UNIVERSITY OF
CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

FINAL REPORT ON EQC RESEARCH CONTRACT 10/SP607: ‘A QUANTITATIVE ANALYSIS OF VOLCANIC ASH DAMAGE TO NEW ZEALAND ROOF STRUCTURES AND MATERIALS’

20 July 2011

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TECHNICAL ABSTRACT

There have been three aspects to this research. The first was to create a pseudo-ash that can be used as a proxy for fresh volcanic ash (+ aerosols) from explosive eruptions, which can be used in tests on the effects of such ash on infrastructure. One use of this pseudo-ash has been to tests effects on fresh ash falling on roofs. The chosen material was crushed basalt from Banks Peninsula, Canterbury, 'dosed' with acidic water from either Crater Lake, Ruapehu or from the crater on White Island. Comparisons were made between this dosed ash and fresh ash to check their properties were similar. Once this was established, the pseudo-ash was used to evaluate the effects of ash on different types of roofing materials (galvanized iron, old corrugated iron, Coloursteel©, and zinc), using the fog chamber at the Building Research Association of New Zealand (BRANZ) facility at Porirua. Samples were subjected to 6 hours of wetting and 18 hours of air drying every 24 hours to simulate types of conditions roofs might experience for periods of 1 day, 1 week and 1 month. The samples were then examined using SEM and XPS analysis at the University of Auckland to check on any corrosion. None was found, indicating that for future tests, conditions in the fog chamber will need to be varied with for example, potentially longer periods of wetting per day or longer periods in the chamber. Checks on gutters involved dropping crushed, non-dosed, dry basalt onto a test frame incorporating a corrugated iron roof, capable of being set at variable angles, with a plastic (Marley) gutter attached. This frame is housed in the Volcanic Ash Testing (VAT) Facility in the Department of Geological Sciences at the University of Canterbury. At low roof angles (15^{o}) most ash remained on the roof; at intermediate angles (25^{o}) ash started to move downslope and form small piles in the gutter. At high angles (45^{o}) almost all the ash went into the gutter, rapidly blocking it.

This preliminary study has provided some important parameters, but has equally shown that a more complete, longer term study is needed to provide the type of information needed by planners to mitigate this type of hazard.

LAY ABSTRACT

The impacts of recent volcanic ashfall on roofs and gutters is very significant and it is important to know how different types of roofing materials will react, and what effects different amounts of ash will have on gutters.

Because of the difficulty of obtaining large quantities of fresh ash, which still contains the soluble gases from the volcanic eruption, a pseudo-ash has been prepared, using crushed rock dosed with acidic waters so that it has the same composition as fresh volcanic ash. This was then used to test various types of roofing materials. The test

samples were placed in a fog chamber and subjected to alternating wetting and drying for periods varying from 1 day to 1 month, but during the relatively short time frame for the project no corrosion occurred. In future tests it will be necessary both to vary the test conditions in the fog chamber and length of time roof samples are subjected to wetting and drying.

Experiments with plastic (Marley) gutters attached to a simulated corrugated iron roof showed that at low roof angles (15^o) most ash stayed on the roof and the effect on the gutter was minimal; at medium angles (25^o) ash began to move downslope on the roof and collect in the gutters, particularly below the troughs of the corrugated iron roof. At high angles (45^o) most ash went into the gutter, rapidly blocking it. Additional tests are needed with wet ash and different types of gutter to see what changes occur.

1.0 INTRODUCTION

This project was undertaken to make a preliminary analysis of the impact of volcanic ashfall on roofing materials and the performance of gutters under ash loading. The objectives included:

- The vulnerability of standard New Zealand metallic roofing and gutter materials to corrosion following volcanic ash exposure over time
- Deterioration rate of metallic roofing and gutter materials
- Performance of standard New Zealand gutters under different ash loadings

This research extents the current characterisation of residential building fragility to volcanic ash. International work has focused on the collapse of roofs or other structural elements of residential buildings following heavy ashfall or pyroclastic flows (e.g. Spence et al., 1996, 2004). However, ash depths are typically >200 mm, and often >400 mm, before structural failures occurs to the building. Field observations in ash fall out zones indicate most residential houses will not be exposed to sufficient ashfall loadings to produce structural failure of roofs. Instead corrosion to metallic roof materials and gutters, and collapse of gutters are the most commonly reported and observed impacts (Table 1). However there is very limited empirical data available in this area to understand what the likely impact will be.

This report is structured to provide background information on the project, then a description of the three key aspects of the research:
1. Pseudo-ash generation
2. Corrosion testing
3. Guttering

This is followed by key conclusions, recommendations, current and potential future outcomes.

Type of damage	Topic/conclusion	Location	Authors
Corrosion	Corrosion of roof cladding	Rabaul, Sakurajima, Mount St. Helens, Ruapehu	· Blong, 1981, 2003 · Deguchi, 1988 · Dillman & Roberts, 1982 · Johnston et al., 2000 · Matsumoto et al., 1988
Roof gutter damage	Damage sustained from tephra falls; housing-related damage	Mount St. Helens, Ruapehu	· Blong, 1981 · Dillman & Roberts, 1982 · Johnston et al., 2000

Table 1: Review of relevant literature regarding roof corrosion and gutter damage.

1.1 Context for the Project

It has been estimated that nine percent of the world's population lives within 100 km of a historically active volcano (Horwell and Baxter 2006). This proportion is likely to continue to increase due to higher-than-average rates of population growth in many regions and countries such as Central America, equatorial Africa, Colombia, Ecuador and the Philippines that are highly volcanically active. Eruption frequencies for a range of volcanically-active countries are shown in Table 1.

Volcanic eruptions can produce a wide range of hazards. Although phenomena such as pyroclastic flows and surges, sector collapse, lahars and ballistic blocks are most destructive and dangerous (Baxter, 1990; Hansell et al. 2006; GFDRR, 2011), volcanic ash fall is by far the most widely distributed eruption product. Volcanic ash can affect many people because of the large areas that can be covered by ash fall. Although ash falls rarely endanger human life directly, threats to public health, disruption to critical infrastructure services (e.g. electricity and water supplies, transport routes, waste water and communications), aviation, building damage and primary production, can lead to significant societal impacts (Horwell and Baxter 2006; Stewart et al. 2006).

1.2 Brief Review of Relevant Previous Studies

Corrosion is a well-established phenomenon in volcanically-active regions (Watanabe et al., 2006; Hawthorn et al., 2007; Lichti et al., 1996). For example, a study conducted at Kilauea volcano, Hawai'i, reported that the rate of corrosion of aluminium test plates was at least seven times greater than that recorded in an industrial site on Oahu with comparable climatic factors (Hawthorn et al., 2007).

The focus of this study is on the corrosive effects of volcanic ash, for the reasons outlined in above. In general, while volcanic ash is thought to have significant potential to cause corrosion (see Section 1.4 for further discussion), this phenomenon has not been systematically studied. Very limited empirical data are available therefore this remains an area of uncertainty in residential building fragility estimations (Magill et al., 2006; Wilson T. et al., 2011).

Corrosion has been attributed to volcanic ash in a small number of field studies (Becker et al., 2001; Johnston, 1997; Blong, 2003; Matsumoto et al, 1988; Deguchi, 1990). Some of these studies have limitations, including a lack of detail or supporting documentation, such as photographs of damage that might indicate pre-existing corrosion or that the reported damage might have been due to volcanic aerosols, gases and/or acid rain. The only manipulative experiment was carried out by Matsumoto et al. (1988). These authors investigated the deterioration of metallic materials (aluminium, copper, stainless and galvanised steel) around Sakura-jima volcano, and found that while acid rain and volcanic gases may have contributed, corrosion was strongly correlated to the amount of ash received.

Following the 1995-1996 eruptions of Ruapehu 203 claims were made to EQC due to damage following the ashfall. Almost 90% of the claims related to the roofs, with 28 related to corrosion of metal roof surfaces (Treblico, 1997). There have been few examples of roof corrosion mentioned in the literature (Table 1) and even less experimental work done to date. Blong (2003) has characterized roof cladding corrosion in Rabaul in 1994 to brand new corrugated iron roofs (and rusting through the sheet very quickly (within months; Emeritus Professor Russell Blong, pers. comm. 2009).

Fig 1: Corrosion to roof cladding and gutter collapse following 200 mm of ashfall in Futaleufu, Chile following the 2008 Chaiten eruption (Photo: T. Wilson).

The 23/01/09 – 12/02/09 volcanic impact reconnaissance trip to areas in Chile and Argentina impacted by heavy ashfalls following the 2008 Chaitén eruption (partially supported by EQC) was directed by David Middleton (EQC) to undertake analysis of ashfall impacts to residential buildings. Residential houses of similar construction to New Zealand (mostly corrugated galvanised iron roofs), in a similar climatic setting, were exposed to a range of ashfall impacts, with many suffering corrosion to metallic cladding on the roof. Where ash depths were >50 mm gutters were damage or collapsed due to ash washing from the roof and causing overloading (Fig 1). A survey of residential buildings in Futaleufu, Chile, following 200 mm of ashfall has shown that extensive damage has occurred to the building inventory there, without structural failure of the roof occurring. This damage includes significant and rapid corrosion of corrugated sheet steel roof cladding and corrosion, infilling and collapse of rain gutters and down pipes. Our analysis of damage sustained in Futaleufú, Chile as a result of the May 2008 eruption Chaitén volcano, Chile shows that over 72% of the roofs were estimated to be damaged (corrosion) in the observed building stock. This is similar to damage reported by Deguchi (1988) in Kagoshima (~55%) and Tarumizu, Japan (~65%) after the 1978 eruption of Sakurajima volcano, one of the few quantified results of roof corrosion damage in the literature. Interviewed residents in Futaleufu stated that damage to their metallic roofs (paint peeling and metal corrosion), gutter damage, and contamination of the house interior was the greatest impact to their personal property and has required municipal aid to assist repairs.

1.3 Corrosion of metals by atmospheric aerosols and particulates

A range of studies have been conducted on corrosion of metals by atmospheric aerosols and particulates (Askey et al., 1993; Comizzoli et al., 1986, Lau et al., 2008; Cole et al., 2011), from which lessons applicable to volcanic ash may be learned.

One of the most important roles played in atmospheric corrosion by airborne substances, such as aerosols and particulates, is the provision of corrosive ionic species, or salts, to metal surfaces. Askey et al. (1993) found that contamination of metal substrates (zinc and mild steel) by fly-ash particulates increased in proportion to the quantity of leachable ionic species present in the fly ash. For the purposes of modelling metal corrosion in Australia, Cole et al. (2011) proposed a direct relationship between corrosion rates due to marine aerosol and metal surface salinity as follows:

$$\textbf{Mass loss (over 3 hours)} = \nu + \beta S \psi \qquad \textbf{(equation 1)}$$

Where mass loss has units of g/m2, S is the salinity (mg/m2) on the surface, and ν, β and ψ are constants having values of 8.3 x 10-4, 11.3 x 10-4 and 0.5 respectively (Cole et al., 2011)

Other studies have established that in addition to the total ionic strength (salinity), ionic composition is a further control on atmospheric corrosion rates. Lau et al. (2008)

studied the effect of the composition of atmospheric aerosols on corrosion of mild steel. The most rapid rates of corrosion were associated with the ionic species Na^+, Cl^- and to a lesser extent SO_4^{2-}, NH_4^+, K^+ and Mg^{2+}, whereas the presence of Ca^{2+} was found to significantly inhibit corrosion. This was thought to be due to the role of calcium in forming insoluble salts such as $Ca(OH)_2$. Comizzoli et al. (1986) pointed to the particular importance of chloride as a corrosive species, due to its ability to form a range of soluble compounds.

Atmospheric sources of acidity are also thought to be important influences on corrosion. It is well known that SO_2 and its acidic oxidation products are in many locations the principal cause of outdoor corrosion of metals (Comizzoli et al., 1986). Cole et al. (2011) studied the interaction of marine aerosols with acidic gases, and found that the presence of both HCl and H_2SO_4 increased the corrosivity of natural seawater aerosol droplets, but that nitric acid did not. Similarly, Askey et al. (1993) found that while in unpolluted atmospheres (defined as having very low levels of SO_2 and HCl), the quantity of leachable ionic species present in fly ash controlled the rate of corrosion, whereas in polluted atmospheres the presence of fly ash had little impact on the rate of corrosion, presumably because the corrosive effects of the acidic gases dominated.

Finally, any discussion of atmospheric corrosion must include mention of the critical role of atmospheric conditions. Important parameters include rainfall amount and composition, wind speed and direction, temperature and relative humidity. Cole et al. (2011) and Johnston (1997) both note that structures such as buildings typically present a range of microclimates – for instance, components under the eaves of a building are sheltered from rain that could remove deposited aerosols, but exposed to winds that can increase deposition.

Relative humidity (RH) is a particularly important control on corrosion. Any deposited hygroscopic salts (salts that attract moisture from the atmosphere) will become deliquescent (dissolve in moisture from atmosphere) when the RH at the metal surface exceeds the deliquescent RH for a particular salt (e.g. 75% for NaCl at 20°C). Thus, even if aerosols or particles are deposited dry they can still promote the formation of a conductive surface film. Even in absence of salt deposition, RH is still considered an important control on rates of outdoor corrosion, as metal surfaces tend to acquire moisture from atmosphere. For most metals the critical RH is in the range 70-80% (Comizzoli et al., 1986).

1.4 Volcanic ash and its corrosive potential

1.4.1 Introduction to volcanic ash

Volcanic ash is the material produced by explosive volcanic eruptions that is < 2 mm in diameter. Fine ash is < 0.063 mm; coarse ash is between 0.063-2 mm. Volcanic ash is made up of various proportions of vitric (glassy, non-crystalline), crystalline and lithic (non-magmatic) particles. The density of individual particles may vary between 700-1200 kg/m^3 for pumice, 2350-2450 kg/m^3 for glass shards, 2700-3300 kg/m^3 for crystals, and 2600-3200 kg/m^3 for lithic particles. Since coarser and denser particles are deposited close to source, fine glass and pumice shards are relatively enriched in ash fall deposits at distal locations (Shipley & Sarna-Wojcicki, 1982).

Vitric particles typically contain small voids formed by expansion of magmatic gas before the enclosing magma solidified, known as vesicles. Ash particles can have varying degrees of vesicularity. Vesicular particles can have extremely high surface area to volume ratios. Exsolved magmatic gases condense onto ash particle surfaces while they are in the conduit and ash plume (Delmelle et al., 2007).

1.4.2 Volcanic ash surface chemistry

It has long been recognised that a range of sulphate and halide (primarily chloride and fluoride) compounds are readily mobilised from fresh volcanic ash (Fruchter et al., 1980; Delmelle et al., 2007; Jones and Gislason, 2008). Delmelle et al. (2007) consider it most likely that these salts are formed as a consequence of rapid acid dissolution of ash particles within eruption plumes, which is thought to supply the cations involved in the deposition of sulphate and halide salts. In support of this contention, Oelkers (2001) reported that selective leaching of metals from silicate lattices is coupled to proton consumption, consistent with metal-proton exchange reactions.

While some 55 ionic species have been reported in fresh ash leachates (Witham et al., 2006) the major species found are the cations Na^+, K^+, Ca^{2+} and Mg^{2+} and the anions Cl^-, F^- and SO_4^{2-}(Witham et al., Jones and Gislason, 2008). Molar ratios between ions present in leachates suggest that in many cases these elements are present as salts such as NaCl and $CaSO_4$ (Witham et al., 2005; Taylor and Lichte, 1980; Smith et al., 1983; Risacher et al., 2001). In a sequential leaching experiment on ash from the 1980 eruption of Mount St Helens, chloride salts were found to be the most readily soluble, followed by sulphate salts (Taylor and Lichte, 1980). Fluoride compounds are in general only sparingly soluble (eg CaF_2, MgF_2), with the exception of fluoride salts of alkali metals. Readily-soluble fluoride may be contained within salts such as NaF and $CaSiF_6$ (Cronin and Sharp, 2002).

More recently, sophisticated techniques have been brought to bear on volcanic ash surface salt coatings. Gislason et al (2011) utilised a wide range of techniques to study the ash from the April 2010 eruption of Eyjafjallajökull volcano in Iceland. There were two distinct phases of the eruption; an early hydromagmatic, explosive phase that generated very fine ash (with 20 mass% <10 µm and a surface area of 4.3 m^2/g) and a later phase (<10 µm less than 2 mass%, and a surface area of 0.45 m^2/g). The surface salt coating was visualised using AFM (atomic force microscopy) and determined to be approximately 0.6 nm thick for the explosive ash and 4 nm for the later ash. The dissolution of surface salts was visualised using SEM and AFM images, and was determined to be rapid (less than 15 minutes). However, ionic release rates were both slower than expected for pure halite (NaCl) or gypsum ($CaSO_4$) and more rapid than for the dissolution of volcanic glass, leading the authors to propose the presence of compounds such epsomite ($MgSO_4.7H_2O$) and scacchite ($MnCl_2$), based on a range of known evaporate and fumarole encrustation minerals.

The pH of fresh ash leachates is highly variable. Jones and Gislason (2008) studied the interaction of a range of different volcanic ashes with both deionised water and seawater. Ash from the 2000 eruption of Hekla was found to be the most acidic, with an initial pH of 3.5 on contact with deionised water. Hekla ash was also very high in fluoride, which in turn led to higher bulk mineral dissolution rates (Frogner Kockum et al., 2006; Wolff-Boenisch et al., 2004). Ash from the 2005 eruption of Galeras, the 2003 dome collapse of Soufriere Hills volcano, Monsterrat, and a 1994 eruption of Sakura-jima volcano, Japan, had similar initial pH values of approximately 4.6. There was little change in pH in the experiments using ash from Mount St Helens (1980 eruption), Lascar, Chile (1993 eruption) or Santiaguito, Gautemala (1968 and 1988 eruptions).

Other authors have also reported neutral to basic ash leachates. Gislason et al. (2011) reported that the pH of ash leachate from the explosive phase of the April 2010 Eyjafjallajökull eruption was slightly basic at pH 8; this was thought to suggest the absence of an acidic gas condensate as volatiles were removed in the glacial meltwaters in this early, hydromagmatic phase. However, the ash from the later phase of the eruption was more acidic, with a pH of approximately 5.1, implying the presence on the ash surface of proton salts. In a study of fresh ash leachates from the 1993 eruption of Lascar, Chile, Risacher and Alonso (2001) reported pH values as high as 10.5 for ash leachates. This was attributed to the presence of basic metal oxides on the ash surface arising from pyrolysis of vegetation by hot ash. This phenomenon was also observed after the May 18 1980 eruption of Mt St Helens volcano (Pereira et al., 1982).

Many authors have noted that the release of salts from freshly-fallen ash is typically very rapid (Taylor and Lichte, 1980; Witham et al., 2005; Jones and Gislason, 2008; Gislason et al., 2011). Gislason et al. (2011) reported that for the Eyjafjallajökull ash, surface salts dissolved rapidly, in less than 15 minutes. Jones and Gislason (2008) noted that ash surface coatings appeared unstable, decaying in situ even if kept unhydrated. This may be due to the deliquescence of surface salts (see Section 1.3). However, this may depend on the depositional environment. Ruggieri et al. (2010) report that for ancient volcanic ash (up to several million years old) deposited in a hyper-arid region of northern Argentina, fluxes of leachable surface salts comparable to modern rates were obtained.

Fewer studies have been concerned with the longer-term release of soluble material from deposited ash. Jones and Gislason (2008) noted that ash leachate dissolution occurs several orders of magnitude faster than dissolution of volcanic glass (Woelff-

Boenisch et al., 2004). Oelkers (2001) provides a useful general review of multioxide silicate mineral and glass dissolution. He notes that multioxide dissolution proceeds via a series of metal-proton exchange reactions, whereby alkali metals are exchanged first, followed by calcium, magnesium, aluminium and finally by the breaking of Si-O bonds. Therefore it is reasonable to expect that long-term interactions between volcanic ash and natural waters will consume, rather than be, a source of acidity. Ghiara et al. (1993) report that after 24 hours, the pH of crushed basaltic glass equilibrated with deionised water was slightly basic (7.5-8.0).

In summary, freshly-fallen volcanic ash clearly has the potential to be corrosive. Its surface coating contains salts and sometimes also acidic gas condensates. These salts are very readily soluble and may deliquesce if relative humidity is high. Light wet weather conditions will also provide sufficient moisture to mobilise ionic components into a surface film, whereas heavy rain will wash ash away or remove soluble components. Field data from a visit to Guatemala City following the May 2010 eruption of Volcan Pacaya (Wardman et al., 2011) provides an illustration of the importance of atmospheric conditions for corrosion. Approximately 2-10 cm of coarse, sand-sized basaltic ash fell on Guatemala City. This was followed shortly afterwards by an intense tropical storm and heavy rainfall. While there were very few reports of corrosion damage across the city, we received one report from a reputable source that corrosion damage had occurred on a vehicle stored under a canvas cover, when the ash infiltrated under the cover. Thus the ash was probably corrosive but because of the heavy rains, it was either washed from metal surfaces or the surface coating was leached.

1.5 Project Team

The project leader was Prof Jim Cole (University of Canterbury; UC) with associate researchers Dr Thomas Wilson (UC), Dr Carol Stewart (Joint Centre for Disaster Research, Massey/GNS), Dr Zhengwei Li (BRANZ Ltd), Dr Christopher Oze (UC) (from 1 October 2010), Dr Allan Scott (UC) (from 1 October 2010), Dean Podolsky (UC) (until 1 October 2010) and Grant Wilson (from 1 October 2010). Dr Sam Hampton has assisted with the construction of a rig for the guttering experiments, and with the gutter testing programme.

1.6 Changes to Contract

The project was initially funded for 1 year, from 1 January – 31 December 2010, but an extension to the completion date for the project until 31 March 2011 was approved in late October 2010. This was due to two factors: 1) one of the AIs, Dean Podolsky, moved to Australia and was no longer available to contribute to the project and 2) the Darfield (Canterbury) earthquake of 4 September 2010 caused significant disruption to the programme, both in terms of university closure and the ability for Dr Tom Wilson to devote appropriate time to it. Tom was heavily involved in monitoring the effects of the earthquake, particularly the liquefaction, and unable to contribute to the EQC programme during September and October.

To replace Dean Podolsky and assist with the programme, Dr Christopher Oze (new geochemist and petrologist within the Department of Geological Sciences, UC), Dr Allan Scott (corrosion expert within the Department of Civil & Natural Resources Engineering, UC), and Grant Wilson (MSc student in the Department of Geological Sciences, UC) were added as AIs in the programme. Their expertise has been invaluable both in setting up the testing and interpreting the results.

The 22 February 2011 earthquake caused further disruption to the project, and the closure of UC (with no access to the Department of Geological Sciences for 7 weeks), meant that the final parts of the contracted research was unable to be completed by the 31 March deadline. In early April, an extension was approved to 30 June 2011. Then on 13 June 2011 there were two more aftershocks (M5.5 and 6.3). Little damage was done to the university but it was closed for a week, causing further disruption to the programme. An agreement was reached that this final report would be submitted by 31 July 2011.

2.0 PSEUDO-ASH GENERATION

Characterisation of metallic roof and gutter material vulnerability to volcanic ash ideally relies on using fresh volcanic ash, as acidic soluble salts attached to recently erupted ash are considered to corrode metallic surfaces. Given the high solubility of the salts it is vital that ash used for laboratory testing has not been leached by rain or been on the ground for more than a few hours (ideally not at all). These requirements create considerable logistical and financial challenges to collect sufficient ash for laboratory testing. The locations of active volcanoes are not always conducive to collection of a sufficient quantity of ash needed for the study, and even if the ash could be collected and transported, MAF biosecurity issues also make importing erupted ash for the study from overseas impractical. A further issue is that fresh ash surface coatings are thought to be unstable (Jones and Gislason, 2008) decaying in situ even if kept unhydrated. Because of these issues, we have produced a ‘pseudo-ash’ which replicates the physical and chemical properties of fresh volcanic ash rather than relying on newly erupted material. This has come from materials that can be obtained readily in New Zealand and ‘dosed’ in a chemical laboratory to simulate the chemistry of fresh volcanic ash (e.g. Ruapehu) which usually contains a wide range of water-soluble elements (e.g. Table 2).

Development of the pseudo-ash was largely undertaken in the early part of the programme by Dr Tom Wilson, and a BSc (Hons) student (Sam Broom), and then later by MSc student Grant Wilson. Large quantities of basalt from Banks Peninsula were crushed and characterized (i.e., grain size, grain shape, density and morphology), and found to have essentially the same geotechnical characteristics as typical ashes from the Taupo Volcanic Zone (Broom, 2010). Crater Lake water from both White Island and Ruapehu was obtained and mixed with the raw pseudo-ash to simulate the chemical properties of freshly erupted ash. Leachate from the 'doped' ash was analysed by ICP-MS and the results were evaluated by Sam Broom and consultant Dr Carol Stewart. The results were then compared to those obtained from 'doped' rhyolitic ash from Tarawera as well as from ash derived from the 2007 Ruapehu break-out lahar (Broom, 2010) and fresh ashes from overseas (Table 3) to ensure the pseudo-ash was similar to freshly erupted volcanic ash before it is used for corrosion testing. Full details of the preparation and doping techniques are given in Broom (2010), which has already provided to the EQC in a previous report. Results indicated the pseudo-ash and fresh ashes were very similar (Broom, 2010). A paper on the pseudo-ash is in preparation (Wilson G. et al, in prep).

Element	-------------------mg/kg dry weight-----------------------			
	Turangi	Tokaanu	Kinloch	Rotorua
As	<4	<4	<4	<4
Ca	6438	3039	3690	3287
Mg	856	119	370	229
Na	662	126	436	290
K	70	74	128	134
S	7344	2772	4092	3294
B	4.6	2.6	3.3	2.2
Fe	85.8	15.6	22.2	13.8
Mn	27.4	4.7	13.5	7.6
Al	351	52	122	109
Cd	<0.2	<0.2	<0.2	<0.2
Cr	<0.2	<0.2	<0.2	<0.2
Cu	2.8	9.5	6.3	2.8
Ni	0.8	<0.8	<0.8	<0.8
Pb	<1.2	<1.2	<1.2	<1.2
Zn	4.8	4.8	4.4	4.6

Table 2: Water-soluble elements attached to 1996 Ruapehu ash from four locations (Cronin et al. 1998)

3.0 CORROSION TESTIING

Preliminary tests were undertaken on a local roof in Christchurch, using the doped pseudo-ash to see the effect, and results evaluated. Different types of roofing material were collected and discussions held with BRANZ Ltd (Dr Zhengwei Li) about tests that could be carried out at their Moonshine Road, Porirua, laboratories, to establish how roofing materials coated with doped pseudo-ash would perform under different weather conditions (e.g. rain, mist. fog) for different lengths of time. Samples (100mm x 100mm) of different types of roofing material (in particular Coloursteel©, galvanized

Element	Basalt Pseudo Ash			Real Ash		
	1:1, 100%	2:1, 100%	4:1, 100%	Minimum	Average	Maximum
Al	3.60	<0.15	<0.15	0.32	3.28	10.3
B	0.60	<0.30	<0.30	0.02	0.09	0.27
Br	0.15	<0.10	<0.10	0.30	0.30	0.30
Ca	29.0	7.30	7.20	29.6	104.9	211.6
Cl	79.0	21.0	21.0	4.07	49.9	205.9
F	2.0	0.41	0.41	0.64	3.24	7.20
Fe	3.20	<0.08	<0.08	0.10	0.60	1.56
Li	0.02	<0.01	<0.01	0.00	0.05	0.10
K	3.50	1.30	1.10	4.01	5.41	7.90
Mg	22.0	5.70	5.70	3.28	12.2	29.8
SiO_2	9.70	4.80	4.90	10.0	10.0	10.0
SO_4	115.0	32.0	32.0	16.3	202.4	702.5

Table 3: Concentrations of selected ions for three different dosed pseudo ashes compared to minimum, maximum and average concentrations of real ash (Mt St Helens 1980, Fuego Ash 1973 and 1974, Pacaya Ash 1974, Santiaguito Ash 1967 and 1975, Ruapehu 1995-96, Popocatepetl 1994-96, 97, 98). All concentrations are in mg/L (Wilson, G., 2011 in press).

iron) were then obtained from Steel and Tube Ltd, and samples of zinc sheeting from Mico Metals. Samples of weathered corrugated iron (c. 60 years old) were obtained from a farm in mid-Canterbury. Results have been compared to samples of roofs obtained from Montserrat which have been affected by ash from the Soufrière volcano over the past 15 years, and from Homer, Alaska, which received minor ash fall during the March-April 2009 Redoubt eruption.

Three tests were initially carried out by Sam Broom in early 2010. The first experiment investigated how roof pitch affected ash accumulation. A range of different variables, such as ash grain size, accumulation thickness and moisture content, was tested across a range of different roofing materials with the aim of characterising what roof types were more susceptible to ash accumulation, making them in turn more vulnerable to ashfall hazards. The second experiment investigated volcanic ash-induced corrosion, one of the most widely experienced but least understood impacts of volcanic ash on roofs (Blong, 2003). This phenomenon is thought to be largely caused by the leaching of the soluble component on ash by rainfall resulting in acidic and salt-rich leachates capable of corroding roofing material (Izumo et al, 1990). The experiment investigated the physical signs of corrosion caused by accumulating ash on both galvanised and painted corrugated iron, with a range of parameters investigated including ash thickness, exposure time and ash soluble salt content. Roofs were covered with ash, dosed with strong acid, and exposed for 7 and 25 days. The third experiment evaluated the abrading effect of removing ash from roofs post ashfall. Removal, both by sweeping and washing with water using a typical garden hose, were investigated as these are both common roof cleaning methods. If abrasive damage was found on a roof, these methods could increase the rate of corrosion, both under normal conditions post eruption and from future ashfall events. This could have significant impacts on the long term damage caused by ash fall and should be included within roof fragility functions evaluating the damage potential from ashfall. The purpose of this experiment was to better understanding the implications of different removal methods and to provide best practice recommendations.

Results of the first test showed that at low ash thickness (<1mm), no ash was shed from the roof, even after tilting to 70^{o}. At greater thicknesses, failure occurred between 30-50^{o} (Fig. 2). After wetting, failure only took place with >20 mm ash (Table 3). In the second test, little damage was observed after 7 days, while after 25 days changes to the surface were evident. This became clear in SEM images, when 'blisters' became apparent (Fig. 3). These blisters appear to be surface features, and are most likely explained by precipitation of iron (C. Oze, pers comm., 2011) from the interaction between the acid dosing and the basalt 'pseudo-ash', and do not represent corrosion. In test 3, SEM images showed significant signs of abrasion (Broom, 2010), even after one dry ash removal, in both painted and non-painted samples (Fig. 4). When water was used, abrasion appeared to be reduced.

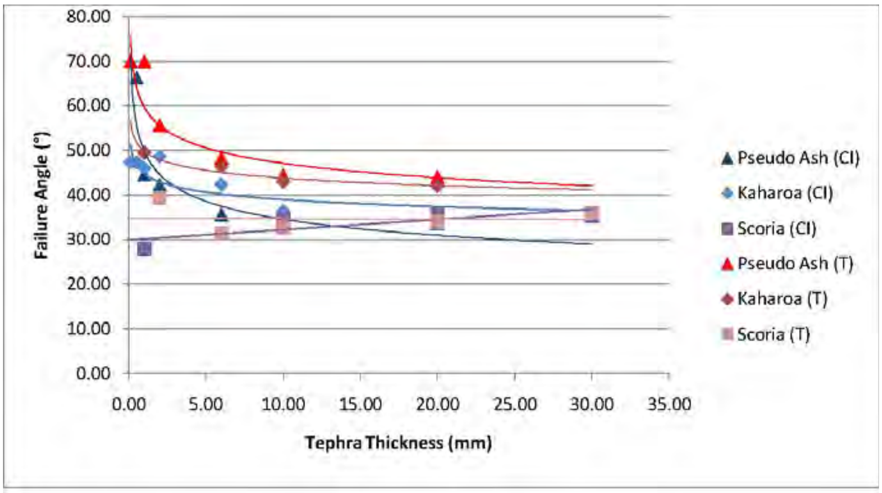

Fig. 2. Scatter plot showing the relationship between the angle of complete sample failure and tephra accumulation thickness in both the corrugated iron (CI) and tile (T) experiments (Note: For tephra thicknesses < 1mm angles are indicative only).

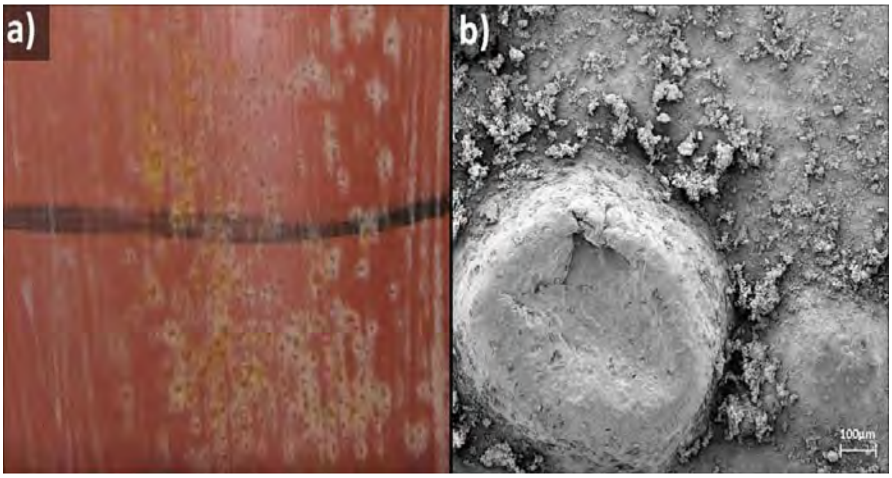

Fig. 3. a) Photograph of part of the 2cm strong pseudo-ash sample showing the development of nodules after 25 days (image width = 7cm. **b)** A x500 magnification SEM image of the same sample showing a collapsed 'blister' surrounded by embedded very fine ash (<10µ). Scale bar = 100µ.

3.1 BRANZ Testing and Preliminary Results

Testing of roofing samples at the BRANZ facilities, Moonshine Road, Porirua, commenced in November 2010. A programme was set up after discussion with Dr Zhengwei Li (BRANZ) in which four different types of roofing material (galvanized iron, Coloursteel©, zinc and old corrugated iron) were coated with ~5 mm of pseudo-ash (Fig. 5), that had been dosed with either Crater Lake, Ruapehu or White Island crater lake water, and subjected to alternating cycles of mist and drying in a Q-fog chamber for periods of 1 day, 1 week or 1 month (Fig 6). The operating conditions were as follows:

First Stage: Water spraying, 6hrs, 25^{o}C, 0.3-0.4mm/hr (Deionised water, <10 µs/cm)
Second Stage: Air drying, 18hrs, 35^{o}C
Total time: 1 day, 1 week and 1 month *Note*: The position and orientation of the sample trays in the chamber were randomly changed every week.

Each sample tray had samples of one water type (to avoid cross-contamination) x two different roofing types x three duplicate samples (to test variability), giving a total of six samples. Four trays were used for each time period (Fig. 7). The total number of samples included in the experiment was 72.

After removal from the Q fog chamber, excess ash was carefully knocked off by tapping the side with a wooden spatula. Samples were transferred from BRANZ to the University of Canterbury in specially designed boxes (Fig. 8) to ensure that no contamination occurred between samples.

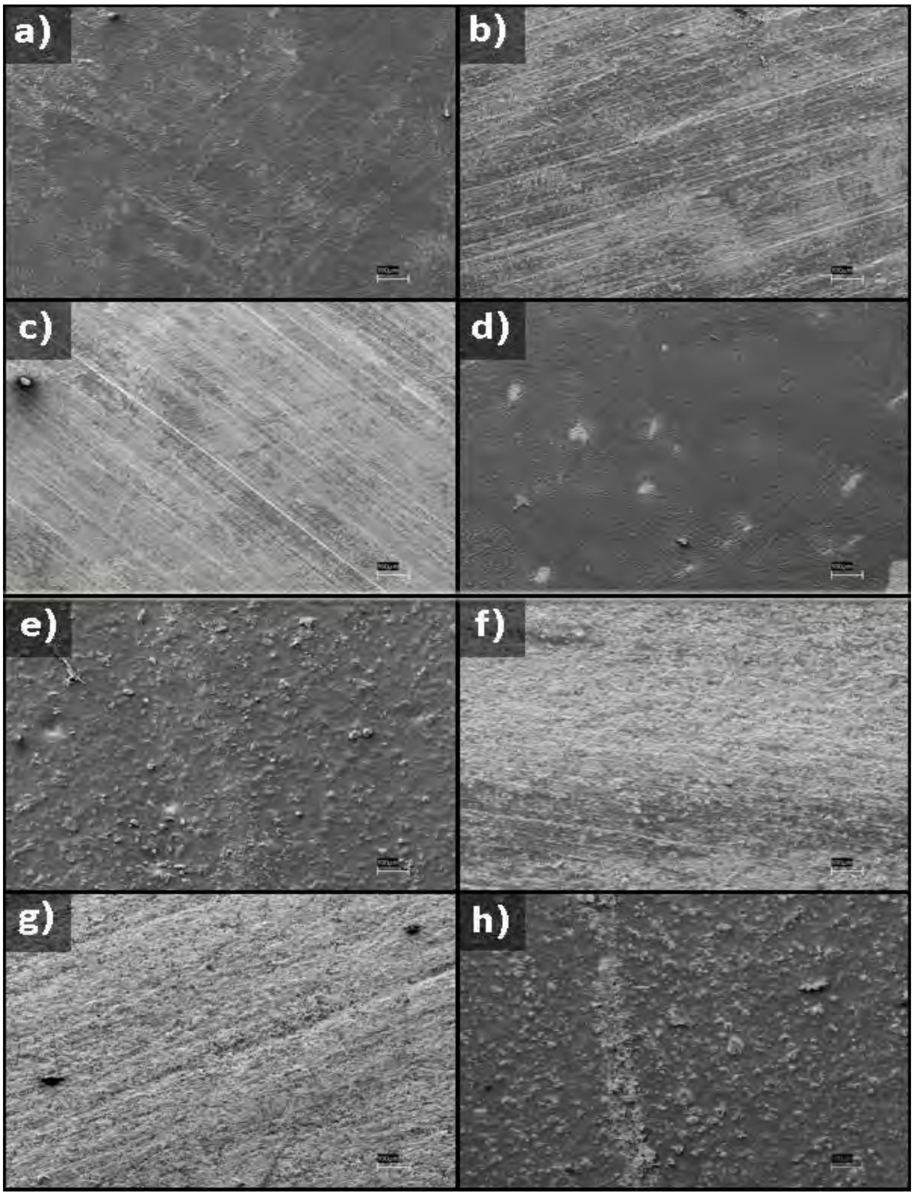

Fig. 4. SEM images all at x500 magnification (all scale bars = 100µ). **a)** Non-painted control sample which has not undergone any testing; **b)** non-painted 1 ash removal sample; **c)** non-painted multiple ash removal sample; **d)** non-painted multiple water cleaned sample; **e)** painted control sample which has not undergone any testing; **f)** painted 1 ash removal sample; **g)** painted multiple ash removal sample; **h)** painted multiple water cleaned sample (From Broom, 2010).

Fig. 5: Allan Scott using a sieve to distribute dosed pseudo-ash over samples of roofing material for one-month trial in environmental test chamber (Photo: C. Stewart)

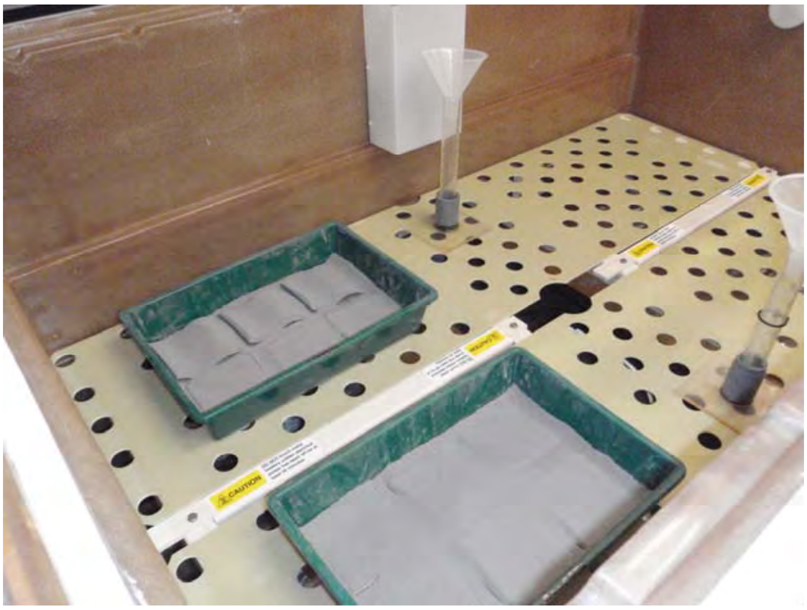

Fig. 6: BRANZ environmental test chamber that can simulate accelerated weathering under controlled conditions using various hot/cold/wet/dry cycles (Photo: C. Stewart)

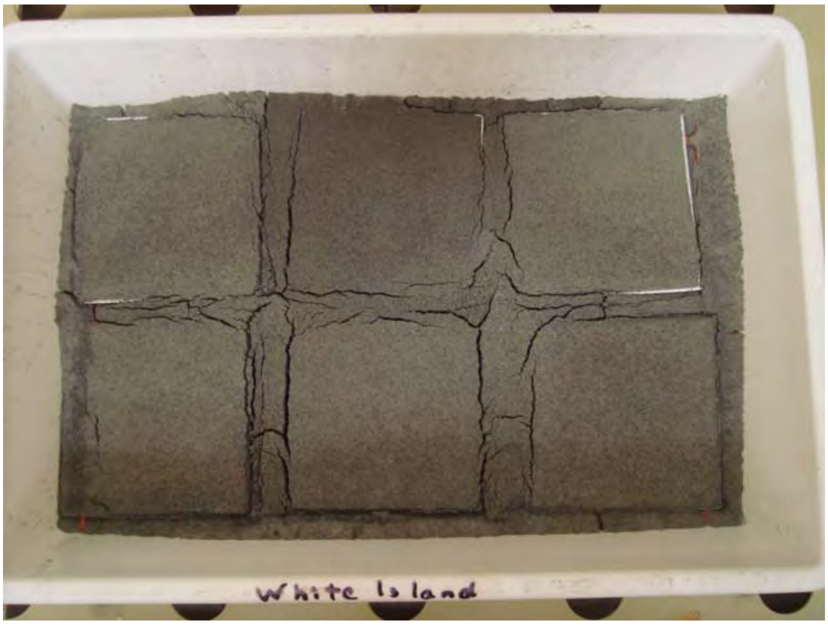

Fig. 7: Roofing samples coated with pseudo ash dosed with White Island crater lake water 9 days after commencing testing within the test chamber (Photo: Z. Li)

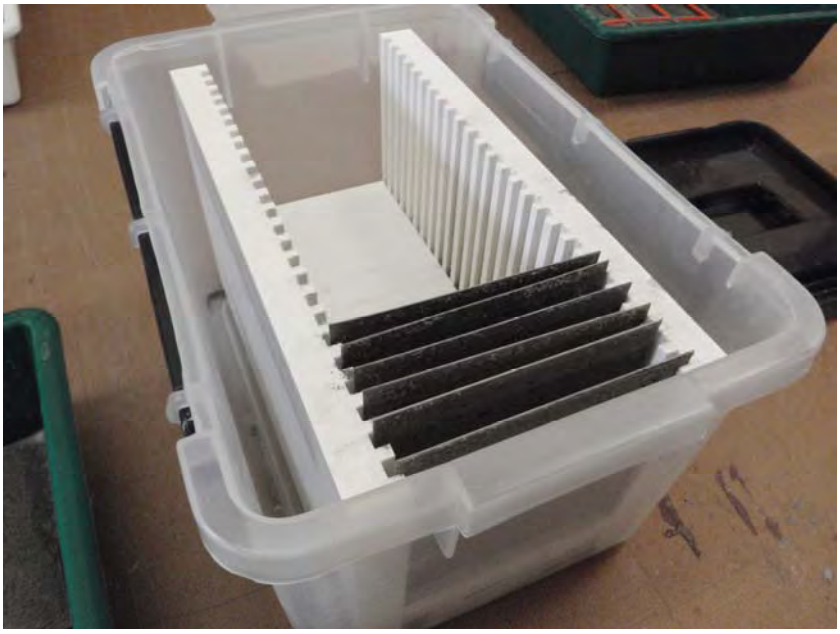

Fig. 8: Box to transport samples from BRANZ to University of Canterbury after testing to avoid contamination (Photo: G.Wilson)

A third of the exposed metal samples (24 samples) were chosen for microanalytical analyses. This included one sample of each metal type, each dosing duration, and each ash type. Eight 10 mm slugs were cut from each sample using a hand operated press, with care taken not to damage the exposed surface. Half of the slugs were washed with a soft bristle brush in deionised water and dried in a $50^{o}C$ oven overnight, to remove ash and expose the metal surface for analysis. Of the 192 slugs that were cut, 14 were chosen at random for SEM, and 80 for XPS. Each slug was labelled with a numerical code and placed inside a corresponding sample bag, which were enclosed in a plastic container for transport to Auckland for analysis.

The samples were first evaluated using an FEI Quanta 200F scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDS) capabilities at the University of Auckland. They were then analysed by X-ray photoelectron spectroscopy (XPS). The data were collected on a Kratos Axis UltraDLD equipped with a hemispherical electron energy analyser. Spectra were excited using monochromatic Al Kα X-rays (1486.69 eV) with the X-ray source operating at 150 W. This instrument illuminates a large area on the surface and then, using hybrid magnetic and electrostatic lenses, collects photoelectrons from a desired location on the surface. In this case the analysis area was a 300 by 700 micron spot (=hybrid/slot). The measurements were carried out in normal emission geometry. A charge neutralisation system was used to alleviate sample charge buildup, resulting in a shift of approximately 3eV to lower binding energy. Survey scans were collected with a 160 eV pass energy, whilst core level scans were collected with a pass energy of 20 eV. The analysis chamber was at pressures in the 10-9 torr range throughout the data collection. Data analysis was performed using CasaXPS (www.casaXPS.com). Shirley backgrounds were used in the peak fitting. Quantification of survey scans utilised relative sensitivity factors supplied with the instrument. Core level data were fitted using Gaussian-Lorentzian peaks (30% Lorentzian). The binding energy scale was corrected for the neutraliser shift by using the C 1s signal from saturated hydrocarbon at 285.0 eV as an internal standard.

Based on visual, chemical and surface analyses, no corrosion was observed in any of the test roofing metal samples under any of the testing regimes. A number of possible explanations can be put forward:

Insufficient exposure time

It is possible that the time frame of one month used in this study was too short for corrosion to be initiated. Other studies conducted at BRANZ, using identical operating conditions and testing the development of rust on galvanised nails in treated and treated timbers, observed corrosion of zinc coatings after one month of exposure (Z. Li, BRANZ, pers. comm.). Thus, the atmospheric conditions within the test chamber are capable of producing corrosion within this time frame. However, the relative susceptibility to corrosion of the different materials (nails versus roofing metal) may not be the same.

Pseudo ash samples not corrosive

Fresh volcanic ash has the potential to be corrosive. Its surface coating contains salts and sometimes also acidic gas condensates, which are rapidly released on contact with water. Furthermore, corrosion has been attributed to volcanic ash in a small number of field studies (Becker et al., 2001; Johnston, 1997; Blong, 2003; Matsumoto et al, 1988; Deguchi, 1990). However, the kinetics of pH change and salinity may vary between natural and synthetic ash.

Insufficient contact time between ash leachate and roofing material
The environmental conditions used in this trial consisted of a six-hour mist cycle, with 0.3-0.4 mm/hour spray of deionised water at 25°C, followed by an 18-hour drying cycle at 35°C, repeated daily. This is equivalent to approximately 2 mm/day rainfall, which is similar to Canterbury's mean rainfall of 50 mm/month. An inspection of Figure 7 suggests little removal of ash by washing away, even after nine days' exposure. Thus there may have been an insufficient rate of watering, relative to the thickness of ash used in the trial (~ 5 mm), that may in turn have limited the formation of a percolating leachate solution.

In previous studies, Dr Li (BRANZ) had tested a lot of mild steel and hot dip galvanised nails embedded into untreated and preservation treated timbers. The operating conditions used in those studies were exactly the same as those used in the test for artificial volcanic ash. The top surface of the head of these nails was exposed to the atmosphere in the fog chamber, so material deterioration on the head surface was largely controlled by the corrosive atmosphere created by water spraying and air drying, although leachants from the timber would contribute in part. This latter observation was supported by the fact that the shaft area was also corroded.

4.0. GUTTERING

The Volcanic Ash Testing (VAT) Facility (Fig. 9), housed in the basement of the von Haast building at the University of Canterbury, is part of a multidisciplinary, multi-organization 'VAT Lab' collaboration, which also includes facilities at Massey University, the University of Auckland, US Geological Survey, University College London, as well as the College of Engineering at the University of Canterbury. At this facility, an adjustable frame, capable of holding roofing iron at different angles and different types of guttering, has been constructed to assess the effects of different loadings of volcanic ash. The frame is able to be tilted at 15^o, 25^o, 35^o and 45^o, and ash is dispensed from an overlying sieve, which dispenses the ash evenly over the surface in a rocking motion (Fig. 9). Because of time constraints due to the successive earthquakes only preliminary tests using this facility were able to be achieved. Only dry ash and only three tilt angles (15^o, 25^o and 45^o) were used at this stage. Also only one type of gutter (Marley plastic) was used. It is anticipated further tests will be carried out later in the year, prior to submitting a paper on guttering (see section 6.2).

Fig. 9: Equipment for roofing and guttering experiments in the VAT facility, University of Canterbury (Photo: G.Wilson)

Observations were made once 1mm, 5mm, 10mm and ~25mm of ash had accumulated on the surface of the roofing iron and in the gutter, with thicknesses on the roofing ridges and troughs, and in the gutter, recorded. How the ash cumulated was also observed and recorded.

4.1. Observations from Guttering Tests

At low angles (15^o), ash covered both ridges and troughs of the roof, generally with nearly double the thickness of ash in the troughs as on the ridges after ~10mm of ash was deposited in the troughs. Thickness in the gutter was relatively low, with the beginnings of piles forming downslope of the troughs (Fig. 10). Small piles were also deposited across the gutter adjacent to each bracket, and each bracket had a small amount of ash on top. Roof nails became covered by thin ash once ~5mm had accumulated on the ridges.

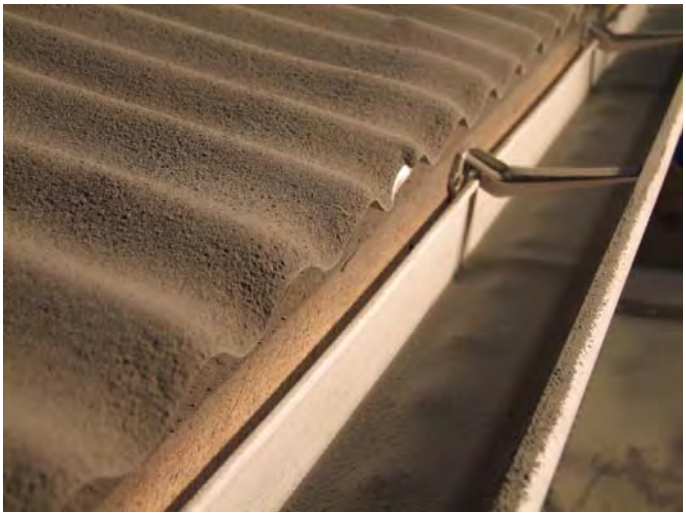

Fig. 10. Deposition of ash on roof with 15° angle. The roof surface was mantled with ash, with some infilling the spouting at end of testing (Photo; S. Hampton).

At intermediate angles (25°), the ash starts to move downslope to form an incipient wedge, with more accumulating in the gutter. Ridge: crest ratios were similar to that at 15°, but eventually troughs completely filled (height difference between ridge and trough = 16mm). Piles adjacent to troughs became significant, 2-3 times the height of the surrounding ash (Fig. 11). Ash thicknesses were higher on the outside (front) of the gutter, but some ash stuck on to the inside of the gutter and got into the roof cavity.

Fig. 11: Deposition of ash on a roof tilted at 25°. There is asymmetric ash accumulation in guttering, with piles accumulating beneath troughs. Ash distribution is grain size controlled, with coarse ash depositing on outer edge of spouting. Fine ash accumulates within the gutter until buoyancy caused the ash to bypass the spouting. In distance, ash accumulation is prominent on guttering bracket, limiting ash accumulation beneath.

Fig. 12: Deposition of ash on a roof tilted at 45°. Talus-like aprons of ash accumulation once spouting is infilled. Position of ash within roof troughs remains static between 200 – 250mm from front edge of roof, with excess ash material shed over front lip of guttering.

At high angles (45°), the ash moved rapidly down the roof troughs and straight into the gutter. This created large piles in the gutter, which grew rapidly until they reached the height of the outer rim of the gutter. At this point fine ash cascaded over the front of the gutter (Fig. 12). Once the gutter became full, ash backed up in the troughs to a distance of 200-250mm, and the fronts of these 'backfills' became unstable and flowed over the front of the gutter to form plumes of fine ash. Once the gutters became full, the central part sagged ~10mm compared to the ends. After about 10mm had collected in the troughs, a small amount of ash accumulated on the ridges, but never more than ~1mm thick. Roof nails trapped the ash during its downwards migration, creating a triangular wedge ~15 mm long and ~4mm high upslope of the nails.

4.2. Future work needed on guttering

1. Investigate angle at which roof cumulation ceases and all ash goes into the gutter
2. See differences between types of guttering (plastic and metal)
3. Repeat test with wet ash

5.0. CONCLUSIONS AND RECOMMENDATIONS

The initial time frame of the project was 1 year, extended to 19 months because of the multiple earthquakes badly affecting Christchurch from September 2010 to June 2011. Results have shown the value of the type of experimentation undertaken, but clearly more tests need to be done.

Production of the pseudo-ash has been invaluable both in this study and other studies related to the effects of ash on infrastructure. Once dosed the ash has proved to have similar properties to fresh ash and is therefore a useful proxy. Considerable interest has been shown in this product from overseas.

The corrosion testing has raised many issues, and will provide the focus for continuing research for some time to come. In hindsight the operating conditions of the fog chamber for the test might not be have been appropriate. For example, 6hrs of mist might not have been long enough. We had expected that any aggressive media generated from the ash would have produced some marks on the underlying steel samples, but this was not the case. Certainly, a longer time period of surface coverage with wet ash (but without visible liquid water) might be more applicable. There could also have been drying at a lower temperature. These options will need to be investigated in future tests.

Key conclusions relating to the corrosion testing include:

1) Our results suggest that if ash is removed within a month of an ashfall event problems are unlikely to arise due to corrosion, but further studies are needed to consider effects of variable rainfall, and longer term effects.

2) As corrosion of roofing materials appears to be a long-term reaction/interaction (>3 months), current policies that require corrosion/damage to be reported to insurance providers less than 3 months after a volcanic eruption is not realistic.

6.0. CURRENT AND FUTURE PROGRAMME OUTCOMES

6.1. Student Projects Related to this Work

Broom, S.J. 2010. Characterisation of “Pseudo-ash” for quantitative testing of critical infrastructure components with a focus on roofing fragility. Unpublished BSc (Hons) project, Department of Geological Sciences, University of Canterbury.

Peters, M. 2011. Environmental implications of volcanic ash in freshwater environments. MSc in progress. Department of Geological Sciences, University of Canterbury.

Wilson, G. 2011. Vulnerability of Laptop Computers and Materials used to Protect Monitoring Equipment from Volcanic Ash and gas. MSc in progress. Department of Geological Sciences, University of Canterbury.

6.2. Manuscripts in Preparation

Oze, C., Cole, J., Stewart, C., Wilson, T., Scott, A., Li, Z., Wilson, G., Broom, S., Gaw, S., Doyle, C., *In prep*. Corrosion of metal roof materials related to volcanic ash interactions. *Corrosion Science.*

Wilson, T., Cole, J., Oze, C., Stewart, C., Scott, A., Wilson, G., Hampton, S. *In prep*. Implications for roofing materials after a volcanic eruption and current policies. *Landscape and Urban Planning*.

Hampton, S., Wilson, G., Cole, J., Wilson, T., Broom, S. *In prep.* Effects of volcanic ash on guttering. *Natural Hazards.*

Wilson, G., Wardmann, J., Broom, S., Wilson, T., Cole, J. *In prep.* A pseudo-ash proxy for fresh volcanic ash. *Applied Volcanology*

6.3. Reports

1st progress report to EQC: 12 June, 2010
2nd progress report to EQC: 31 October 2010
3rd progress report to EQC: 15 April 2011

6.4. Talks

Broom, S. 2010. Characterisation of "Pseudo-ash" for Quantitative Testing of Critical Infrastructure Components with a focus on Roofing Fragility. BSc (Hons)/MSc Symposium, University of Canterbury, May 27, 2010.

Stewart, C. 2011. Volcanic ash impacts on infrastructure: information for the workshop on ash leachate methodologies. Presentation made to Volcanic Ash Leachate Workshop, 14-15 June 2011, Durham University, U.K.

Wilson, T.M., et al. 2010 – An update from VAT Lab. National Engineering Lifeline Committee workshop, October 2010, Wellington.

Wilson, T.M., et al. 2010 – Impact of Volcanic Hazards to Critical Infrastructure. Taranaki Volcanic Impacts Study Group, October 2010, New Plymouth.

Wilson, G. 2011. Ash, gas and Computers: resiliency of volcanic surveillance electronics to volcanic hazards. MSc Symposium, University of Canterbury, May 26, 2011.

Wilson, T.M., et al. 2011. Volcanic Impact and Risk Assessment. Volcanic Risk in Saudi Arabia (VORiSA), May 2011, Science Seminar Day, Jeddah, Saudi Arabia.

7.0 ACKNOWLEDGEMENTS

The project team would like to thank EQC and the Science-to-Practice Programme for the award of $30,000 to undertake the project described in this final report. We would also like to thank Dr Hugh Cowan (Research Manager for the duration of the project) and Priscilla Cheung (Senior Advisor, Research) for all their help during the course of the project.

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