

PUMICE AGGREGATES FOR STRUCTURAL LIGHTWEIGHT AND INTERNALLY CURED CONCRETES

Samuel Green¹, Nicholas Brooke² and Len McSaveney³

ABSTRACT

This paper presents research on the utilisation of New Zealand's abundant resources of pumice aggregates for producing structural lightweight and internally cured concretes. Mixture designs were developed for lightweight concrete containing both partially saturated and fully saturated pumice aggregates. A vacuum saturation system was developed to completely saturate the normally partially saturated aggregates and consequently avoid a loss of workability attributed to the high absorption capacity of pumice. Shear strength and bond strength of pumice concrete was investigated, as well as the application of saturated fine pumice aggregates as an internal curing media for both high performance concrete and ready-mixed full scale thin concrete slabs with a low water-cementitious materials ratio. The research presented demonstrates the potential to commercially produce structural lightweight concrete containing naturally occurring pumice aggregates, while meeting the requirements of New Zealand Concrete Design Standards.

¹S.G. Structural Engineer, Arup Pty Ltd, Sydney, Australia. samuel.green@arup.com.au

²N.B. Former Lecturer, Department of Civil and Environmental Engineering, University of Auckland, New Zealand.

³L.M. Market Development Manager, Golden Bay Cement, Auckland, New Zealand.

INTRODUCTION

New Zealand currently has abundant resources of pumice aggregates that are underutilised in the construction industry. Products containing pumice aggregates do exist, such as lightweight masonry blocks and non-structural precast elements, but there has been no recent research in New Zealand which focuses on the production of structural grade (25+ MPa) lightweight pumice aggregate concrete (LPAC).

In the early 1970's, much effort went into researching LPAC in New Zealand due to the large quantity of pumice resources spread throughout the central North Island, and a lack of alternative artificially produced lightweight aggregates [1]. A paper published in New Zealand Concrete Construction [2] highlighted issues of volume stability in pumice concrete products. Shrinkage cracking of wall panels was a common problem, which subsequently led to a decline in consumer confidence. The research appeared to cease and ever since pumice aggregates have primarily only been utilised for non-structural purposes and for other non-concrete related applications [1].

The first use of structural lightweight concrete in New Zealand was in the construction of the Wellington "Westpac Stadium". Built in 2000, the Stadium was constructed out of concrete containing artificially expanded shale aggregate imported from California. The project clearly demonstrated the commercial feasibility and benefits of utilising lightweight concrete in New Zealand construction [3]. The need for increased research and development into lightweight concrete, in particular the utilisation of New Zealand's abundant resources of pumice aggregates, has been highlighted by past researchers [1]. The opportunity to produce an economic, structural lightweight concrete for the New Zealand market which contains naturally occurring pumice aggregates undoubtedly exists.

Following the purchase of a large pumice resource by Winstone Aggregates, a partnership was formed between Winstone Aggregates, Golden Bay Cement, Humes Pipeline Systems and The University of Auckland to undertake an investigation into the production of structural grade LPAC. This paper presents the results of this investigation, including the development of LPAC mixture designs, the development of a vacuum saturation system required to fully saturate pumice aggregates to a wet moisture condition, and the results of both bond and shear strength testing. Additionally, this paper discusses a study into the utilisation of saturated pumice as an internal curing media for high performance concretes and thin concrete sections, which are both typically prone to significant shrinkage problems.

PUMICE AGGREGATES

The name "Pumice" is a generic term for a range of porous vesicular materials produced during explosive volcanic eruptions. Pumice is essentially composed of solidified frothy lava which is generally rhyolitic in composition, but can also be produced in a less acidic form. Aggregate strength ranges from very weak and porous, to stronger and less porous. Absorption is generally high, with the specific characteristics being largely dependent on the porosity and size of the aggregates. The principal requirements for pumice to be considered a desirable aggregate for use in structural lightweight concrete are a low density and relatively high strength. The density is determined by the voids content, which is a function of the type of deposit from where the pumice is found [4, 5].

Figure 1 shows a cross section obtained using X-ray CT scanning of a typical fine pumice aggregate. The porosity of the pumice is clearly illustrated by the relatively large internal and external voids.



Figure 1. Cross-section of pumice aggregate (Courtesy of Dr. N. Kikkawa)

PUMICE AGGREGATES UTILISED IN THIS STUDY

Pumice aggregates were obtained from the Winstone Aggregates Te Puke Quarry, otherwise known as "Cameron's Quarry". Located in the Central North Island, Cameron's Quarry is the largest licensed pumice resource in New Zealand, with estimated reserves in excess of 150 million tonnes [6]. Typical properties of the various pumice aggregates and normal weight Helensville beach sand used throughout this study are given in Table 1. These properties were either provided by Winstone Aggregates or found experimentally according to NZS 3111 Methods of Test for Water and Aggregate for Concrete [7]. Table 2 presents the results of chemical analysis using X-ray fluorescence (XRF) on a range of pumice aggregates obtained from Cameron's Quarry.

Table 1. Pumice aggregate properties

Aggregate Size Range	SSD Density (kg/m ³)	OD Density (kg/m ³)	Absorption (%)
Helensville Sand	2660	2640	0.58
0 - 4.75 mm Pumice	1550	1290	16.6
4.75 - 9.5 mm Pumice	1380	630	54.3
9.5 - 16 mm Pumice	1290	560	56.3

Table 2. Chemical analysis of pumice aggregates

Element	0 - 4.75 mm Pumice	4.75 - 9.5 mm Pumice	9.5 - 16 mm Pumice
SiO ₂	65.69	67.2	66.63
Al ₂ O ₃	15	14.7	14.94
Fe ₂ O ₃	3.55	3.45	3.37
CaO	4.1	4.14	4.38
MgO	0.74	0.74	0.71
SO ₃	0.06	0.06	0.06
Na ₂ O	3.29	3.54	3.57
K ₂ O	1.87	1.99	1.96
Mn ₂ O ₃	0.12	0.12	0.13
Loss on Ignition	5.59	4.06	4.26

DEVELOPMENT OF PRELIMINARY PUMICE CONCRETE MIXTURE DESIGNS

A preliminary investigation based on previously published international research [8, 9] was conducted to develop an understanding of the behaviour of LPAC using New Zealand materials. Results from this investigation provided a benchmark for further refinement of the mixtures discussed later in this paper.

Two classes of LPAC were defined for the purpose of this research as follows:

Ordinary Strength Lightweight Pumice Aggregate Concrete (OS-LPAC) - having a unit weight not exceeding 2000 kg/m³ and 28-day compressive strength (f'_c) of not less than 17.5 MPa, nor greater than 35 MPa.

High Performance Lightweight Pumice Aggregate Concrete (HP-LPAC) - having a unit weight not exceeding 2000 kg/m³ and 28-day f'_c greater than 35 MPa.

The lower limit of 35 MPa for HP-LPAC was chosen for this research following the ASTM International Standard ASTM C567 [10] definition for high-strength lightweight concrete, as a concrete with a 28-day f'_c greater than 34.5 MPa. Although the upper limit on unit weight of 2000 kg/m³ defined above for both OS-LPAC and HP-LPAC is inconsistent with the New Zealand Concrete Structures Standard NZS 3101 [11] upper limit of 1850 kg/m³ for structural lightweight concrete, this value has not been chosen arbitrarily. Other international design standards impose similar limits; for example the International

Standard Model Code for Concrete Construction [12] and Eurocode ENV 1992-1-4 [13] impose upper limits of 2000 and 2050 kg/m³ respectively.

Mixture designs were investigated utilising pumice aggregates in the air-dry moisture condition (as provided by Winstone Aggregates), with maximum aggregate sizes of 16 mm and 9.5 mm adopted for the OS-LPAC and HP-LPAC mixtures respectively. Normal weight Helensville beach sand was used as fines for all the OS-LPAC mixtures, while sand in combination with a small fraction of 0 - 4.75 mm pumice was used for the HP-LPAC mixtures.

All cement utilised in this study was Golden Bay Cement Ordinary Type GP Portland cement. The HP-LPAC mixtures contained "Microsilica 600" (MS 600), a fine naturally occurring amorphous silica and a highly reactive pozzolan, and Grace ADVA 142, a standard high range water-reducing superplasticising admixture.

The preliminary LPAC mixture designs investigated in this research are shown in Table 3 and Table 4 for the OS-LPAC and HP-LPAC mixtures respectively. Table 3 and Table 4 also include the water-cementitious materials (w/cm) ratios and the resulting 28-day f'_c and unit weight results. All testing was carried out according to the relevant sections of NZS 3112 Methods of Test for Concrete [14]. Unit weight is presented as the equilibrium unit weight, which is defined by ASTM C567 as the oven-dry unit weight plus 50 kg/m³. Equilibrium unit weight is assumed to be obtained after ninety days of air-drying [10].

Table 3. OS-LPAC mixtures

Mix Reference	OS-M1	OS-M2	OS-M3
Cement (kg/m ³)	544	635	469
Water (kg/m ³)	201	97	211
Sand (kg/m ³)	575	651	695
Fine Pumice (kg/m ³)	-	-	-
Coarse Pumice (kg/m ³)	496	558	455
w/cm	0.37	0.15	0.45
28-day f'_c (MPa)	24.5	30.5	21.0
Equilibrium unit weight (kg/m ³)	1610	1690	1610

Table 4. HP-LPAC mixtures

Mix Reference	HP-M1	HP-M2	HP-M3
Cement (kg/m ³)	539	573	576
Water (kg/m ³)	155	140	152
Sand (kg/m ³)	934	899	855
Fine Pumice (kg/m ³)	42	45	46
Coarse Pumice (kg/m ³)	259	275	280
MS 600 (kg/m ³)	82	87	87
ADVA 142 (kg/m ³)	12.6	13.4	13.4
w/cm	0.25	0.21	0.23
28-day f'_c (MPa)	37.5	42.5	41.0
Equilibrium unit weight (kg/m ³)	1910	1960	1890

Following recommendations given by NZS 3152 Specification for the Manufacture and Use of Structural and Insulating Lightweight Concrete [15], and a mixing procedure used in research conducted by Hossain and Lachemi [8], the mixing sequence consisted of 3 minutes of mixing both the fine and coarse aggregates with 50 % of the mix water, followed by an additional 3 minutes of mixing with the cement, admixtures (where used) and remaining water until a visually workable mixture was achieved. The initial mixing of the water with the aggregates was carried out in an attempt to saturate any partially filled external voids of the air-dry pumice aggregates, and to reduce a potential loss of cement into the outer vesicles on the surface of the pumice aggregates. Total water added to the mixtures was closely monitored to enable the calculation of water absorbed by the pumice aggregates, and thus the remaining free mix water.

The results presented in Table 3 for the OS-LPAC trials demonstrate that mixtures containing pumice as coarse aggregates with a maximum size of 16 mm in combination with normal weight sand as fines can produce concrete with compressive strength in excess of 30 MPa. Equilibrium unit weight was than the NZS 3101 specified upper limit of 1850 kg/m³.

The results presented in Table 4 for the HP-LPAC trials demonstrate that the addition of microsilica and ADVA 142 into the mixtures developed, as well as an increase in cement content and reduction in water and total pumice content results in compressive strengths in excess of 40 MPa. Equilibrium unit weight values were within the maximum limit of 2000 kg/m³ defined for HP-LPAC.

Due to the aggregates being in an air-dry moisture state during batching, and an inherent difficulty in obtaining pumice aggregates in the saturated surface-dry (SSD) or wet moisture states, calculating precise mixture proportions by considering the free available moisture and absorption of the aggregates proved to be complicated. Free moisture content was particularly difficult to determine as the pumice appeared to be absorbing mix water during batching. Neville [16] and Mindess *et al.* [17] both discuss the great difficulty in determining the free mix water quantities for most lightweight aggregate concretes, with only approximate *w/cm* ratios typically given.

Although not directly measured, a loss of workability, which resulted in stiffening of the mixtures, was observed to occur within approximately 20 minutes of batching for all the mixtures investigated. The most likely cause of the

stiffening is the aforementioned ability of pumice to absorb relatively large quantities of water.

VACUUM SATURATION OF PUMICE AGGREGATES

Following the preliminary mixture design development, the need for an effective method of saturating pumice aggregates to the SSD or wet moisture state was identified as a solution to the loss of workability that occurred, and to aid in the accurate determination of the actual free moisture content. Neville [16] and the American Concrete Institute Standard ACI 213R-03 Guide for Structural Lightweight Aggregate Concrete [18] both discuss the technique of utilising vacuum saturation to efficiently saturate lightweight aggregates and overcome the unfavourable ability of lightweight aggregates to absorb mix water during batching. Lura *et al.* [19] discusses the use of vacuum saturation in the context of pumice aggregates as they noted the inefficiency of saturating pumice by the conventional practice of submersion in water.

A vacuum saturation procedure was subsequently developed following a study by Williamson [20]. The procedure adopted can be broken down into the following five phases:

- Phase 1: Place aggregates in a sealed vacuum chamber
- Phase 2: Apply a vacuum for a sufficient period of time to evacuate all air from within the chamber and external pores of the aggregates
- Phase 3: Seal chamber under vacuum
- Phase 4: Release water into chamber
- Phase 5: Immerse aggregates in water for 24 ± 1 hours.

Phase 2 (vacuum) and Phase 4 (water saturation) are illustrated graphically in Figure 2 below.

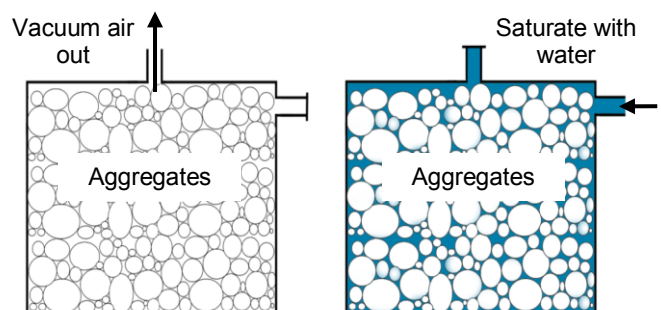


Figure 2. Phase 2 and Phase 4 of vacuum saturation procedure

By evacuating the air from the external voids of the pumice aggregates, the water released into the chamber should theoretically fill these empty pores and fully saturate the aggregates to a wet moisture state [19].

A vacuum saturation system was subsequently developed to trial the concept on pumice aggregates, and then utilise these aggregates for producing LPAC and internally cured concretes discussed later in this paper. The system developed was capable of processing 0.16 m³ of vacuum saturated pumice aggregates in approximately 10 minutes.

The effectiveness of the vacuum saturation system was determined by comparing the moisture content of the pumice aggregates, obtained in accordance with Section 7 of NZS 3111 Methods of Test for Water and Aggregate for Concrete [7], pre and post vacuum saturation. Aggregate size ranges representing the full scope of available aggregates applicable to this research were utilised for verification of the system. These being: 0 – 2.36 mm, 0 – 4.75 mm, 4.75 – 9.5 mm and 9.5 – 16 mm. The aggregates were vacuum saturated from an initial air-dry moisture condition as supplied by Winstone Aggregates.

Figure 3 presents the results of the pre and post vacuum saturation moisture contents. Aggregate moisture content is significantly increased in all instances through the use of vacuum saturation.

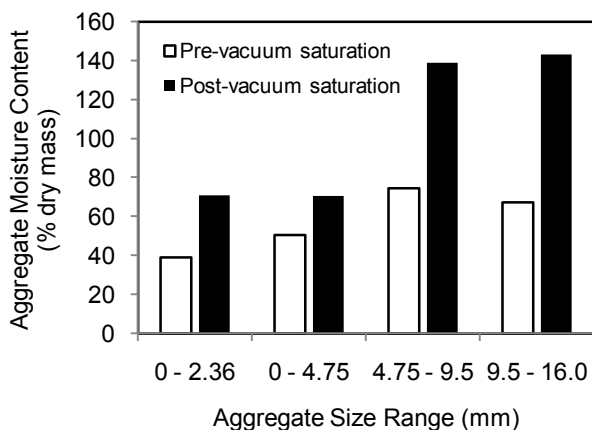


Figure 3. Increase in moisture content of pumice aggregates through vacuum saturation

The larger aggregates appeared to be absorbing a relatively greater quantity of water when compared to the smaller aggregates, which is most likely attributed to an increase in the size of the external pores of the larger aggregates and therefore absorption capacity [19].

The results indicate the system developed is effective in vacuum saturating pumice aggregates to a moisture condition representative of the wet moisture state for practical purposes. The capacity of the system, coupled with the reasonably short period of time required to process the aggregates enabled the processing of sufficient quantities of vacuum saturated pumice aggregates necessary to undertake further laboratory investigations into

the effectiveness of these aggregates for producing LPAC and internally cured concretes. As an aside, further investigations into designing a vacuum saturation system capable of producing saturated pumice aggregates on a commercial scale are currently underway. Additionally, the potential to economically stockpile the aggregates while avoiding significant surface moisture loss is also under consideration.

VACUUM SATURATED PUMICE CONCRETE MIXTURES

Following the investigation into the preliminary pumice concrete mixture designs and the development of the vacuum saturation system, a further investigation was conducted utilising the vacuum saturated pumice aggregates to produce HP-LPAC. Updated properties for the vacuum saturated pumice aggregate are given in Table 5.

Table 5. Vacuum saturated pumice aggregate properties

Aggregate Size Range	SSD Density (kg/m ³)	OD Density (kg/m ³)	Absorption (%)
0 - 4.75 mm Pumice	1610	1090	32.4
4.75 – 9.5 mm Pumice	1361	611	55.1

Table 6 shows the mixture proportions, including the *w/cm* ratio, for the vacuum saturated HP-LPAC mixtures investigated. 28-day *f_c* and unit weight results are also given.

Table 6. Vacuum saturated high performance lightweight pumice aggregate concrete mixtures

Mix Reference	HP-M1-VS	HP-M2-VS
Cement (kg/m ³)	518	599
Water (kg/m ³)	65	71
Sand (kg/m ³)	958	1042
Fine Pumice (kg/m ³)	70	55
Coarse Pumice (kg/m ³)	370	276
MS 600 (kg/m ³)	79	92
ADVA 142 (kg/m ³)	8.7	10
<i>w/cm</i>	0.11	0.10
28-day <i>f_c</i> (MPa)	39.5	46.0
Equilibrium unit weight (kg/m ³)	1840	1860

The above results demonstrate that the application of vacuum saturated pumice aggregates can produce LPAC achieving a compressive strength in excess of 40 MPa while maintaining a unit weight within 1 % of the NZS 3101 specified upper limit of 1850 kg/m³ for lightweight structural concrete. Furthermore, loss of workability and complications with calculating mix water quantities were not observed to occur for the vacuum saturated pumice mixtures due to the aggregates being in a wet moisture state during mixing.

STRUCTURAL TESTING OF PUMICE CONCRETE

An experimental study was conducted to assess the bond and shear performance of HP-LPAC by comparing the results of testing with the requirements of NZS 3101. NZS 3101 contains various provisions for detailing and assessing the shear strength and bond strength of structural lightweight concrete elements.

Bond Strength of LPAC

Bond strength was assessed by performing tensile pullout tests on reinforcing bars embedded at variable lengths into HP-LPAC, and calculating the resulting average bond stress developed along the embedded length of the reinforcing bar. The procedure adopted was similar to that utilised in research conducted by Hossain [21], which also investigated the bond strength of pumice concrete. Deformed bars with nominal diameters of either 12 mm or 16 mm were used, with both Grade 300 and Grade 500E bars tested. Further details on the bond test specimen geometry and testing procedure can be found in Green [22].

Table 7 contains data on the reinforcing bar diameter (d_b), embedment length (l_e), specified yield strength (f_y) and 28-day compressive strength (f'_c) of the bond test specimens investigated. The mean average bond stress (u_b) results as well as details on the failure mode for the various configurations tested are also given. The average bond stress (u_b) was calculated using Equation 1. The steel stress (f_s) was calculated as the maximum tensile force applied to the bar divided by the nominal cross sectional area of the bar.

$$u_b = \frac{d_b}{4l_e} f_s \quad (1)$$

The average bond stress relied upon by NZS 3101 for lightweight concrete (u_{br}) is given by Equation 2.

$$u_{br} = \frac{\alpha_c \alpha_d \sqrt{f'_c}}{\alpha_a \alpha_b 2.66} \quad (2)$$

Table 7. Bond strength test details and results

Specimen ID	d_b (mm)	l_e (mm)	f_y (MPa)	f'_c (MPa)	f_s (MPa)	u_b (MPa)	u_{br} (MPa)	$u_b/\sqrt{f'_c}$	u_b/u_{br}	Failure Mode
B125-D12	12	125	300	35.5	332.8	7.99	3.36	1.34	2.38	Yield
B125-D16	16	125	300	35.5	243.7	7.80	3.36	1.31	2.32	Slip/Split
B75-D12H	12	75	500	37	264.7	10.59	3.43	1.74	3.09	Slip/Split
B75-D16H	16	75	500	37	159.6	8.51	3.43	1.40	2.48	Slip/Split
B175-D12H	12	175	500	36.5	466.1	7.99	3.41	1.32	2.35	Slip/Split
B175-D16H	16	175	500	36.5	310.3	7.09	3.41	1.17	2.08	Slip/Split
Mean								1.34	2.37	
Standard Deviation								0.19	0.34	

Table 7 also compares the test results with the bond requirements of NZS 3101 using values of 1.0 for α_a (less than 300 mm fresh concrete beneath the bars), α_b (zero flexural reinforcement) and α_d (zero transverse reinforcement), and 1.5 for α_c (cover greater than $1.5d_b$), for all test specimens.

To accurately gauge the consistency of the results across the range of different bar sizes and embedment lengths, the variation in compressive strength f'_c must be taken into consideration. As the average required bond stress found using Equation 2 is linearly proportional to the square root of the compressive strength, the average bond stress can be normalised by dividing by $\sqrt{f'_c}$. The normalised bond stress ($u_b/\sqrt{f'_c}$) is also presented in Table 7.

The results from bond pullout testing indicate the bond strength of HP-LPAC is greater than the nominal required bond strength of lightweight concrete found using the provisions of NZS 3101 by an average factor of 2.37. The results were reasonably well spread, having a standard deviation of 0.19 when the effects of differing compressive strengths were taken into consideration.

Shear Strength of LPAC

Shear strength of LPAC was assessed by performing shear tests on beams constructed out of HP-LPAC. Equivalent strength normal weight concrete beams were also tested to provide control results. The shear beam test specimen details chosen for this study were an adaptation of the specimens used in research conducted by Li *et al.* [23]. The shear beam geometry and loading configurations are shown in Figure 4 and Figure 5 respectively.

Longitudinal D16 Grade 300 deformed bars were included at the top and bottom of the beams to prevent the possibility of flexural failure and to ensure a shear mode of failure occurred. No shear reinforcement was provided.

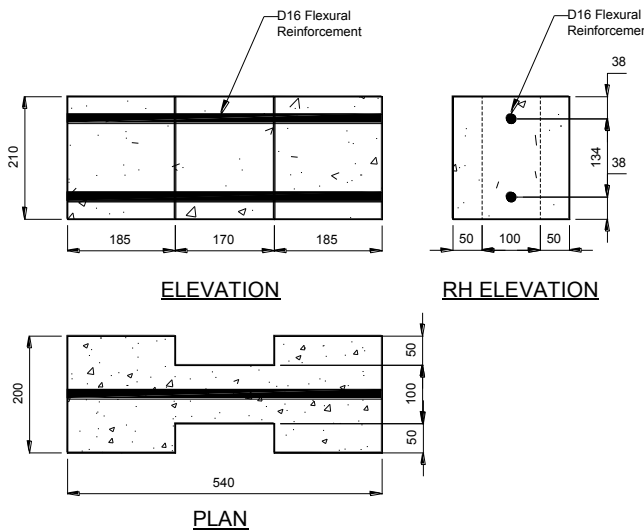


Figure 4. Shear beam geometry (dimensions in mm)

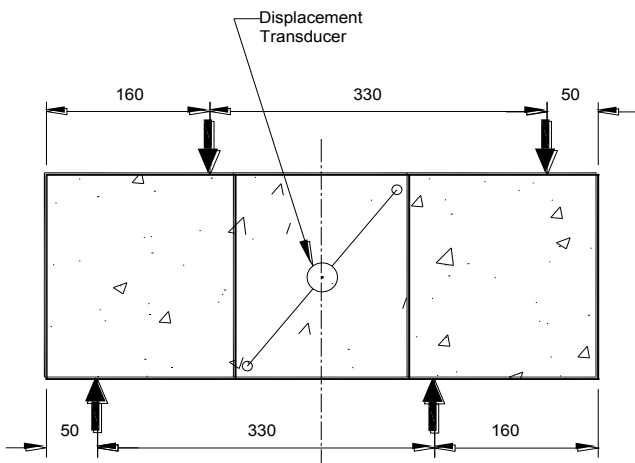


Figure 5. Load configuration for shear tests

Tests were performed by applying gradually increasing equal uniformly distributed loads onto roller supports located on the top surface of the shear beam specimens at the load positions (arrows) shown in Figure 5. Roller supports were also provided on the bottom surface of the specimens. A load cell was used to measure the magnitude of forces applied during testing. Portal displacement transducers were attached perpendicular to the assumed crack path on each side of the thinner central shear panel to measure the propagation of shear cracks, and to indicate the first crack load and ultimate load. Loading was increased until a dramatic loss of strength occurred in the beams. Further details on the testing procedure can be found in Green [22].

Three different concrete mixtures were investigated; SP1 (non-vacuum saturated HP-LPAC), SP2 (vacuum saturated HP-LPAC) and SNC1 (normal weight concrete control mixture). Average 28-day compressive (f'_c), splitting tensile

(f_{ct}) and flexural tensile (T_f) strengths, as well as unit weight values for the three mixtures are summarised in Table 8.

Table 8. Shear test specimen material properties

	Mix SP1	Mix SP2	Mix SNC1
28-day f'_c (MPa)	36.5	37.0	40.5
28-day f_{ct} (MPa)	3.8	4.0	4.4
28-day T_f (MPa)	5.8	4.8	6.0
28-day SSD unit weight (kg/m ³)	2090	2050	2360
OD unit weight (kg/m ³)	1890	1840	2190
Equilibrium unit weight (kg/m ³)	1940	1890	2240

Average first crack (v_{crack}) and ultimate shear strength ($v_{ultimate}$) results from shear testing are given in Table 9, with results compared with the NZS 3101 estimation of nominal shear strength calculated using both approaches (a) and (b) of Clause 9.3.9.3.5. The average shear stress resisted by the beams was estimated as the shear force at the beam centreline divided by the cross-sectional area resisting the shear. When calculating the NZS 3101 nominal shear strength, values of 0.85 for k_a (maximum aggregate size of 10 mm or less) and 1.0 for k_d (effective depth less than 400 mm) were adopted following the provisions of NZS 3101 Clause 9.3.9.3.4. For approach (b) of Clause 9.3.9.3.5, a reduction factor of 0.85 was applied as the HP-LPAC mixtures investigated are classed as "sand-lightweight" concrete. Figure 6 illustrates the average shear stress and crack width vs. time for a typical test specimen, and is given to demonstrate the first crack stress and ultimate failure stress.

Table 9. Average shear strength test results

Specimen ID	f'_c (MPa)	v_{crack} (MPa)	$v_{ultimate}$ (MPa)	NZS 3101 (MPa)	
				(a)	(b)
SB-SP1	36.5	2.48	4.02	0.94	0.80
SB-SP2	37	2.72	4.57	0.95	0.81
SB-SNC1	40.5	2.76	3.89	0.99	0.99

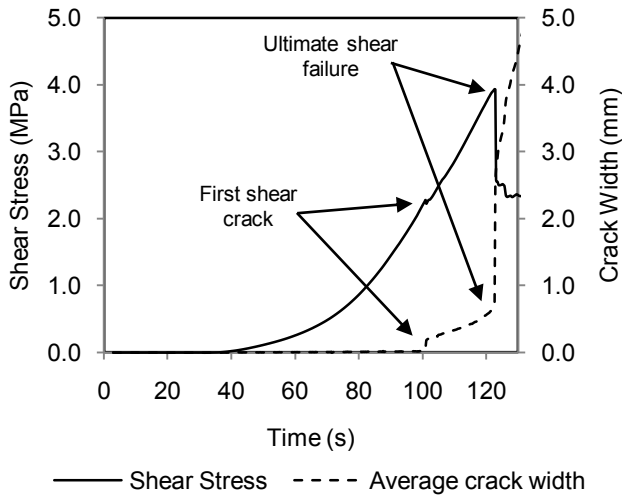


Figure 6. Comparison of average shear stress and crack width

The results presented above indicate that the shear strength of HP-LPAC is greater than the nominal shear strength found using the provisions of NZS 3101 for structural lightweight concrete. However, the shear test procedure adopted appeared to over predict the shear strength of the concrete and therefore further research is recommended to validate these findings.

APPLICATION OF PUMICE AGGREGATES FOR INTERNAL CURING

Two further investigations were conducted to study the effectiveness of 0 – 2.36 mm vacuum saturated pumice aggregates as an internal curing media in high performance concrete (HPC) and thin concrete sections with a relatively low w/cm ratio and high surface area to volume ratio. Compressive strength, unit weight and shrinkage properties of the internally cured concretes were investigated.

Internal Curing of High Performance Concrete

The utilisation of HPC with a low w/cm ratio is becoming ever more prevalent as advances in concrete technology allow practical mixes to be developed. The combination of a low w/cm ratio coupled with the inclusion of silica fume and other admixtures alters both the internal pore structure of the concrete and the chemistry of the hydration reactions. A major issue influencing the performance of HPC is early age cracking caused by autogenous shrinkage. Autogenous shrinkage is accompanied by self-desiccation during hardening of the concrete, which is characterised by internal drying. An effective technique developed to help mitigate and overcome the issues of autogenous shrinkage and self-desiccation is internal curing. Internal curing utilises small internal reservoirs of water introduced into the concrete by water bearing

media dispersed throughout the cement paste matrix. Under conventional curing conditions, the generally low permeability of HPC impedes the ability of water to migrate through the concrete, limiting the water available for cement hydration. The addition of internal curing water therefore greatly aids in the efficient hydration of cement [24].

Research by Bentz *et al.* [25] recommends using Equation 3 for determining the mass of saturated fine lightweight aggregates required to prevent self desiccation in HPC. Further details can be found in the literature.

$$M_{LWA} = \frac{C_f \cdot CS \cdot \alpha_{max}}{S \cdot \phi_{LWA}} \quad (3)$$

where:

- M_{LWA} = Mass of fine lightweight aggregates required per unit volume of concrete (kg/m^3)
- C_f = Cement content for concrete mixture (kg/m^3)
- CS = Chemical shrinkage of cement (g of water / g of cement)
- α_{max} = Maximum expected degree of cement hydration (%)
- S = Degree of saturation of aggregates (0 = 0 % saturation, 1 = 100 % saturation)
- ϕ_{LWA} = Absorption capacity of lightweight aggregates (%)

Based on the research by Bentz *et al.* [25], an experimental investigation was carried out to determine the effects of utilising saturated fine pumice aggregates as an internal curing media for HPC. A HPC mixture with a w/cm ratio of 0.29 was chosen, and the pumice aggregate requirements were calculated using Equation 3. Properties of the saturated fine pumice aggregates used in this study are given in Table 10.

Table 10. Saturated fine pumice aggregate properties

Aggregate Size Range	SSD Density (kg/m^3)	OD Density (kg/m^3)	Absorption (%)
0 – 2.36 mm Pumice	1780	1330	25.0

The original, base HPC mixture contained normal weight aggregates (both fine and coarse), ordinary Type GP Portland cement, fly ash, microsilica (MS 600) and a high-range water reducing admixture. Three mixtures were studied: C1 (control - 0 % calculated required pumice), P1 (100 % calculated required pumice), and P2 (50 % calculated required pumice). The pumice was added to the mixtures by replacing an equal volume of normal weight fine aggregates, effectively maintaining a constant yield and

consistent mixture proportions. The resulting effects on the concrete properties were assessed by gathering data on shrinkage, compressive strength and unit weight.

All mixture production was completed at the Golden Bay Cement Portland Manufacturing Plant Cement Laboratory (GBC lab) in Whangarei. Compressive strength and unit weight measurements were also completed at the GBC Lab according to the relevant sections of NZS 3112 [14]. Early age shrinkage data was obtained by sending 280 L x 75 W x 75 H (mm) shrinkage beams to the Wellington BRANZ laboratory for shrinkage testing.

Average 7 and 28-day compressive strength results, and 7-day unit weight results are given below in Table 11. These indicate that the inclusion of saturated 0 – 2.36 mm pumice aggregates within the mixtures trialled have a detrimental effect on the compressive strength, reducing the 7-day and 28-day strengths by up to 18.6 % and 17.3 % respectively, for the mixtures containing pumice, when compared to the control mixture C1.

Table 11. Internally cured HPC average compressive strength and unit weight results

	C1	P1	P2
7-day f'_c (MPa)	56.5	46.0	48.0
28-day f'_c (MPa)	81.0	67.0	67.0
7-day SSD unit weight (kg/m^3)	2340	2270	2300
7-day OD unit weight (kg/m^3)	2260	2200	2170
7-day equilibrium unit weight (kg/m^3)	2310	2250	2220

This unexpected reduction in compressive strength could be due to the pumice aggregates being in a wet moisture state during mixing, as Zhutovsky *et al.* [26] suggested the SSD moisture state is more preferable than the wet moisture state for batching internally cured mixtures. Additionally, the specific aggregate size chosen and distribution of the aggregates within the cement paste matrix effects the resulting compressive strength of the mixtures. Shrinkage results, as shown in Figure 7, indicate the inclusion of saturated 0 – 2.36 mm pumice aggregates does not appear to significantly influence the shrinkage of the concrete at early ages (up to 7-days). An increase in shrinkage for the internally cured mixtures was observed for drying times up to 21 days.

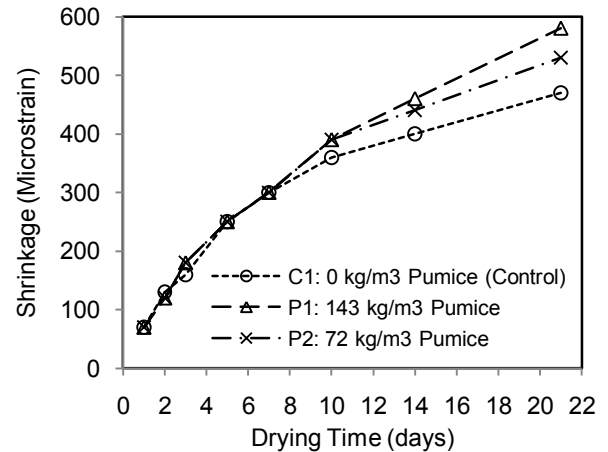


Figure 7. Internally cured HPC shrinkage measurements

The effects of microsilica and fly ash on the values of shrinkage were not taken into consideration when calculating the required saturated pumice contents. Previous research by Bentz *et al.* [25] and Zhutovsky *et al.* [26] highlighted the significant influence that silica fume (similar to microsilica) has on the effectiveness of internal curing due to dense packing of the silica fume particles around the aggregates inhibiting moisture movement. It is therefore recommended that the influence of microsilica on the effectiveness of pumice aggregates for internal curing of HPC be further investigated.

Internal Curing of Ready-Mixed Full Scale Thin Concrete Slabs

Previous research and field experience has demonstrated that elements having high surface area to volume ratios and relatively low w/cm ratios can be particularly vulnerable to stresses developed as a result of changes in volume at early ages [27]. Based on this premise, three thin concrete slabs were constructed at the Humes Pipelines Papakura Precast Manufacturing Plant to study the effects of saturated fine pumice aggregates as an internal curing media on the compressive strength (both in-situ core tests and laboratory based cylinder tests) and the early age and long-term in-situ shrinkage of the concrete.

The base mixture chosen for this study had a w/cm ratio of 0.395, and was originally designed and utilised for pavement construction at the Auckland International Airport. An alternative approach to the one discussed in the previous section was used for calculating the required pumice content, and was based on research by Jensen and Hansen [28]. Jensen and Hansen [28] developed a set of theoretical equations for calculating the required amount of water entrained in an internal curing media to enable full hydration of cement and to mitigate self-desiccation of concrete. These are

presented here as Equation 4 and Equation 5. Equation 4 is applicable for a $w/cm \leq 0.36$ and Equation 5 is applicable for $0.36 \leq w/cm \leq 0.42$.

$$(w/cm)_e = 0.18(w/cm) \quad (4)$$

$$(w/cm)_e = 0.42 - (w/cm) \quad (5)$$

where:

$(w/cm)_e$ = Additional water entrained in an internal curing media to theoretically obtain complete hydration of cement

Three slabs were investigated (Slab A, B and C) having pumice contents as follows: Slab A contained 100 % of the calculated required pumice, Slab B contained 50 % of the calculated required pumice, and Slab C (control mixture) contained 0 % of the calculated required pumice. To maintain a constant yield and consistent mixture proportions, the pumice was added to the mixtures by replacing an equal volume of normal weight fine aggregates. Table 10 shows the properties of the saturated fine pumice aggregates used in this investigation.

All batching was completed at the Firth East Tamaki ready-mix plant in Auckland. The batching sequence consisted of addition of all aggregates to the concrete truck mixers, followed by the cement and additives, and finally water. The vacuum saturated pumice aggregates were added to the mixture at the same time as the sand, and were in the wet moisture state during batching.

Studs with a central sharp v-groove (similar to DEMEC points) were cast flush into the slabs in a grid arrangement for gathering shrinkage data. A large vernier calliper (600 mm length) with pointed jaws was used for taking measurements of the distance between the studs. These distances were used to calculate the average concrete strain for each of the three slabs. Further details of the slab specifications and testing regime can be found in Green [22].

Preliminary results from both in-situ and laboratory based compressive strength tests of the three mixtures used in the slabs are given in Table 12. These indicate that the inclusion of pumice aggregates into the mixtures appears to reduce the in-situ compressive strength of the concrete. The laboratory based cylinder compressive strength results however were reasonably consistent across the three mixtures investigated.

Table 12. Average cylinder and in-situ core sample compressive strength results for internally cured slabs

	Slab A		Slab B		Slab C	
	Lab	Core	Lab	Core	Lab	Core
7-day f'_c (MPa)	41.5	37.5	40.0	31.0	42.5	37.0

Preliminary shrinkage data (strain) is given below in Figure 8. These limited data indicate that the addition of saturated pumice into the mixtures slightly increases the early age shrinkage encountered in the slabs.

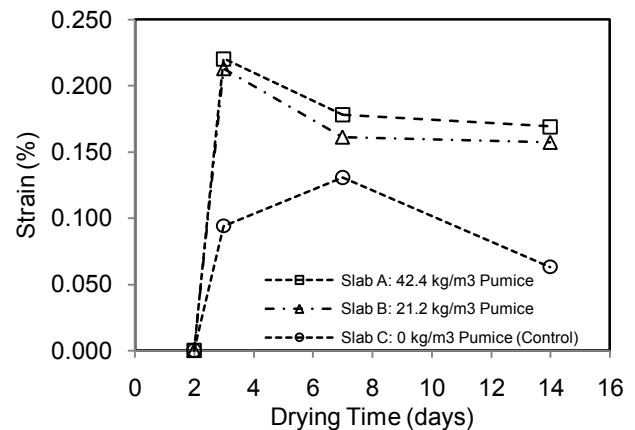


Figure 8. Internally cured concrete slab shrinkage

The specific site chosen for the investigation into internally cured concrete slabs may have had an effect on the resulting in-situ strength and shrinkage of the concrete. As the site chosen had many variables not encountered in a laboratory environment, such as sun exposure, uneven shading and precipitation, their influence on the effectiveness of internal curing using saturated pumice aggregates needs to be studied in greater detail. At the time of writing this paper, only limited results were available for publication. These results are part of an on-going investigation, with data planned to be acquired over a 1 year period. This will allow more conclusive long-term data to be obtained.

CONCLUSIONS

This paper has presented research conducted on the utilisation of New Zealand's naturally occurring lightweight pumice aggregates for producing structural grade (25+ MPa) lightweight concrete, and as an internal curing media in both HPC and thin concrete sections with a relatively low w/cm ratio and high surface area to volume ratio. Additionally, the development of a vacuum saturation procedure for efficiently saturating pumice aggregates to a wet moisture state has been discussed. The research presented demonstrates the potential to commercially produce high performance lightweight concrete containing naturally occurring pumice aggregates

reaching compressive strengths greater than 40 MPa, while meeting the requirements of New Zealand Concrete Design Standards. Results from both the internal curing investigations indicate that the inclusion of saturated fine pumice appears to cause a slight, unexpected, increase in shrinkage and a small reduction in compressive strength of the concrete at an early age. More detailed research is recommended to determine the effects of silica fume and site specific conditions for the HPC and thin slab investigations respectively.

The effective utilisation of New Zealand's abundant resources of naturally occurring lightweight pumice aggregates will provide an environmentally friendlier and more cost effective solution to the commercial production of structural lightweight concrete for the New Zealand concrete industry.

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