

# Development and Implementation of Locally-Sourced Extensive Green Roof Substrate in New Zealand

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## Abstract

The paper describes development of extensive green roof substrate suitable for new and retrofit construction under the Auckland, New Zealand climate. NZ's geographic isolation and absence of an existing green roof "market" creates challenges in obtaining suitable materials. Design objectives were imposed on the substrate to completely retain a water quality design storm (25 mm in 24-hr event), while maintaining a wet system weight  $\leq 100 \text{ kg m}^{-2}$ , dry bulk density  $\leq 800 \text{ kg m}^{-3}$ , high water permeability, and support a range of plants. Constraints imposed by retrofit potential (namely wet system weight) are the most limiting design factor, but quality assurance in raw material supply and the blending process also emerged as decision-influencing variables. FLL testing procedures are difficult to interpret for alternative climates; some parameters were modified to achieve an acceptable substrate. Field evaluation is necessary for assessment of stormwater control. A blend of 70% 4-10 mm pumice, 10% 1-3 mm zeolite, 15% pine bark fines plus mushroom farm waste, and 5% peat and installed at a depth of 70 mm was determined to satisfy design objectives while maintaining quality control in bulk supply and blending.

**Keywords:** substrate design, FLL standards, extensive green roof, stormwater management, New Zealand

## Background

### Industrial Context

Aggressive development in the Auckland, New Zealand (NZ) Region results in detrimental water impacts from stormwater runoff, and/or puts significant pressure on an often under-capacity stormwater drainage system, exacerbating combined sewer overflows. Green roofs present an opportunity to introduce stormwater management in the space-limited urban Auckland Isthmus. To promote implementation, the Auckland Regional Council (ARC, the local environmental regulatory authority) Stormwater Action Team provided funding to the University of Auckland and Landcare Research for a collaborative research project to develop extensive green roof design standards suitable for new and retrofit construction, and with the primary design focus on stormwater control.



## Problem

Very few examples of extensive green roofs are found in NZ, and until the current project, it is believed that none have been designed specifically for stormwater control. NZ's geographic isolation and absence of an existing green roof "market" creates challenges in obtaining materials suitable for green roof implementation. Developers shy away from building new, "risky" technologies when there is little information on the "how-to". Likewise, in order to permit and encourage the construction, the regulatory community requires information on design vs. stormwater performance.

In NZ, branches of international companies provide a range of waterproofing options, plastic drainage mats, root barriers and filter geotextiles. The landscaping industry has broad experience with containerized and intensive roof or balcony gardens. However, there are no proprietary intensive or extensive substrate mixes, and few suppliers of specialist green roof plants, let alone information on maintenance, performance, or cost.

While many jurisdictions internationally provide design "guidance", it is believed that the only standards for designing green roofs and/or testing materials are contained in the German FLL *Guidelines for the Planning, Execution, and Upkeep of Green-Roof Sites* (2002) (heretofore referred to simply as the FLL). The American Society of Testing Materials (ASTM) is in process of modifying the FLL documentation such that copyright and publication issues are avoided; yet that is the extent of the current scope of work (Chuck Friedrich, personal communication 2008). While the FLL guidelines are very specific in terms of methodology and numerical objectives, they lack explanation or rationale behind objectives. Hence, the industry is left somewhat unsupported when attempting to adapt requirements to suit local climate, consider locally available materials, or specify alternative (locally familiar) methodology. Information is not readily available (in English) on relating FLL objectives to actual field performance or field testing procedures.

If extensive green roofs are to be promoted as mitigation for impacts of urbanization and intensification in NZ, locally tested substrates and performance data are needed. The specification requires cooperation and compromise between engineers and plant specialists, professionals who are unlikely to commonly cross paths.

### Learning Objectives:

- Considerations for substrate component selection to design specifically for stormwater control.
- Design constraints imposed by the FLL.
- The importance of implementation constraints and quality assurance procedures in specifying supply and blending of substrates.

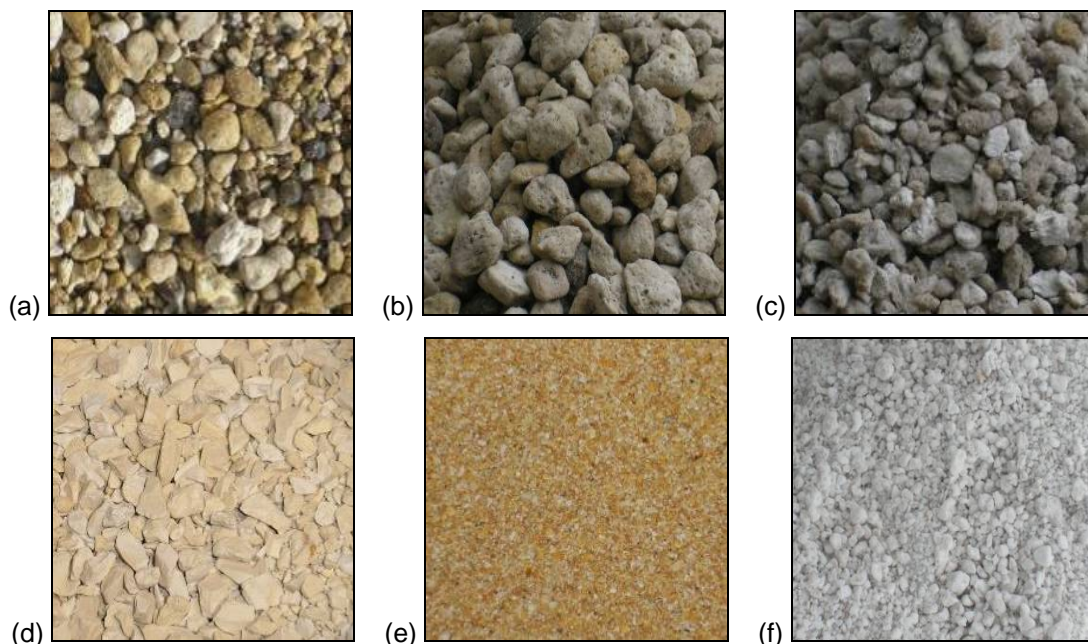
## Approach

From the outset, the research team defined specific design objectives to dictate a minimum level of stormwater control, while also minimizing structural loading to maintain suitability for retrofit. Maximum targets were set: substrate dry bulk density at  $\leq$

800 kg m<sup>-3</sup>, system weight at  $\leq 100$  kg m<sup>-2</sup>, and substrate depth at  $\leq 100$  mm. These targets all fall within ranges reported in the literature for extensive systems.

The design goal to fully retain stormwater (e.g. no runoff from the rooftop) the design storm for water quality treatment is motivated by creating developer incentives. The 25 mm water quality design storm in Auckland City would easily be retained by a 100 mm depth substrate with only 25% water holding capacity (conveniently also on the order of the minimum requirement to support plant life according to the FLL). A rooftop control could therefore significantly decrease the size of land-grabbing “on the ground” stormwater management practices.

Locally available materials were considered key to minimizing cost. Garden mixes and plant growth media were evaluated for components, particularly those developed for high-value sports turfs, which also need to balance rapid drainage with water holding for plant growth as well as high bearing strength. Substrate aggregates such as expanded clay, slate and shale, crushed brick or crushed lava were immediately ruled out due to lack of local supplier (for the former) and/or weight (for the latter). Fortunately, NZ has large deposits of light-weight volcanic material (Figure 1) in the Central North Island including: 2000-year-old pumice (quarried primarily for concrete) and pumicite; zeolite (used in golf course greens), and raw materials for perlite and vermiculite (supplied for horticultural applications). NZ subsoils were excluded due to generally high proportions of clay and silt and overall inconsistent composition.



**Figure 1. Light-weight volcanic aggregates quarried in the Central North Island (New Zealand) (a) Pumice 1-7 mm; (b) pumice 4-10 mm; (c) pumicite 1-7 mm; (d) zeolite 1-8 mm; (e) zeolite 0.5-3.0 mm; (f) expanded perlite (manufactured from raw materials).**

A range of potential organic materials was reviewed. A relatively high organic fraction (20%) was deemed necessary for nitrogen supply as atmospheric deposition rates in NZ are low, and to increase substrate water holding capacity. Friedrich (2005) reports that the instability of green waste/lawn clipping-generated composts may generate high

nitrogen leachate, cause runoff discoloration, and may contain herbicides and pesticides. Locally, readily available garden mixes were ruled out, as previous work indicated either inconsistent composition, significant weed content, and/or unacceptable organic leachate generation (Simcock et al. 2005). However, individually, components were feasible in isolation, including: processed waste bark (Figure 2 (a-b) supplied by a large forestry industry based on the exotic softwood, *Pinus radiata*), peat, sphagnum moss, tree fern fibre (Figure 2 (c-d)), imported coconut coir, and composted wastes from mushroom growing.



**Figure 2. Organic materials: timber industry waste products (a) pine bark chips and (b) pine bark fines; (c) Sphagnum moss (saturated); (d) tree fern fibre.**

Despite the limitations cited above, the FLL guidelines and procedures were adopted as a starting point for the current investigation. In addition to the above-mentioned design goals, FLL-defined requirements for saturated permeability (minimum 0.1 cm/s) and maximum water capacity (20-65%) were also adopted (FLL 2002). Both organic matter and aggregates were tested for the ability to support plant life, while not compromising other design objectives. The key chemical criteria were pH (in water), Cation Exchange Capacity (CEC) and Total Carbon:Total Nitrogen ratio. Consistent with FLL methodology, tests were performed on the < 2-mm fraction of the substrate (10–30% of the substrate by volume).

Three mixtures were selected for field implementation based on ability to meet design objectives at a range of costs. A trial 200 m<sup>2</sup> green roof system was subsequently constructed on the roof of the School of Engineering at the University of Auckland in September 2006. Each of the three substrate combinations were installed at two different depths (50 mm and 70 mm) in individual plots, for a total of six design combinations.

Observations of quality control (or lack thereof) in the raw material supply and bulk blending process, combined with post-implementation FLL testing of the substrates, initiated a



second round of laboratory testing (discussed in detail below in the quality assurance section). A single revised blend was field implemented on four reinforced garden sheds each with a plantable area of ~1.6 m x 2 m.

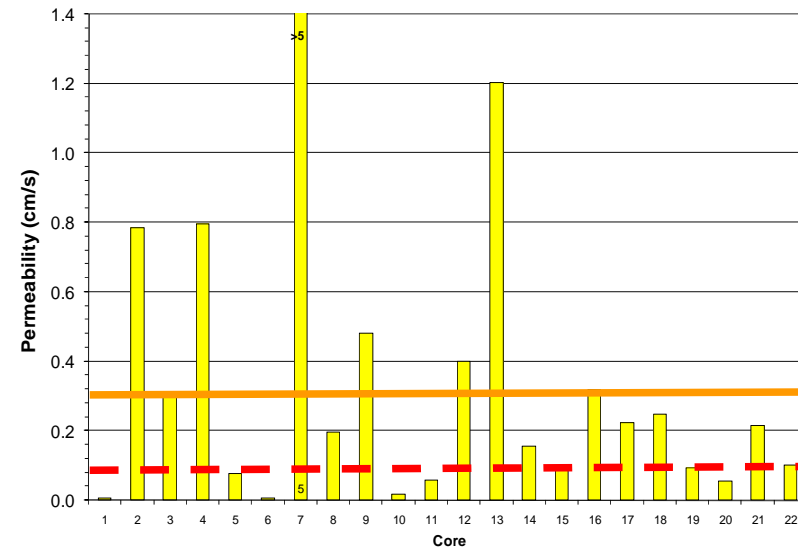
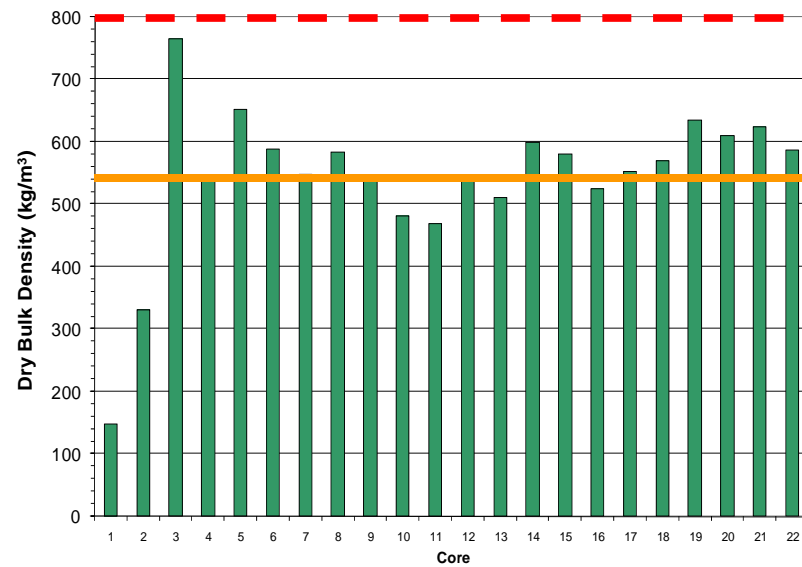
## Analysis

### Substrate Component Selection

Altogether, 7 aggregates and 8 organic components were trialled in isolation and/or in at least one of 30 blends. Physical characteristics of 37 core samples, each replicated at least 3 times were assessed for compliance with the FLL and/or meeting stormwater design goals. A subset of the results is presented in Figure 3. Unfortunately, the rigorous and time-consuming testing procedure did not result in any clear indication of the most suitable substrate (The authors acknowledge the small images in Figure 3; however, they are presented only to highlight that the testing procedure had limited value in substrate selection). Chemical analysis did not necessarily prove helpful either, as all of the substrate blends adequately met objectives. Implementation factors, however, proved useful:

- Inability to identify a long-term, consistent supply ruled out tree fern fibre;
- Stringy, fibrous nature of sphagnum moss presented issues for ensuring homogeneous mixing;
- Very low density of expanded perlite caused it to float in core samples, which created concern over it washing from a roof top.

As stormwater control is the primary design point, significant consideration was given to the maximum water capacity. From an engineering perspective, the maximum water capacity provides a simple metric for estimating stormwater storage for a given substrate depth. While almost all blends easily met the stormwater design objective, a scientific basis for selection of the “best” blend was still sought. The authors acknowledge that at the time the research started, it was assumed that the substrate was the primary mode of storage for precipitation. Berghage et al. (2007) recently indicated that plants may contribute up to 40% of a green roof’s water budget. Additional work is needed to understand implications of this finding on system design for stormwater control and will not be included herein.



— Average of all cores      - - - Max/min objective

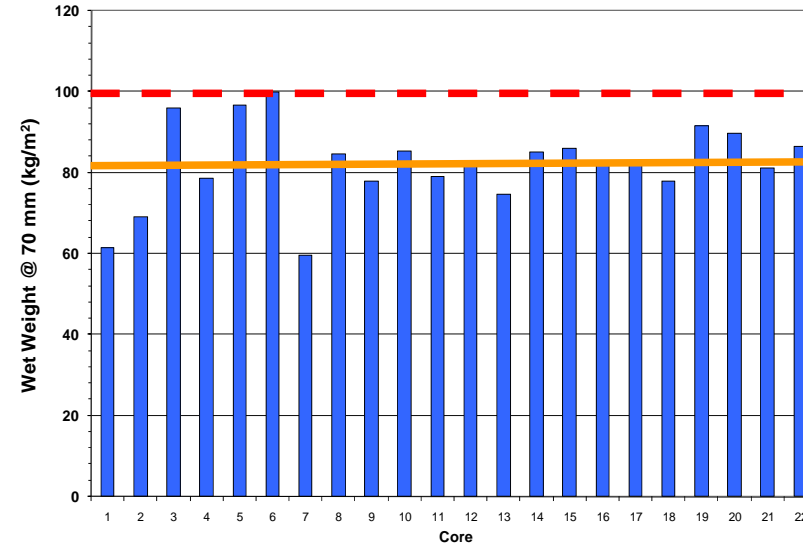
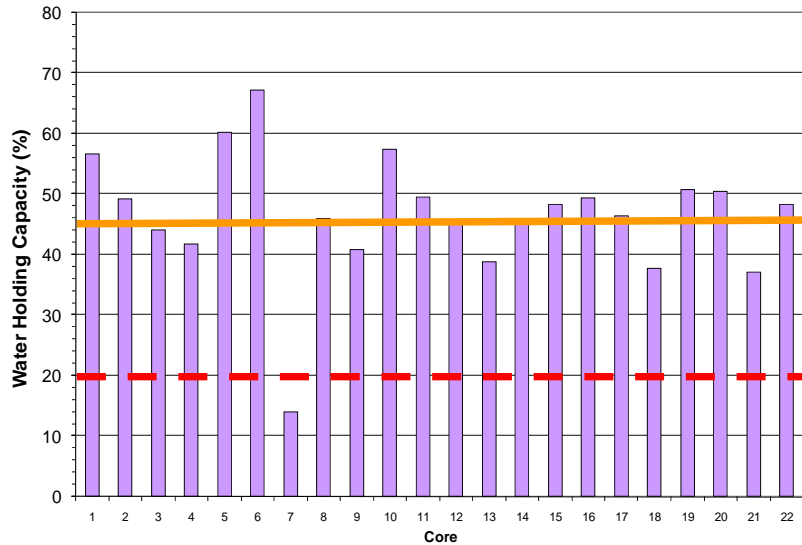


Figure 3. Physical characterisation of potential substrate components and blends: (a) dry bulk density; (b) permeability; (c) water holding capacity; (d) wet weight at maximum water capacity and 70 mm depth.

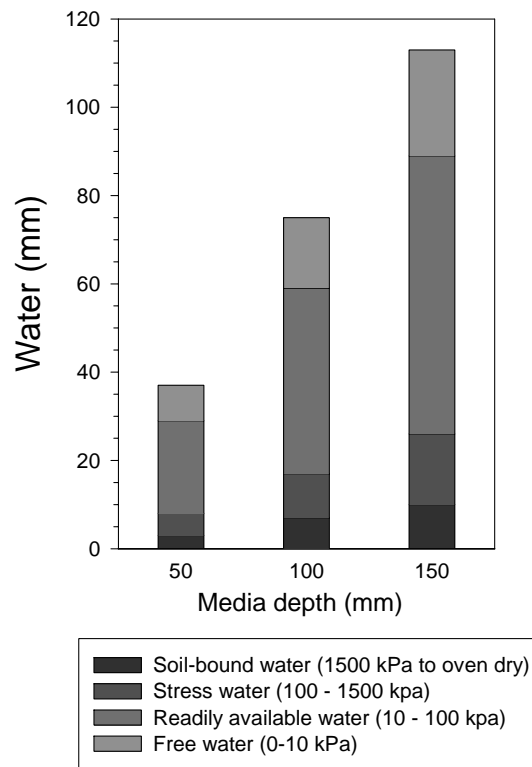
A breakdown of water holding capacity in terms of standard soil science and horticultural definitions provides additional insight (presented in Figure 4 for one substrate blend investigated). Free water alludes to saturation; a condition which should not be met in an extensive green roof (inferred from the high permeability requirements of the FLL, coupled with the excess loading saturation would generate). “Stress water” and readily available water are the main components of storage for rainfall events. Stress water is held tightly to the substrate matrix and will take much longer to be lost via evapotranspiration (ET) compared to the readily available water. Below the stress point, the plants are wilted and some will die. Soil-bound water is held so tightly to the matrix that it is unlikely to ever be lost, thus it will be a misleading component in the FLL water capacity metric.

Interpreting the breakdown in Figure 4 in terms of plant survival, fairly frequent rainfall events are needed to keep plants alive in a thin extensive green roof (50 mm). However, a 100 mm substrate will likely sustain plants for over a week before reaching the stress point. At depths greater than 100 mm, the added storage potential is unlikely to be used when considering high Auckland rainfall frequency and typical ET (not drought ET).

The analysis has significant implications with respect to satisfying design objectives. Under ideal conditions (dry substrate), even a thin green roof should capture the water quality storm. Realistically, depth should be greater than 50 mm for consistent stormwater control (e.g. for back-to-back events). The 100 mm depth for plant survival with minimal irrigation violates the maximum weight objective ( $100 \text{ kg m}^{-2}$ ). Reducing substrate depth to 70 mm should satisfy both stormwater and maximum weight requirements, but periodic irrigation is more likely to be needed during the summer.

Field testing is needed to verify stormwater control claims, as ET will play a significant role in the ability of a green roof to control frequent events. Stormwater runoff monitoring from the UoA Engineering School extensive green roof is inconclusive to date. However, while not discussed specifically in this paper, the *Sedum* species trialled have successfully established in 50-70 mm depths with very minimal irrigation during extended dry periods. Since the locally developed substrate has such a high water holding capacity, the additional weight created by some commercial drainage layers may not be necessary to enhance stormwater control or plant viability.

20%Mushroom bark peat:20%Zeolite:60%Pumice



**Figure 4. Water storage in an extensive green roof substrate.**

## Quality Assurance in Component Supply and Mixing

When substrates were produced in bulk quantities using commercial equipment, critical physical properties manipulated in the laboratory were significantly degraded (Table 1). Post-testing implicated particle size distribution (PSD) (Figure 5). Although the PSD is still within FLL limits, the field implemented blends had significantly greater fractions of particles < 2 mm, adding weight and reducing pore size.

Three factors were implicated:

1. Uncovered stockpiles of compost and pumice:
  - a. Uncovered stockpiles were open to rain, which increased the moisture content of raw materials. Significant overnight rain prior to mixing meant the compost was more vulnerable to compaction and breakdown on mixing. Furthermore, mechanical equipment relied on mass data; conversion of volume ratios to mass using 'as delivered' moisture factors changed the relative mix of components. Few manufacturers have covered stockpiles.
  - b. Pumice is typically quarried for application in the concrete industry, which has a much greater tolerance for variation in acceptable particle sizes, particularly fine-sand, sand, and high-density small rock. Samples provided for laboratory testing by suppliers extracted from the outer edges

of stockpiles had a coarser PSD, with fewer fines, compared with bulk loads (and later representative samples) taken from the centre of stockpiles. Pumice supplied by two different quarries had significantly different composition.

2. Mixing using a hopper with rotating metal tines:

The vigorous mechanical action smashed larger particles. The resultant small particles clogged pore space and increased density. Once installed, the pumice/compost substrate developed a crust that had to be manually disrupted several times, adding cost and causing some root disturbance. The zeolite seemed less effected by the mixing process.

3. Residual material retained in the hopper:

Visual contamination of the mixes was evident, including sand, a critical component of concrete mixes.

Inability to meet the FLL saturated permeability target in the bulk blended substrates was initially of concern. However, the minimum requirement ( $\geq 0.1$  cm/s for single-course extensive systems) is much greater than expected rainfall intensity in Auckland. Ponding has never been observed on any of the trial systems on the UoA Engineering School roof, including a 10-yr event occurring 2 weeks after initial installation (and well before significant plant establishment). In the absence of a clear understanding behind the minimum required value, the research team has relaxed the laboratory requirement for the garden shed blend to 0.05 cm/s.

**Table 1. Degradation of Physical Characteristics from Bulk Supply and Blending Process**

Mixture	Composition (% by volume)				Max. Water Capacity (%)	Dry Bulk Density (kg/m <sup>3</sup> )	Wet System Weight <sup>1</sup> (kg/m <sup>2</sup> )	Permeability (cm/s)
	Pumice 4-10 mm	Pumice 1-7 mm	Zeolite 1-8 mm	Bark Fines <sup>2</sup>				
Pumice (lab)	60	20		20	48	586	86.4	0.101
Pumice (field)	60	20		20	47	1003	115.8	0.005
Pumice/Zeolite (lab)	50		30	20	48	581	86	0.096
Pumice/Zeolite (field)	50		30	20	49	839	118.1	0.007

All results are mean values of at least three replicates.

1. Determined at max water capacity and 70 mm substrate depth, assuming 1.6 kg/m<sup>2</sup> for the drainage layer and 10 kg/m<sup>2</sup> for mature plants. "Wet" weight is used as the measure does not reflect saturation, but the most likely condition during and immediately after a storm event.

2. Composted pine bark generated as a byproduct from timber processing.

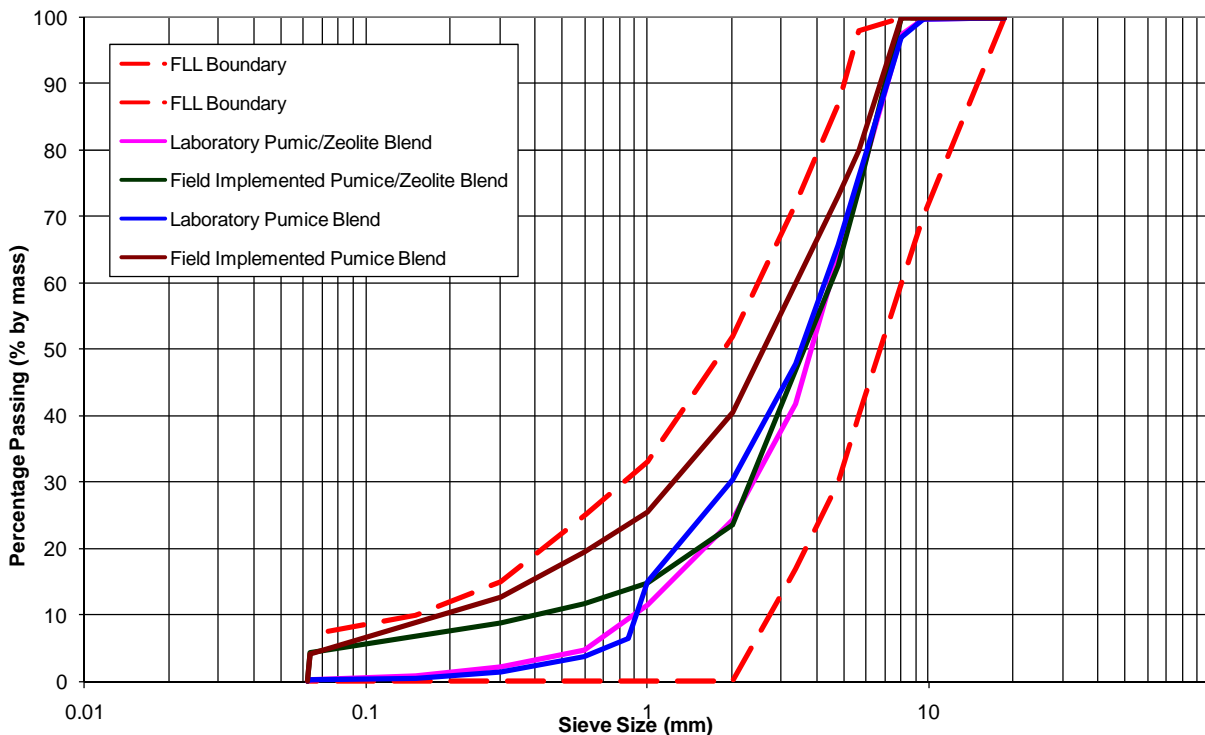


Figure 5. Particle size distribution comparison between laboratory hand-mix and field bulk-mixed substrate blends.

### Achieving Objectives with Implementation Constraints

Despite the detailed scientific approach adopted, since a clearly superior blend for meeting objectives wasn't evident, raw material cost and quality assurance emerged as the driving factors behind allocating distribution. At NZ\$24 m<sup>-3</sup>, pumice became the dominant component (70-90%) of all blends for field testing, despite relatively poor quality control. Conversely, zeolite is quarried and processed under strict quality control for application in golf courses. Although significantly costlier at NZ\$180 m<sup>-3</sup>, the consistent product coupled with perceived value in promoting robust plants (especially due to high CEC and water holding capacity) warranted inclusion.

In the original blends (Table 1), the small pumice or zeolite was specified to provide finer particles needed to promote plant growth. The specification was a significant debate between the authors, since the small particles would add weight and reduce permeability (contrary to engineering objectives but considered necessary by the plant specialist). A much smaller fraction of zeolite (Table 2) was used in the revised blend to minimize cost but still reap plant growth benefits (Ming and Allen 2001).

In NZ, suppliers are very interested in the green roof industry (and have been very helpful to the research team); however, they are not yet willing to invest significantly in their own research and development, or to change existing processes. The exception again was the zeolite supplier: the 1-3 mm specification was co-produced with another existing product to suit green roof needs at the same cost.

Table 2 demonstrates that working with the suppliers to better understand the entire source and supply process can lead to a consistent final product for an extensive green

roof mix. Rather than create additional cost by imposing stricter quality control on the supply, the research team worked within the imposed limitations of the existing industry to develop a viable mix. The aggregate combination in the revised blend (newly installed on reinforced garden sheds for field trial) is comprised of only large sized pumice and small sized zeolite. It is assumed that the required small particle fractions to support plant life will be provided by the zeolite and supplemented by the pumice contamination. Mixing was achieved using a tractor with bucket attachment, rather than the hopper with rotating tines.

**Table 2. Composition of Revised Blends**

Revised Mixture	Composition (% by volume)				Max. Water Capacity (%)	Dry Bulk Density (kg/m <sup>3</sup> )	Wet System Weight <sup>1</sup> (kg/m <sup>2</sup> )	Permeability (cm/s)
	Pumice 4-10 mm	Zeolite <sup>2</sup>	Bark Fines+ Mushroom Compost <sup>3</sup>	Peat				
Lab	70	10	10	10	57	475	90	0.05
Field	70	10	15	5	63	539	92	0.04

All results are mean values of at least three replicates.

1. Determined at max water capacity and 70 mm substrate depth, assuming 1.6 kg/m<sup>2</sup> for the drainage layer and 10 kg/m<sup>2</sup> for mature plants. "Wet" weight is used as the measure does not reflect saturation, but the most likely condition during and immediately after a storm event.

2. Lab blend: 0.5-3.0 mm; field blend 1-3 mm.

3. Composted pine bark pre-blended by supplier with mushroom farm compost.

## Results and Business Impacts

### Key Findings

Setting design objectives enabled initial decision-making. In this case, while stormwater management was the primary design goal, constraints imposed by retrofit potential (namely wet system weight) were the most limiting design factor for substrate depth. Measures of plant-available water indicate that a design depth of 50-100 mm should address stormwater control objectives while maintaining plant viability. Lower depth will likely require periodic irrigation in summer even under Auckland's rainy semi-tropical climate, and is less likely to provide complete retention for the design storm when subject to back-to-back events. New structures should design for loads imposed by a 100 mm depth, in order to minimize needs for irrigation. A compromise solution for retrofit application is 70 mm depth, which results in the objective of 100 kg m<sup>-2</sup> maximum weight during and immediately after a storm event.

Finer particles have the greatest contribution to water and nutrient holding, characteristics which have potentially deleterious effects on substrate weight and permeability. Aggregates produced for the concrete industry are unlikely to strictly adhere to the PSD referenced on product packaging. Imposing additional quality control for the major component of a substrate would likely increase cost substantially. While the relevant



suppliers have been very supportive to date, they are unlikely to change production practices until a green roof market is established.

## Business Impacts

Quality assurance in source material generation and blending is critical to satisfying design objectives. In the event that a commercial market emerges in NZ for green roof substrates (as it has in North America), a standard approach to testing must be specified, and suppliers must be required to provide reliable values. Key physical parameters include maximum system weight and saturated hydraulic conductivity (similar to FLL permeability). Testing must be done on the bulk mixed product; as the blending process may compromise suitability of materials susceptible to compaction or physical degradation. Testing of the mixed product gives confidence in these key parameters, allowing extensive green roofs to be constructed and retrofit onto lighter-weight structures.

From a regulatory perspective, extensive green roofs constructed from locally available materials in NZ present a viable solution to stormwater control in urban areas for both new and retrofit construction. However, laboratory testing may have limited use in determining actual field performance.

## Conclusions

An extensive green roof substrate mix comprised of locally sourced components has been developed to balance stormwater control objectives and plant viability subject to the Auckland climate. The mix is 70% 4-10 mm pumice, 10% 1-3 mm zeolite, 15% pine bark fines plus mushroom farm compost, and 5% peat. While a scientific approach to material selection was rigorously followed, quality assurance in material supply and blending as well as cost emerged as the predominant decision-making variables.

Coupling plant needs with stormwater control objectives (complete retention of a 25 mm event) yields a design depth suitable for retrofit applications at 70 mm. At this depth, periodic irrigation is likely necessary to sustain plants through the summer, but weight during and immediately after storm events is maintained at 100 kg m<sup>-2</sup>. Increased substrate depth over load-bearing walls or columns may provide a storage reservoir for unusually dry periods. For new construction, a 100 mm depth is recommended to sustain plants for over a week in summer without rain. At depths greater than 100 mm, the added precipitation storage potential is probably superfluous when considering Auckland rainfall frequency and typical ET.

A key method for decreasing system weight is to consider increasing quality of the pumice to remove heavier rock and sand. Else, since the locally developed substrate has such a high water holding capacity, the additional weight created by some commercial drainage layers may not be necessary to enhance stormwater control or plant viability.

### Key Lessons Learned:

- Maintaining high quality assurance in material selection and supply is critical to substrate composition.
- Substrate testing to characterise physical and chemical composition must be performed on blended materials to ensure structural loadings and plant viability.
- Significant stormwater control should be created by extensive green roofs even at only 50-70 mm deep.
- Development of extensive green roofs for environmental control benefits from a unique partnership between engineers, plant, and soil specialists.

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## Authors' Biographies



Elizabeth is a Senior Lecturer in Civil and Environmental Engineering at the University of Auckland. She comes to New Zealand by way of Duke University and the University of Virginia, where she obtained undergraduate, ME and Ph.D. degrees in civil and environmental engineering. Elizabeth's research focuses on field-scale evaluation of stormwater management devices, with particular emphasis on emerging "low impact" technologies for receiving water protection.



Robyn is a graduate from Massey University, initially in Horticultural Science, with a focus on Soil Science, and followed by a Ph.D. investigating soil compaction and mine rehabilitation. She joined Landcare Research, a Crown Research Institute, in 2001 where she has increasingly focussed on creating ecosystems with designed substrates that mitigate stormwater runoff, namely rain gardens and green roofs.