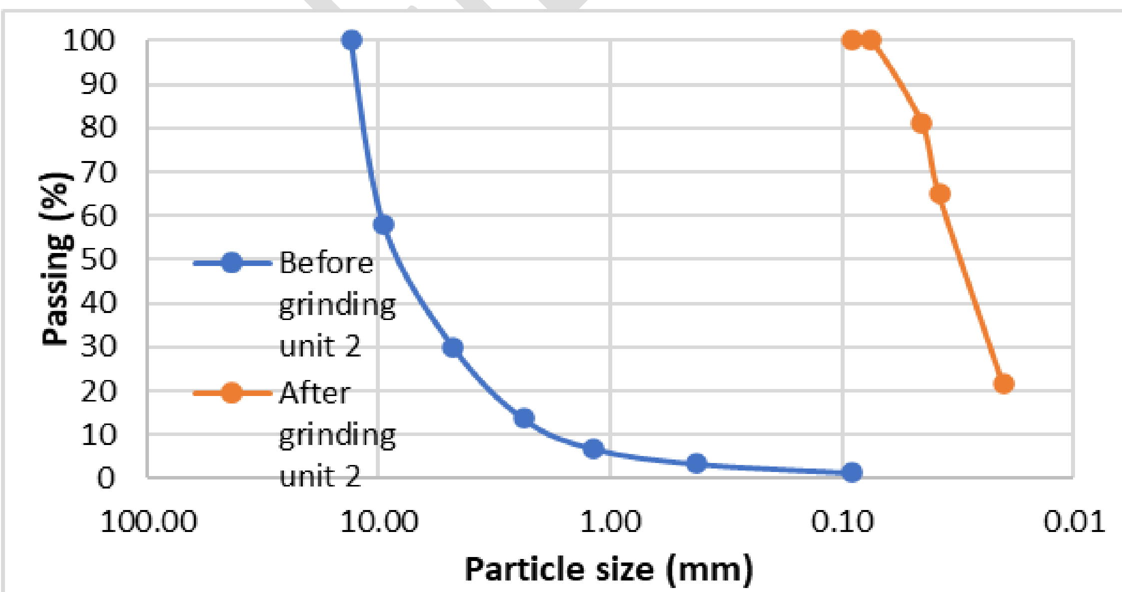


Figure 3. 6: Particle size distribution of tephra unit 2

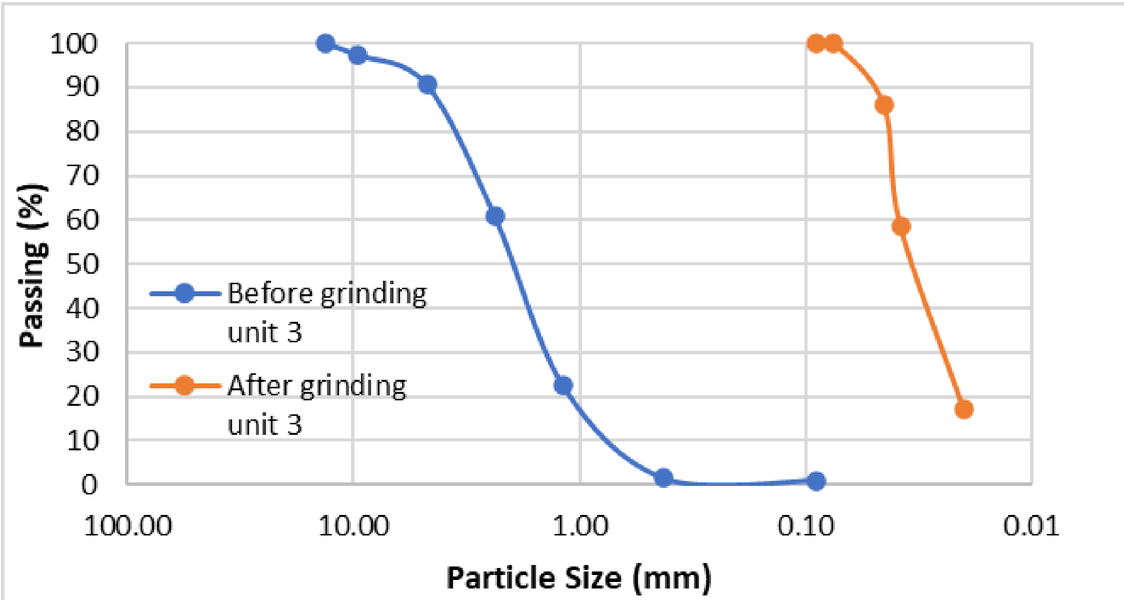


Figure 3. 7: Particle size distribution of tephra unit 3

Table 3. 2: Chemical composition of tephra

Oxide	**Percentages in unit 1**	**Percentages in unit 2**	**Percentages in unit 3**
SiO_2	61.1	56.7	52.5
Al_2O_3	12.6	12.3	12.8
Fe_2O_3	1.4	1.4	1.4
CaO	1.5	1.3	1.3
MgO	0.2	0.2	0.2
LOI	2.3	2.4	2.4

3.2 Experimental Procedure

The experimental works of this study were divided into four parts, as presented in **Figure 3.8**.

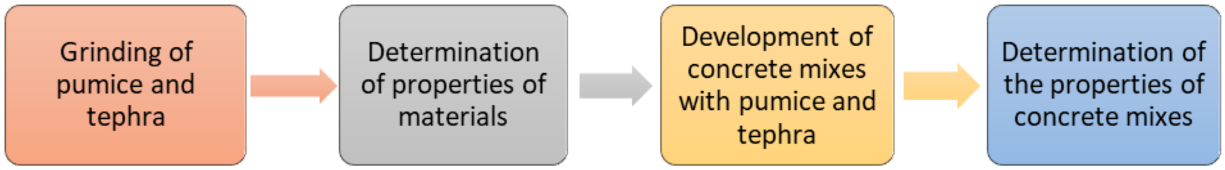


Figure 3. 8: Experimental procedure

First, pumice and tephra were ground using a ball mill to get all particles below 75 microns. **Figure 3.9** shows the ball mill used for grinding in this study.

Figure 3. 9: Ball mill

Then, the properties of the materials were tested through various tests, as explained above. Then, a concrete mix was developed to achieve the target average compressive strength of 20 MPa. **Table 3.3** presents the proportions of the concrete mix used in this study.

Table 3. 3: Concrete mix design

Material	**Quantity (Kg/m3)**

Cement	250
Sand	445
Crushed stones (7 mm)	435
Crushed stones (13 mm)	340
Crushed stones (19 mm)	695
Water	190

Then cement was partly replaced with pumice and tephra. Tephra units 1, 2 and 3 were added in equal amounts when replacing the cement. This decision was made because the chemical composition of the three layers is relatively homogeneous, and because of the practical necessity to mine as deep deposits as possible for economic reasons, which would result in different combinations of the three units in a production environment. By using three replacement levels of 10%, 20% and 30% for each of pumice and tephra, the resulting number of mixes was 6, in addition to the two control mixes used as benchmark. **Table 3.4** shows the cement replacement levels and mix ID of concrete mixes.

Table 3. 4: Mix ID of concrete mixes

Cement replacement level (%)	ID of pumice mixes	ID of tephra (unit 1+unit 2 + unit 3) mixes
0	Control	Control
10	P10	T10
20	P20	T20
30	P30	T30

Twelve cylinders and six beams were cast with every mix in accordance with New Zealand Standard NZS 3112.2:1986. Finally, various tests were conducted to investigate the performance of concrete and select the optimal mix for making low traffic concrete roads. Slump, temperature, pH and density were determined as fresh concrete properties at the time of mixing. Compressive strength was measured after 7, 28, 56 and 91 days, and flexural strength was measured after 7, 28 and 56 days. In addition, the potential for carbonation of the binder was measured using paste cubes in accordance with international standard ASTM C1910.

4.0 Project outcomes

The milestones and deliverables of this project were achieved successfully, as shown in **Table 4.1**.

Table 4. 1: Milestones and deliverables

Item	Milestone	Deliverables	Completed or not	Notes
1	At least five concrete mixes were developed, and testing parameters confirmed	An experimental investigation of at least five concrete mixes that include waste materials and natural pozzolana, aimed at producing concrete road pavements that are low-carbon and built with locally sourced materials	Completed	Six concrete mixes were developed using natural pozzolana.
2	Testing of potential properties of the concrete mixes completed	-	Completed	Fresh and hardened concrete properties were tested.
3	Carbon footprint analysis of the mixes using life cycle analyses modified with local data completed	Identification of two mixes suitable for further field testing upon completion of the project	Completed	The environmental impact of the six concrete mixes regarding three batching plants in New Zealand was analysed.

5.0 Key findings

The following findings were derived from this research study.

- The slump of concrete mixes reduced with increasing the pumice and tephra content, and 10P, 20P and 10T concrete mixes had a higher slump than 50mm.
- The temperature of concrete mixes with pumice or tephra was lower than the control mix. The temperature of the control mix was 19^{0}C, and 30P and 30T mixes showed 15.6^{0}C as the lowest temperature.
- The pH of concrete mixes reduced with increasing the pumice or tephra content, so there is a potential impact of pumice and tephra on alkali-silica reaction (ASR) and carbonation of concrete.
- The density of all concrete mixes with pumice or tephra was less than 2410 Kg/m^3, but the reduction in density was minor.
- The compressive strength of concrete mixes decreased with increasing the pumice or tephra content. The average compressive strength of 10P and 10T mixes was only higher than 20 MPa at 28 days of curing. This concrete would be suitable for many uses that have low strength requirements, such as footpaths and ancillary infrastructure. However, there is a potential for strength improvement of all mixes by incorporating finer pozzolans and adjusting the water content as per the water absorption of pumice and tephra.
- The flexural strength of concrete mixes decreased with increasing the pumice or tephra content. 30P and 30T mixes showed a higher strength loss than other concrete mixes. There is a potential to improve the flexural strength of all concrete mixes using finer pozzolans and adjusting water content.
- As per the life cycle assessment, the environmental impact in GWP, AP, EP, POCP, and ADPF categories of 10P, 20P, and 30P mixes was less than in the control mix. The reduction in GWP closely aligned with the percentage of cement replacement in concrete mixes (i.e. approximately 10%, 20% and 30% reductions). This relationship held true across the three batching plant locations.
- 10P and 10T mixes were the best mixes for making road pavements based on the properties of concrete and life cycle assessment.

Properties of concrete and life cycle assessment are discussed in the following subsections.

5.1 Fresh properties

5.1.1. Slump

The slump of the concrete mixes were tested as per the NZS3112.1:1986[14]. **Figure 5.1** and **Figure 5.2** show the slump variation of concrete mixes with pumice and tephra, respectively. The slump of concrete mix decreased with increasing the pumice or tephra content. The control mix had the highest slump of 85 mm. The lowest slump of 35 mm belonged to both 30P and 30T mixes. Regarding concrete mixes with pumice, the slump reduced by 12%, 29% and 59% for 10P, 20P and 30P mixes. Regarding concrete mixes with tephra, the slump reduced by 41%, 53% and 59% for 10T, 20T and 30T mixes respectively. In this study, total water to binder (w/b) ratio was maintained at 0.76 without changing the water to ensure that only the impact of pumice and tephra on the slump was investigated without additional parameters having an influence on workability. Therefore, the only reason the slump was reduced was the use of these volcanic materials. Pumice and tephra have a porous nature, so they absorb water. Increasing the pumice and tephra increased the absorbed water into their porous structure and reduced the free water content available to lubricate the fresh concrete mix. Although all particles of pumice and tephra were less than 75-micron, tephra had larger particles than pumice. Large particles can absorb more water into their voids. Therefore, concrete mixes with tephra showed more slump reduction than concrete mixes with pumice. A concrete mix needs a slump higher than 50 mm to be easily used to construct concrete pavements, so admixtures would be necessary if mixes with a slump lower than 50mm were to be implemented. Admixtures are commonly used in the concrete industry and have been for many years, so the investigation of these materials was not considered. Regardless, the effect of the pozzolana on water demand, and thus on slump and strength, will need to be further investigated, especially considering that the particle size has a significant effect on these parameters.

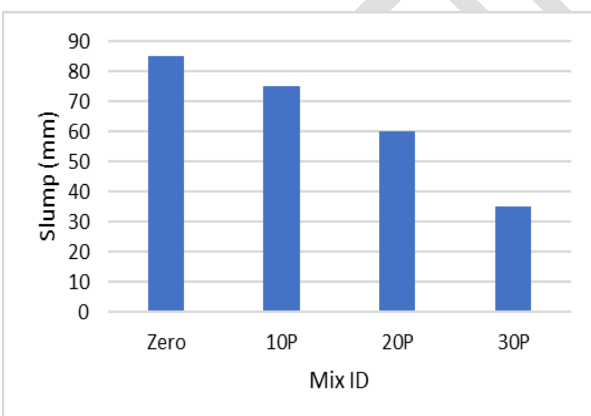


Figure 5. 1: Slump of pumice mixes

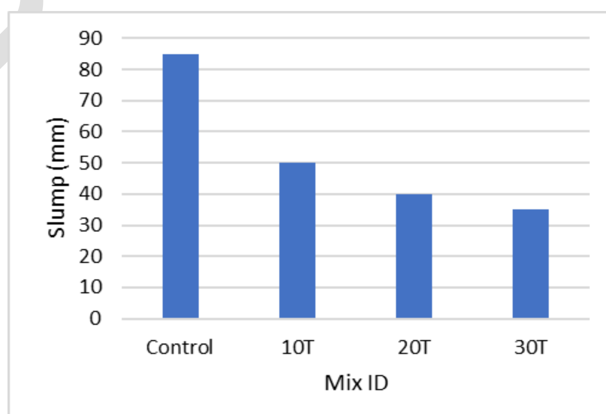


Figure 5. 2: Slump of tephra mixes

5.1.2. Temperature

Temperature of a concrete mix is typically used as a proxy for setting times, and in some cases needs to controlled to avoid the cracking of concrete while curing, but the temperature is significantly affected when SCMs are included in the concrete mix. Temperature of concrete mixes was measured using a thermometer. **Figure 5.3** and **Figure 5.4** show the temperature of various concrete mixes with pumice and tephra, respectively. The temperature of concrete mixes with pumice or tephra (10P, 20P, 30P, 10T, 20T and 30T) was lower than the control mix. The temperature of concrete mixes reduced with increasing the pumice or tephra content. The temperature of the control mix was 19^0C, and the temperature of the 30P and 30T mixes was 15.6 ^{0}C, making it clear that pumice and tephra contribute to the temperature drop of concrete mixes. There were two reasons for this drop in temperature. The first reason was the reduction of cement content in concrete mixes. The cement and water reaction is exothermal – heat is generated during the reaction - and it increases the temperature of a concrete mix. By reducing the cement content, heat generation due to cement hydration was reduced[15]. The second reason was that pumice and tephra are pozzolanic materials. They react with calcium hydroxide, which is a by-product of cement hydration. However, those reactions are delayed because they depend on cement hydration. The temperature of concrete mixes with pumice and tephra was low because pumice and tephra delayed the heat generation. Higher temperatures cause thermal cracking in concrete, so the concrete temperature at the discharge point shall be less than 35^0C[16]. All concrete mixes with pumice and tephra showed a lower temperature than 35^0C; therefore, all concrete mixes are suitable for road pavements from a temperature perspective.

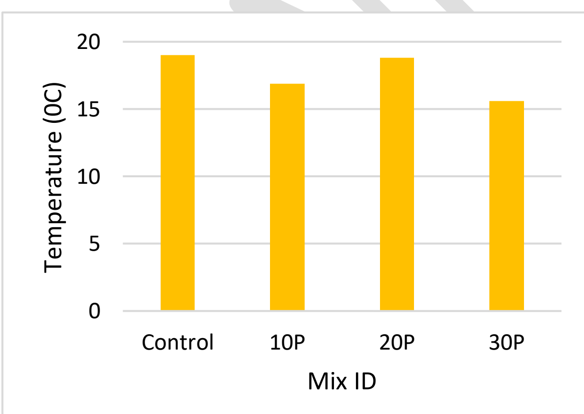


Figure 5. 3: Temperature variation of pumice mixes

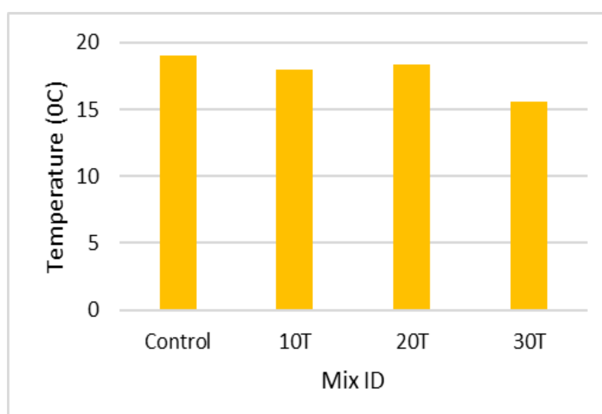


Figure 5. 4: Temperature variation of tephra mixes

5.1.3. pH

The alkaline environment created by the high pH in concrete helps to passivate and protect the reinforcing steel embedded in concrete against corrosion. Typically, the pH of concrete is alkaline due to the presence of calcium hydroxide formed during the hydration of Portland cement. The pH of concrete mixes in this study was measured using a pH meter. **Figure 5.5** and **Figure 5.6** show the pH of concrete mixes with pumice and tephra. The pH of concrete slightly decreased with the increase in pumice or tephra content. The control mix showed the highest pH of 12.9. The 20P mix showed a lower pH than 30P, which might be attributed to a measurement error. Therefore, the pH of 20P mix is chosen to be excluded from consideration. 30P and 30T mixes showed the lowest pH of 12.6 pH of the concrete mixes with pumice or tephra varied from 12.9 to 12.6. The reason for the reduction of pH increasing with the pumice or tephra content was the reduction of calcium hydroxide because of low cement content and the consumption of calcium hydroxide during the pozzolanic reactions triggered by the pumice and tephra. This study shows that pumice and tephra contribute to reducing the pH of concrete, but the reduction was insignificant. Therefore, all concrete mixes can be selected for making road pavements from the alkalinity perspective.

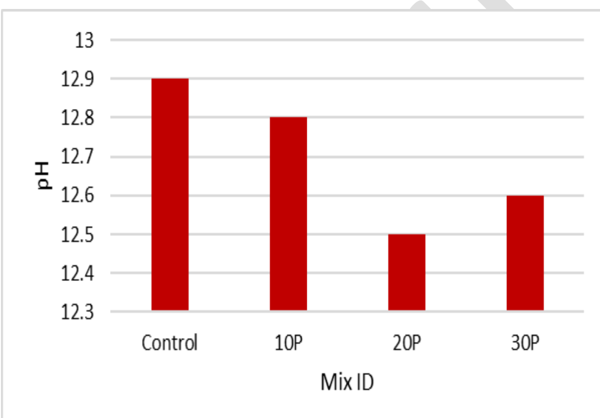


Figure 5. 5: pH variation of pumice mixes

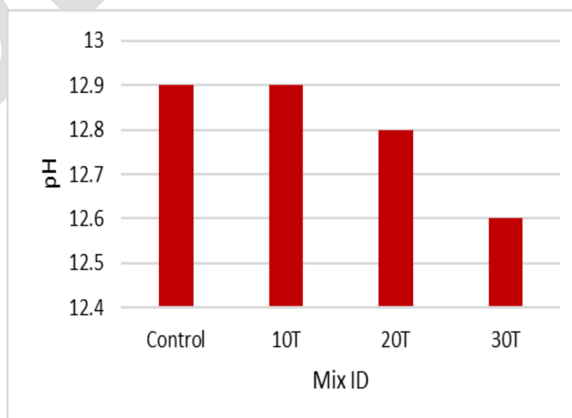


Figure 5. 6: pH variation of tephra mixes

5.2 Hardened properties

5.2.1. Density

The density of concrete is significant because it affects the self-weight of a structure, which in turns affects how strong the structure needs to be to support its own weight. In this study, the density of concrete mixes was measured as per the ASTM C138[10]. The variation of density of concrete mixes with pumice and tephra is illustrated in **Figure 5.7** and **Figure 5.8,** respectively. The density of concrete mixes gradually decreased with increasing pumice and tephra content. The control mix had the highest density of 2410 Kg/m^3. 30% cement replacement mixes showed the lowest density. 30P and 30T mixes had densities of 2382 Kg/m^3 and 2175 Kg/m^3, respectively. The density reduction of 10P, 20P and 30P mixes was 0.2%, 0.8% and 1.2% and 10T, 20T and 30T mixes was 0%, 0.8% and 9.8% respectively. The decrease in density of 10P, 20P, 10T and 20T is negligible. The reason for the density reduction of concrete mixes with pumice and tephra was that the specific gravity of pumice and tephra is lower than cement[17,18]. The 30T mix exhibited a significant reduction in density compared to the 30P mix, primarily due to the larger particles and porous nature of tephra, contributing to lower specific gravity. Overall, the drop of the density of concrete mixes with pumice or tephra was not significant, and therefore, all concrete mixes can be used for road pavements from a density perspective.

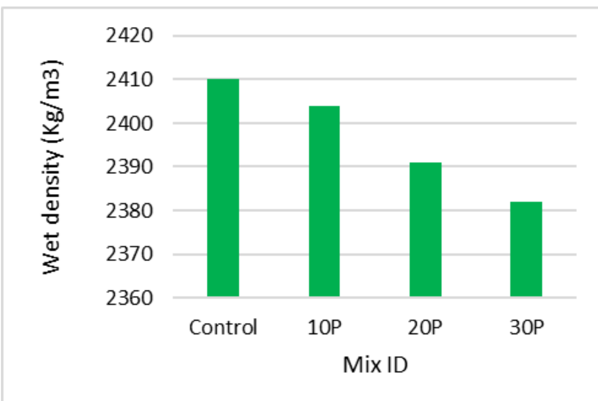


Figure 5. 7: Density variation of pumice mixes

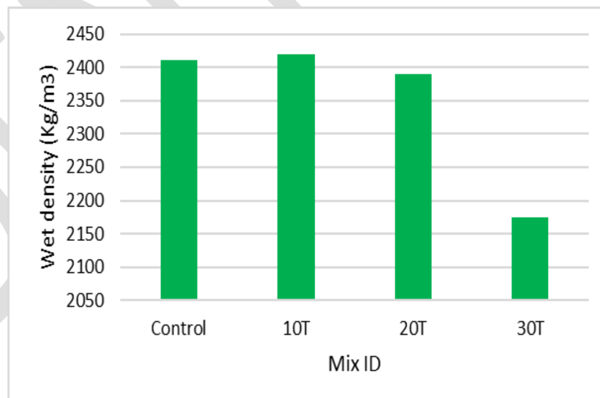


Figure 5. 8: Density variation of tephra mixes

5.2.2 Compressive strength

Compressive strength is the most crucial parameter of concrete, and it indicates how well concrete can withstand loads before failure. The compressive strength of concrete mixes was the most significant property in this study when selecting the adequate mixes for road pavements. The control mix was developed to achieve the target average compressive strength of 20 MPa after 28 days of curing. In this study, twelve cylinders were cast to test in 7, 28, 56 and 91 days to test three cylinders per testing age. The compressive strength test was performed as per the NZS3112.2:1986[14] using the universal testing machine.

Figure 5.9 and **Figure 5.10** show variations in the compressive strength of concrete mixes with pumice and tephra, respectively. The compressive strength of the control mix was 23.50 MPa after 28 days of curing and increased with age. Regarding the control mix, primary calcium silicate hydrate (CSH) gel was formed when cement reacted with water, and it contributed to the strength increment. Concerning concrete mixes containing pumice or tephra, the strength was enhanced not only by the primary CSH gel but also by the secondary CSH gel, resulting from pozzolanic activity. The compressive strength of concrete mixes at all ages decreased with increasing the pumice or tephra content. The reason for the strength reduction with increasing the pumice or tephra content was the reduction of primary CSH gel. At 28 days, the strength loss of 10P, 20P and 30P mixes was 9%, 22% and 44%, while the strength loss of 10T, 20T and 30T mixes was 13%, 37% and 40%, respectively. Overall, concrete mixes with pumice had lower strength loss at 28 days because pumice particles were smaller than tephra. Smaller particles are more reactive than larger particles, so future work should be focused on determining the reactivity of different materials based on the particle size. It is speculated that using particles in the 10-15 microns range in a 20% to 30% replacement would not significantly compromise the compressive strength of concrete. At 91 days, the strength loss of 10P, 20P and 30P mixes was 19%, 26% and 44%, while the strength loss of 10T, 20T and 30T mixes was 2%, 24% and 30%, respectively. Overall, concrete mixes with tephra had lower strength loss at 91 days because tephra had a higher pozzolanic reactivity (based on the sum of SiO_2, Al_2O_3, and Fe2O3) than that of pumice. The strength of 10P and 10T mixes was 21.46 MPa and 20.45 MPa at 28 days, and strength loss was significantly lower than that of other concrete mixes. Therefore, 10P and 10T mix can be selected for road pavements based on the compressive strength and following the particle size used in this study. Despite having a lower compressive strength than the control, these mixes still comply with the requirement of at least 20 MPa at 28 days. It is also important to note that the reactivity of pozzolana heavily depends on particle size, so grinding the materials further down to a smaller size would significantly improve these results.

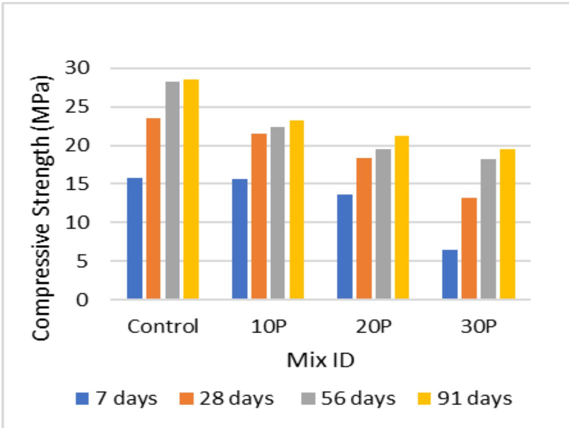


Figure 5. 9: Compressive strength of pumice mixes

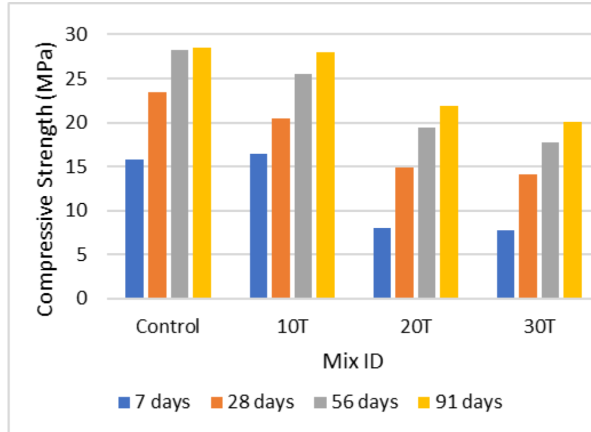


Figure 5. 10: Compressive strength of tephra mixes

5.2.3 Flexural strength

Flexural strength is an indirect measure of the tensile strength of unreinforced concrete. Flexural strength is particularly important for road pavements because the wheels of moving vehicles induce bending or flexural stresses. This study measured the flexural strength of concrete mixes as per the NZS3112.2:1986[14]. Six beams were cast and tested at age of 7, 28, and 56 days.

Figure 5.11 and **Figure 5.12** show the variation of flexural strength of concrete mixes with pumice and tephra, respectively. The flexural strength of the control mix was 4.16 MPa at 28 days and increased over time, similar to the compressive strength. Primary CSH gel contributed to the strength of control mix and primary and secondary CSH gel contributed to the strength of concrete mixes with pumice and tephra (10P, 20P, 30P, 10T, 20T and 30T) due to the pozzolanic activity. Flexural strength decreased with increasing the pumice or tephra content at 7 and 28 days because of the reduction of primary CSH gel in concrete. Strength loss at 28 days for 10P, 20P and 30P mixes was 12%, 21% and 33% and for 10T, 20T and 30T mixes was 23%, 25% and 28%, respectively. At 56 days, strength loss of 10P, 20P and 30P mixes was -16 %, 9% and 24%, and 10T, 20T and 30T were -1%, 6% and 17%, respectively. Overall, concrete mixes with tephra had lower strength loss because tephra had a higher pozzolanic effect and contributed to more secondary CSH gel. However, 10P and 10T mixes had higher strength than the control mix at 56 days because of higher primary and secondary CSH gel. For all ages, strength loss of 30P and 30T was considerably greater than other concrete mixes. As per the flexural strength, 10P, 10T, 20P, and 20T concrete mixes still meet the specifications for road pavements.

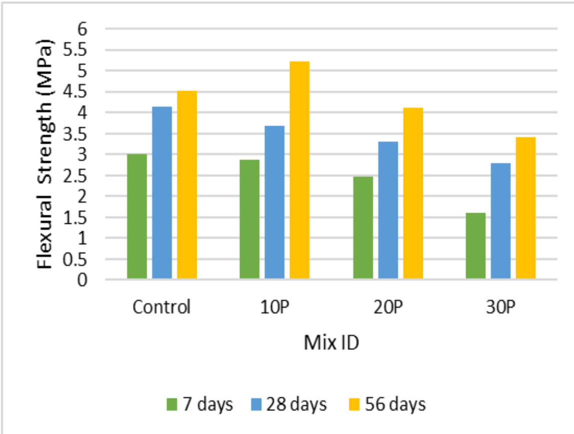


Figure 5. 11: Flexural strength of pumice mixes

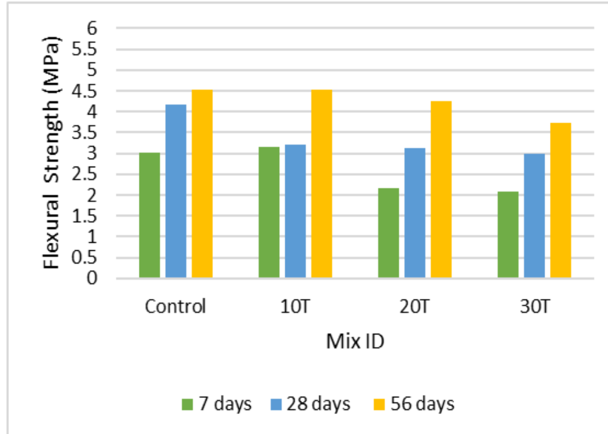


Figure 5. 12: Flexural strength of tephra mixes

5.3 Life cycle assessment (LCA)

Life cycle assessment is essential due to the significant environmental impact associated with concrete production and use. First, the carbonation potential of the concrete mixes was identified. Then, the environmental impact of seven concrete mixes (Control, 10P, 20P, 30P, 10T, 20T and 30T) was analysed as shown in this section.

5.3.1. Potential for carbonation

Concrete carbonation is a chemical reaction between carbon dioxide in the air and calcium hydroxide in hydrated cement paste. Carbonation lowers the pH of concrete, which contributes to the corrosion of reinforcing steel. Carbonation potential refers to the maximum amount of carbon that a concrete structure can absorb in an idealised setting. In this study, 50x50mm paste cubes were cast using the same cement/pozzolana ratios as for the concrete mixes above. Following a 28 day curing period, the cubes were placed in the carbonation chamber with a 2.5% carbon dioxide level. The cubes were then cut using a power saw and phenolphthalein was sprayed on the cut surface to measure the carbonation depth. **Figure 5.13** shows the colour changes of paste cubes. All cubes with pumice or tephra showed a pink shade that was fuller and brighter the more pozzolana was used in the concrete mix, especially compared to the control mix that has only a pale pink colour. This brighter shading indicates that paste with pumice or tephra has less carbonation potential than cement paste, or in other words the pozzolana prevents the carbonation of the concrete thus protecting the reinforcement inside. As per this analysis, there was no significant difference between mixes with pumice or tephra. Therefore, all concrete mixes with pumice or tephra can be used to make road pavements based on the potential for carbonation.

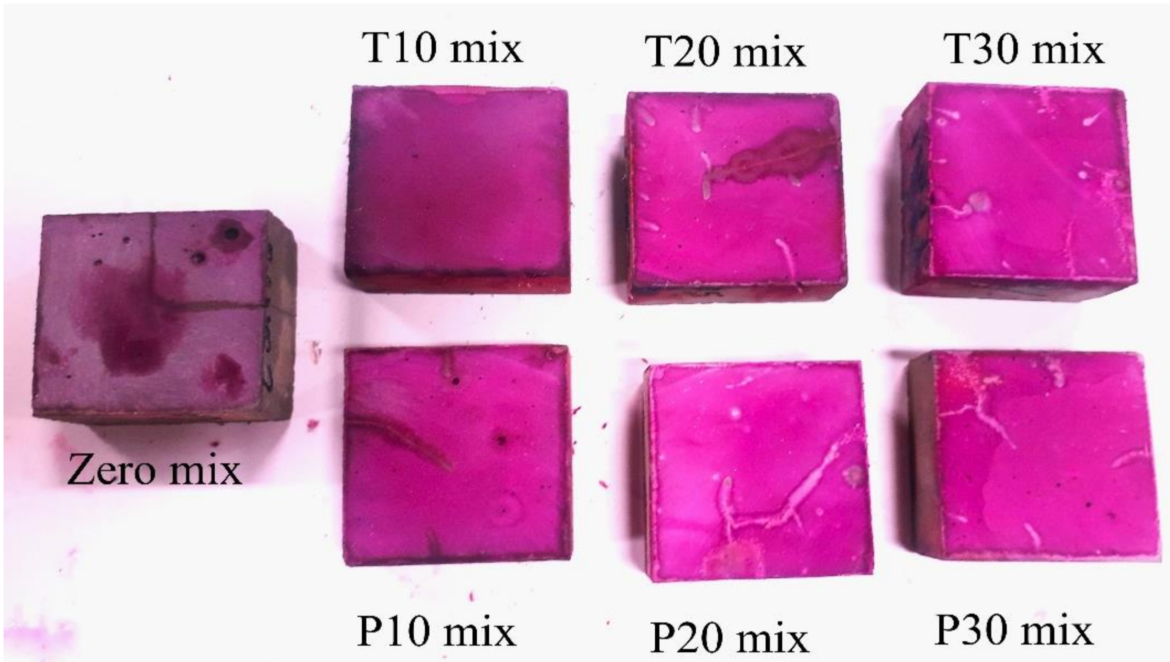


Figure 5. 13: Colour changes of paste cubes

5.3.2. Environmental impact assessment

The concrete industry is responsible for significant greenhouse gas emissions due to the cement, and pumice and tephra can replace the cement to reduce the greenhouse gas emissions. It is essential to compare the environmental impact of control mixes and mixes with pumice or tephra. A life cycle assessment (LCA) was carried out using the framework outlined in the BS EN 17472:2022 standard[19]. According to the standard, the life cycle of an infrastructure project is subdivided into five stages: pre-construction stage (A0), product stage (A1-A3), construction process stage (A4-A5), use stage (B1-B8), and end of life stage (C1-C4). In this study, the comparison focuses on the product stage by considering the quantity of raw material supply (A1) and their transport (A2). The batching process (A3) is ignored because the batching process is the same for all mixes. According to the BS EN 15804 (2012)+A1 (2013)[7] life cycle assessment was evaluated under seven categories: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), formation potential of tropospheric ozone (POCP), abiotic depletion potential for non-fossil (ADPE) and fossil resources

(ADPF).

Selection of concrete batching plants

Generally, concrete is ordered from the nearest batching plant to the construction site. Therefore, three main concrete batching plants were considered to calculate environmental impact. Batching plant 1 is located in Warkworth, Batching plant 2 in Mount Wellington, and Batching plant 3 in Mount Maunganui. The cement plant is located at Portland, near Whangarei. Pumice and tephra are brought from Taupo and Rotorua volcanic deposits respectively. Batching plants, cement plant and mining locations at volcanoes are shown on the map in **Fig 5.14.**

Figure 5. 14: Locations of plants and volcanoes

Functional unit

The functional unit for this study is the production and delivery of materials to the batching plant to produce a cubic meter of concrete. The system boundary is shown in **Figure 5.15.** The following processes are included for concrete production: (1) Cement production and transport, (2) sand extraction and transport, (3) gravel extraction and transport and (4) Pumice or tephra grinding and transport.

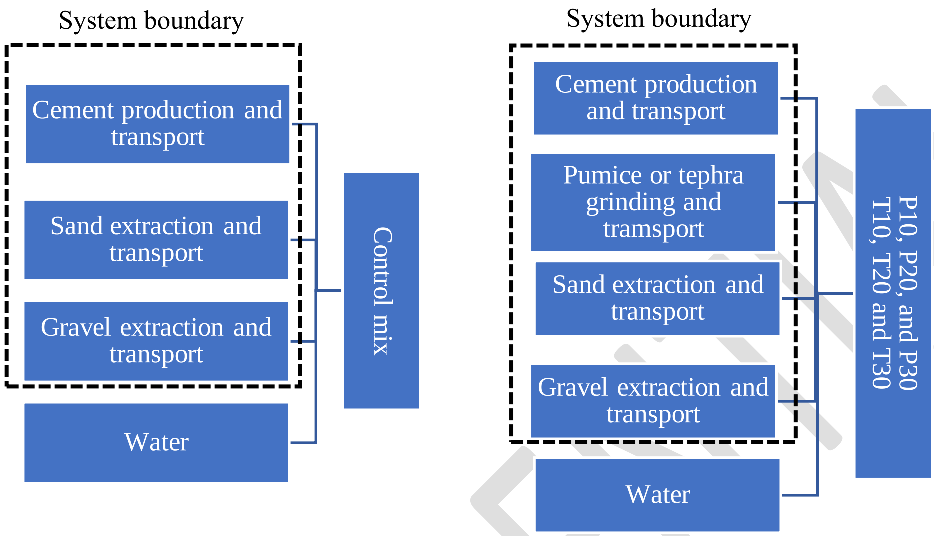


Figure 5. 15: System boundary

Data underpinning the study

The seven environmental impact categories for concrete mixes were calculated using several data sourcesas shown in **Table 5.1.** Environmental product declarations (EPDs) are based on international standards like ISO 14025, which ensures that the methodology used in EPDs is consistent across different regions. Therefore, even if the EPD is from another country, it can give insights into the environmental impacts of a similar material product in New Zealand.EPDs for hydroelectricity and trucks are not available in New Zealand, but the Ministry for the Environment has published the emission factors for the GWP impact category. Therefore, those emission factors were used to calculate the GWP impact category of concrete mixes. EPDs have been published for hydroelectricity produced in the Trollheim power station in Norway. Therefore, those EPDs were used in this study to calculate the other six impact categories of concrete mixes. 25-30 tonnes capacity truck is used to transport materials over long distances and, emission factors regarding the GWP for trucks have been published by the Ministry for the Environment. Those emission factors were used to calculate the GWP impact category of concrete mixes, and similar truck was selected from GaBi database to calculate the other six impact categories of concrete mixes. Pumice or tephra could be ground near the volcanoes to achieve the desired particle size. The environmental impact of grinding pumice and tephra was calculated based on the energy consumption of the ball mill. Pumice and tephra are transported to the batching plant from Taupo and Rotorua respectively as quarry locations. The cement used in this study is produced in Portland next to Whangarei. Sand and gravel are bought from the nearest supplier to the concrete batching plant. All materials are produced locally. The environmental impact of concrete mixes depends on the location of the concrete batching plant because of changing transport distances.

Table 5. 1: Data sources

Input	Data Source	Geographical scope	Year	EPD Reg. N	Travel distance to		
					Plant 1	Plant 2	Plant 3
Cement	[a]EPD (EcoSure GP cement and EcoFast HE cement)[9]	New Zealand	2023	S-P-01170	100	160	380
Pumice	Ground using hydroelectricity	NA	N/A	N/A	330	260	150
Tephra	Ground using hydroelectricity	NA	N/A	N/A	280	220	60
Fine aggregate	[a]Winstone Aggregates[20]	New Zealand	2022	S-P-04664	35	30	20
Coarse aggregate	[a]Winstone Aggregates[20]	New Zealand	2022	S-P-04664	35	30	20
Energy	[a]Ministry for the Environment[21]	New Zealand	2023	N/A	N/A	N/A	N/A
Energy	[b]Hydroelectricity from Trollheim Power Station[22]	Norway	2019	NEPD-1685-676-EN	N/A	N/A	N/A
Road transport	[a]Ministry for the Environment: 25-30 tonnes truck[21]	New Zealand	2023	N/A	N/A	N/A	N/A

Road transport	[b]GaBi Database: Truck, Euro 3[23]	Global	2022	N/A	N/A	N/A	N/A

[a] data source used to calculate the GWP impact category based on New Zealand

[b] international data sources

Environmental impact of concrete mixes produced in the batching plant 1

Environmental impact categories of concrete mixes were calculated based on the production and transport of raw materials. Regarding pumice and tephra, the environmental impact for production was the same, and there was only a little bit of difference for transport. Therefore, the potential environmental impacts of concrete mixes were the same for the same replacement level with pumice or tephra. **Table 5.2** shows the environmental impact of control mix and mixes with pumice or tephra produced in batching plant 1, which is in Warkworth. **Fig 5.16** shows the percentage of the environmental impact reduction for concrete mixes in seven impact categories. The GWP impact category of concrete mixes is based on New Zealand databases, and other impact categories are based on New Zealand and international databases. Concrete mixes with pumice or tephra reduced the environmental impact for the GWP, AP, EP, POCP and ADPF categories. The environmental impact of concrete mixes with pumice or tephra was slightly higher than the control mix in the ODP and ADPE categories. GWP is a significant impact category because it contributes to the effects of climate change and concrete mixes with pumice or tephra had the highest environmental impact reduction in the GWP category. In batching plant 1, environmental impact in the GWP category was reduced by 8.5%, 16.9% and 25.4% by replacing 10%, 20%, and 30% of the cement, respectively. The reduction of GWP approximately equals the cement replacement percentage since the carbon footprint of pumice and tephra is negligible when compared to the carbon footprint of cement.

Table 5. 2: Environmental impact of mixes at batching plant 1

Impact category	Unit	Control	10P/10T	20P/20T	30P/30T
GWP	kg CO2 -eq.	1.86E+02	1.71E+02	1.55E+02	1.39E+02
ODP	kg CFC11 -eq	1.06E-11	1.58E-09	3.16E-09	4.73E-09

AP	kg SO2 -eq	2.23E-01	2.05E-01	1.88E-01	1.70E-01
EP	l kg PO4 3- -eq.	5.90E-02	5.53E-02	5.16E-02	4.79E-02
POCP	kg C2H4 -eq.	4.05E-02	4.04E-02	4.03E-02	4.02E-02
ADPE	kg Sb -eq.	1.19E-06	1.29E-06	1.40E-06	1.50E-06
ADPF	MJ NCV	7.12E+02	6.60E+02	6.08E+02	5.56E+02

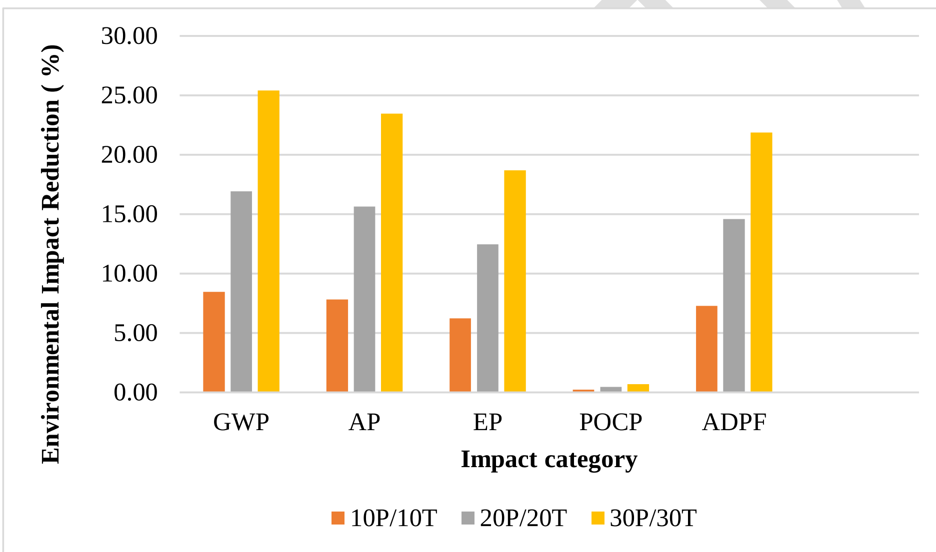


Figure 5. 16: Impact reduction of mixes at batching plant 1

Environmental impact of concrete mixes produced in the batching plant 2

Batching plant 2 is located in Mount Wellington, and the environmental impact for the production of raw materials was not changed according to the location of the batching plant. Transport distances of raw materials were different, so the total environmental impact changed. Environmental impacts of concrete mixes for the same replacement with pumice or tephra were approximately the same because there was only a little difference between the transport distances of pumice and tephra. **Table 5.3** presents the environmental impact of concrete mixes produced in batching plant 2. The environmental impact reduction of concrete mixes with pumice or tephra is illustrated **in Figure 5.17**. The GWP impact category of concrete mixes is based on New Zealand databases, and other impact categories are based on New Zealand and international databases. The environmental impact of concrete mixes was reduced by increasing the pumice or tephra content in the GWP, AP, EP, POCP, and ADPF categories. Concrete mixes had a slightly higher impact in the ODP and ADPE categories. Compared with the control mix, concrete mixes with pumice or tephra exhibited the highest environmental impact reduction in the GWP category. GWP is a significant environmental impact category, and it was reduced by by 8.6%, 17.1% and 25.6% by increasing the pumice or tephra content by 10%, 20% and 30%. GWP reduced in similar cement replacement percentages of concrete mixes because the carbon footprint of pumice and tephra is negligible.

Table 5. 3: Environmental impact of mixes at batching plant 2

Impact category	**Unit**	**Control**	**10P/10T**	**20P/20T**	**30P/30T**
GWP	kg CO2 -eq.	1.87E+02	1.71E+02	1.55E+02	1.39E+02
ODP	kg CFC11 -eq	1.06E-11	1.58E-09	3.16E-09	4.73E-09
AP	kg SO2 -eq	2.23E-01	2.05E-01	1.88E-01	1.70E-01
EP	l kg PO4 3- -eq.	5.90E-02	5.53E-02	5.16E-02	4.79E-02
POCP	kg C2H4 -eq.	4.17E-02	4.09E-02	4.00E-02	3.92E-02
ADPE	kg Sb -eq.	1.19E-06	1.30E-06	1.40E-06	1.50E-06
ADPF	MJ NCV	7.16E+02	6.62E+02	6.07E+02	5.53E+02

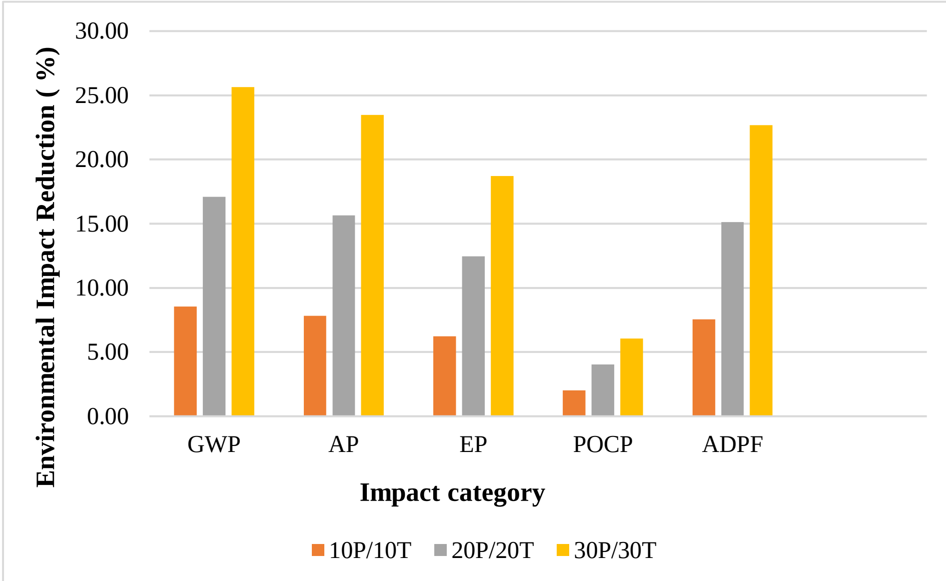


Figure 5. 17: Impact reduction of mixes at batching plant 2

Environmental impact of concrete mixes produced in the batching plant 3

Batching plant 3 is located in Mount Maunganui, and environmental impact was calculated by considering the production and transport of raw materials for making concrete. The environmental impact of concrete mixes with pumice or tephra for the same replacement was approximately the same because there was a little difference in environmental impact due to the transport. The environmental impact of concrete mixes with pumice or tephra at batching plant 3 is given in **Table 5.4**. In comparison to the control mix, the environmental impact reduction of concrete mixes with pumice or tephra is illustrated in **Figure 5.18**. The GWP impact category of concrete mixes is based on New Zealand databases, and other impact categories are based on New Zealand and international databases. Environmental impact in GWP, AP, EP, POCP, and ADPF categories of the concrete mixes was reduced with increasing the pumice or tephra content. Concrete mixes with pumice or tephra had a slightly higher impact in the ODP and ADPE categories. The GWP category had the highest impact reduction for concrete mixes with pumice or tephra and it was reduced from 8.7% to 26.1% when increasing the pumice or tephra content from 10% to 30%. The reduction of GWP is approximately equal to the percentage of cement replacement because the carbon footprint of pumice and tephra is negligible.

Table 5. 4: Environmental impact of mixes at batching plant 3

Impact category	Unit	Control	10P/10T	20P/20T	30P/30T
GWP	kg CO2 -eq.	1.89E+02	1.72E+02	1.56E+02	1.39E+02
ODP	kg CFC11 -eq	1.06E-11	1.58E-09	3.16E-09	4.73E-09
AP	kg SO2 -eq	2.23E-01	2.05E-01	1.88E-01	1.70E-01
EP	l kg PO4 3- -eq.	5.90E-02	5.53E-02	5.16E-02	4.79E-02
POCP	kg C2H4 -eq.	5.00E-02	4.72E-02	4.45E-02	4.17E-02
ADPE	kg Sb -eq.	1.21E-06	1.31E-06	1.41E-06	1.51E-06
ADPF	MJ NCV	7.40E+02	6.80E+02	6.21E+02	5.61E+02

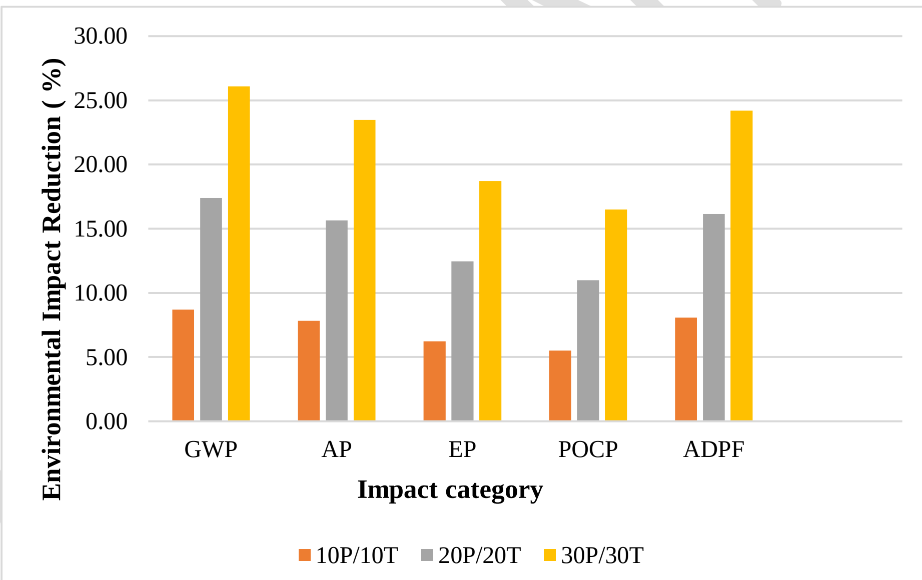


Figure 5. 18: Impact reduction of mixes at batching plant 3

5.3.3. Summary of environmental impact of concrete mixes

In this study, environmental impact was considered in seven categories - global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), formation potential of tropospheric ozone (POCP), abiotic depletion potential for non-fossil (ADPE) and fossil resources (ADPF) – according to the BS EN15978:2011. Life cycle assessment of concrete mixes was limited to raw material supply and transport processes because production processes were the same for all concrete mixes in the batching plants 1, 2 and 3. The environmental impact of concrete mixes with pumice or tephra was the same for the same replacement level in each batching plant. The environmental impact of concrete mixes was reduced by increasing the pumice or tephra content in GWP, AP, EP, POCP and ADPF categories when producing in the batching plants 1, 2 and 3. Concrete mixes had a slightly higher impact in OPD and ADPE categories when produced with pumice or tephra. According to the environmental impact of concrete mixes produced in batching plants 1, 2 and 3, the reduction ranges of concrete mixes are shown in **Table 5.5**. The GWP category of the concrete mixes had the highest impact reduction for all replacement levels. Batching plant 3 concrete mixes had the highest impact reduction in GWP, AP, EP and ADPF categories. As per the life cycle assessment, the environmental impact of concrete mixes in five categories reduces with the increase in pumice or tephra content. GWP is a significant impact category of concrete mixes, and it was reduced by 8.5 – 8.7%, 16.9 -17.4% and 25.4 – 26.1% with an increase in pumice or tephra content from 10% to 30%. The reduction of the GWP category of concrete mixes is approximately equal to the cement replacement percentages because the carbon footprint of pumice and tephra is negligible. In addition, GWP due to transport is very low compared to GWP due to production, so the GWP of concrete mixes are approximately the same in any batching plant.

Table 5. 5: Impact reduction at batching plants 1, 2 and 3

Impact category	**10P/10T mix**	**20P/20T mix**	**30P/30T mix**
GWP	8.5 – 8.7 %	16.9 – 17.4 %	25.4 – 26.1 %
AP	7.8%	15.6%	23.5%
EP	6.2 %	12.5 %	18.7 %
POCP	0.2 - 5.5%	0.5 - 11.0%	0.7 - 16.5%
ADPF	7.3 - 8.1%	14.6 – 16.1%	21.9 – 24.2%

6.0 Insights

This research was conducted to identify the best two concrete mixes with pumice or tephra to reduce environmental impact. The control mix was designed to achieve the average compressive strength of 20 MPa at 28 days of curing. Seven concrete mixes were developed to replace the cement from 10% to 30% with pumice and tephra.

The properties of pumice and tephra were observed through XRF analysis, sieve analysis, moisture content test and loss on ignition test. Slump, temperature, pH and density were measured as fresh concrete properties. Compressive strength and flexural strength of hardened concrete were measured. Life cycle assessment of the concrete mixes was conducted based on three main concrete batching plants in New Zealand. Pumice and tephra achieved the requirement of ASTM C618 to be used as a natural pozzolana in concrete. As per the fresh concrete properties, P10, P20, and T10 mixes were suitable for road pavement, and as per the hardened concrete properties, only P10 and T10 mixes were suitable for road pavement. Life cycle assessment found that all concrete mixes with pumice or tephra had a reduced the environmental impact compared to the control mix. T10 and P10 concrete mixes were selected as the best mixes according to the concrete properties and life cycle assessment.

There were some challenges during this study. Initially, four extra volcanic materials were ready for use in this research in addition to the pumice and tephra units 1, 2 and 3. This study needed a large quantity of dried materials for making concrete. Therefore, ovens in the laboratory were used to dry aggregates, taking longer than expected. They were ground using the ball mill, but the ball mill broke down several times due to overuse by research students at the university. Therefore, grinding was limited to passing all pumice and tephra particles through a 75-micron sieve to prevent delay in casting concrete mixes. The quality of the concrete is, therefore, compromised by this limited grinding. The concrete strength can be significantly higher when the cement-replacing materials is more finely ground. Despite these limitations, which can be significantly improved upon by industry-based product development, the research outputs yielded positive outcomes and gave confidence in the use of these materials as partial cement replacement.

7.0 Recommendations

The following are some recommendations for future studies.

- More comprehensive investigation is necessary to complement this pilot study.
- The grinding period should be increased to get more fine particles to replace the cement.
- Water absorption of pumice and tephra should be considered to adjust the free water content of concrete.
- Various volcanic materials should be used to make more concrete mixes to evaluate the performance of concrete.
- The durability of concrete mixes should be investigated.

8.0 Next steps

The results show that pumice and tephra from the Taupo Volcanic Zone can be used for concrete mixes, but the study, being a pilot study, has significant limitations:

1) the materials were not ground finely enough, compromising the strength,
2) the water demand has not been investigated, which influence the workability during construction, and
3) only two materials were considered for one concrete mix.

These limitations, along with the critical aspect of durability, will be investigated under a PhD project scheduled to be completed in 2026-2027.

References

1. U. S. Geological Survey. *Mineral Commodity Summaries, 2009*. Government Printing Office; 2009.

2. Concrete needs to lose its colossal carbon footprint. *Nature*. 2021;597(7878):593-594. doi:10.1038/d41586-021-02612-5

3. Price RC, Gamble JA, Smith IEM, et al. The Anatomy of an Andesite Volcano: a Time–Stratigraphic Study of Andesite Petrogenesis and Crustal Evolution at Ruapehu Volcano, New Zealand. *Journal of Petrology*. 2012;53(10):2139-2189. doi:10.1093/petrology/egs050

4. Wilson CJN, Houghton BF, McWilliams MO, Lanphere MA, Weaver SD, Briggs RM. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. *Journal of Volcanology and Geothermal Research*. 1995;68(1-3):1-28. doi:10.1016/0377-0273(95)00006-G

5. Alqarni AS. A comprehensive review on properties of sustainable concrete using volcanic pumice powder ash as a supplementary cementitious material. *Construction and Building Materials*. 2022;323:126533. doi:10.1016/j.conbuildmat.2022.126533

6. Kabay N, Tufekci MM, Kizilkanat AB, Oktay D. Properties of concrete with pumice powder and fly ash as cement replacement materials. *Construction and Building Materials*. 2015;85:1-8. doi:10.1016/j.conbuildmat.2015.03.026

7. BS EN 15804:2012+A1:2013: Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. Published online 2012.

8. ACI PRC-211.1-22: Selecting Proportions for Normal-Density and High Density-Concrete - Guide. Published online 2022. Accessed February 9, 2024. https://www.concrete.org/store/productdetail.aspx?ItemID=211122&Language=English&Units=US_AND_METRIC

9. Golden Bay. Environmental Product Declaration. Published online 2019.

10. Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. Published online 2008. doi:10.1520/C0136-06

11. Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate. Published online 2007. doi:10.1520/C0136-06

12. Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. Published online 1998. doi:10.1520/C0136-06

13. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. Published online 2009. doi:10.1520/C0136-06

14. NZS 3112.1:1986 : Tests relating to the fresh concrete. Published online 1986. Accessed February 27, 2024. https://www.standards.govt.nz/shop/nzs-3112-21986/

15. John E, Lothenbach B. Cement hydration mechanisms through time – a review. *J Mater Sci*. 2023;58(24):9805-9833. doi:10.1007/s10853-023-08651-9

16. Concrete. Complementary British Standard to BS EN 206 Method of specifying and guidance for the specifier. Published online 2023.

17. Yamada I, Shoji S. Heavy solution methord for determination of volcanic glass content in tephras and tephra-derived soils. *Soil Science and Plant Nutrition*. 1990;36(3):505-509. doi:10.1080/00380768.1990.10416920

18. Rashad AM. A short manual on natural pumice as a lightweight aggregate. *Journal of Building Engineering*. 2019;25:100802. doi:10.1016/j.jobe.2019.100802

19. BSI. BS EN 15978:2011: Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method. Published online 2012.

20. Winstone aggregates. Environmental Product Declaration- For Aggregate and Sand Products. Published online 2022.

21. Ministry for the Environment. Measuring emissions: A guide for organisations: 2023 summary of emission factors. Published online 2023.

22. The Norwegian EPD Foundation. Environmental Product Declaration- Hydroelectricity from Trollheim Power Station. Published online 2019.

23. Sphera. Life Cycle Assessment Datasets. https://lcadatabase.sphera.com/