Low carbon rules: an interdisciplinary approach to writing standards for earth and straw construction in Aotearoa New Zealand.

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Abstract: In order to realise a future where a variety of low carbon building options is readily available, their consenting needs to be supported by relevant standards to assist their path through the regulatory process. The recently published suite of revised and expanded Earth Building Standards, NZS 4297-99: 2020, does just that. The product of a collaboration between a team of architects, engineers, builders, consenting officers, and academics, the standards provide normative and informative guidance for using a wide range of earth and straw building techniques. A key aspect of the interdisciplinary collaboration involved testing of both materials and testing methods included in the revised standards. These standards enable a 'low-tech' approach, making self-help methods available to owner builders, including simplified material testing with low cost equipment. This paper reviews the standards development including testing of materials, verification of low-tech material testing. Given the challenges associated with the changing roles of government and other stakeholders, the problems that arise when the maintenance and development of building standards relies heavily on industry funding, an international collaboration is proposed with lobbying for national government support for on-going development.

Keywords: Earth construction; straw bale construction; building standards; low carbon.

1. Introduction

The widely used term 'low carbon' in relation to building materials is somewhat misleading; it does not refer to the carbon content of the materials being used, but to the CO_2 emissions generated during the extraction, manufacturing and transportation of both the raw materials and the final product to the construction site. Unfired adobe bricks, for instance, have embodied CO_2 emissions of -20Kg/m^3, while fired ceramic bricks have +375Kg/m^3 (Alcorn, 2010). Low carbon materials have an important part to play in the construction industry if greenhouse gas (GHG) emissions are to be reduced to the levels

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recommended by the Intergovernmental Panel on Climate Change (IPCC) and, in the case of Aotearoa, the targets set by the New Zealand Government in 2019 (New Zealand Government, 2019).

As well as adobe bricks, other unfired and unstabilised earthen materials such as rammed earth, cob, and pressed earth bricks are also low carbon, and since 1998 their use has been guided by a suite of New Zealand Earth Building Standards (NZS, 1998). These standards have been cited by the Ministry of Business Innovation and Employment (MBIE) as a means of compliance with the New Zealand Building Code (NZBC), but, after 22 years of existence, they required revision and amendment to bring them into line with changes to other parts of the NZBC, and to reflect recent practical and research findings. The reviewed, revised and expanded Earth Building Standards were published in February 2020 (NZS 2020).

Since 1998, a modest number of earth buildings have been constructed annually, their design, consenting and construction were guided by the standards. During that time skills and expertise have developed, and major earthquakes have provided real-life testing of the structural performance of earthen buildings constructed before and after the 1998 standards came into being (Morris et al 2010, 2011). The government agencies responsible for the administration and development of the regulatory framework have also changed markedly, which has had a significant effect on the process of reviewing and updating the standards. At one point, there was a very real danger that the review would be stopped in its tracks, with the result that building with earth could become extremely difficult to achieve in Aotearoa. At the time of writing, although the revised standards have been published, they have yet to be cited by MBIE as a means of compliance for clauses B, E and H of the NZBC (see detail later). Once this has been done, the necessary rules for the use of a wider range of low carbon building materials will be in place, and they can be further explored to encourage wider uptake.

This paper discusses the standards development including testing of materials, verification of low- tech material testing, challenges associated with the changing roles of government and other stakeholders, and discusses the problems to be overcome when the maintenance and development of building standards relies heavily on industry funding.

2. Background

2.1 Brief history of earth building in Aotearoa New Zealand

The history of earth as a building material in Aotearoa is as long as its human occupation. When Māori arrived from the warmer northern Pacific 700 years ago (King, 2003), they did not use earth as a structural building component, but they did use it for floors, for insulation by mounding against timber framed walls, and as a binder for fibrous wall materials (Phillips, 1952, p.15). In the nineteenth century, settlers arriving from Europe, Australia and China brought earthen wall building techniques with them, including cob, sod, rammed earth, and adobe brick. These were easily translated to the new environment, and earth buildings became an integral part of New Zealand's vernacular architecture. However, as sawn timber became readily available in most regions towards the end of the nineteenth century, the use of earth declined; during the first half of the twentieth century it became non-existent in most parts of the country (Hall, 2019).

After the Second World War building materials, including timber, were in short supply, and a new interest in earth emerged. Both the government and private individuals looked to rammed earth, soil cement and sun-dried brick for constructing houses (Hall, 2019). Clusters of earth houses appeared in Otago, Canterbury, Nelson, and Wellington. However, Government withdrew support in 1959, choosing to focus solely on timber construction, and building with earth slowed down (Hall, 2019).

It was when the global counterculture movement reached New Zealand in the 1970s that interest in earth building grew. During the 1970s and 1980s a number of adobe brick, rammed earth and pressed brick houses were built. Hands-on skills and design expertise grew and in 1988 the Earth Building Association of New Zealand (EBANZ) was established. The 1990s represented a golden era of building with earth, particularly amongst owner-builders (Hall, 2012). Earth bricks were being manufactured commercially, and in 1998 the New Zealand Earth Building Standards were published.

While buildings in earth are only one and three percent of total annual residential building consents, growth has continued at a steady rate into the 21st century (Hall, 2012). As well as adobe, rammed earth and pressed earth brick, other methods such as cob, in-situ adobe, light earth, straw clay, and lower density adobe have been implemented. In February 2020 the revised and updated Earth Building Standards were published, this time including informative appendices on earth floors, straw bale construction, light earth construction, and internal adobe brick veneer.

2.2 Brief history of earth building regulations in Aotearoa New Zealand to 1840-2010

Prior to 1992, when the Building Act 1991 and associated NZBC came into being, building regulations were set and controlled by multiple agencies, as outlined by Nigel Isaacs in *Early Building Legislation* (Isaacs, 2011). Early regulations were concerned particularly with fire, structure and sanitation; earth construction was neither specifically covered nor excluded. When the performance based NZBC came into force in 1992 it had a much broader scope dictated by the Building Act, which required it "to address the wellbeing, sustainable development and safety and health of building users" (Buckett, 2014). There are two ways to comply with the NZBC: using Acceptable Solutions or Alternative Solutions. The former is by far the easiest path to gaining a building consent, and complying with NZ standards that are cited as a means of compliance with particular clauses of the NZBC provides a way of doing this.

When EBANZ was formed in 1988, its founding members were well aware of the proposed overhaul of the New Zealand building regulatory system. Their aim was to generate design guidelines for earth building systems that specifically addressed the New Zealand environment; systems that could withstand earthquakes, wind-driven rain storms, and a climate ranging from sub-tropical to dry temperate. They also ensured that building guidelines produced in 1989 and 1991 would assist owner- builders as well as qualified builders (Drupsteen, 1989 Hodder, 1991).

In 1993 Standards New Zealand (SNZ) were approached by the Standards Association of Australia (SAA) about writing a joint standard for earth building. A steering group met to work out parameters for the standards and initiate writing of the first drafts. The full Joint Technical Committee (JTC) comprised academics, engineers, architects, builders, building officials, and regulators from both countries. At that time there were no substantive international Earth Building Standards; consequently, work had to start from scratch. In order to fit both the accepted building standards framework and the innovative approaches demanded by the new performance based NZBC and proposed Building Code of Australia (BCA), it was decided that three complementary standards were required: an engineering design standard, a deemed-to-comply design standard, and a materials and construction standard to support the other two. The JTC members worked productively together to draft, review, revise and edit the standards but difficulties arose; most significantly the fact that the proposed BCA covering the whole of Australia had still not come into being. The committee was de-jointed in February 1997 and the New Zealand-only committee went on to complete the suite of New Zealand Earth Building Standards, which were eventually published in October 1998 (SNZ, 1998).

In 1999 NZS 4297 and 4299 were cited as Acceptable Solutions and Verification Methods in the New Zealand Building Code (NZBC) for clauses B1 (Structure), B2 (Durability), E2 (External Moisture) and H1 (Energy Efficiency). The standards have therefore provided building officials, architects, engineers, builders, and owner-builders with a clear and confident path to assess, design, and build earthen walled houses using adobe, rammed earth, and pressed earth brick, with some additional advice for poured earth, cob, earth floors, and earth plasters. As changes to the NZBC occurred, corresponding amendments were made to accommodate the Earth Building Standards. These included changes to H1 in 2007 and E2 in 2008.

2.3 Brief history of testing to support standards development 1990-2000

Experimental work and testing of earthen materials and building techniques is an important aspect of any standards development. The important post-war work carried out by engineering lecturer P.J. Alley in Aotearoa and George Middleton at the New South Wales Research Station in Australia continued in both countries before and after the 1998 standards were published. In Australia, informal experimental work on rammed earth had been undertaken by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in support of Middleton's Bulletin 5 (Middleton, 1987) and research on soil cement materials was also undertaken at the University of Technology Sydney. In New Zealand, a number of informal material trials were undertaken during the 1990s in preparation for proposed guidelines or standards and a modest test programme was undertaken at the University of Auckland, initially investigating in-plane performance of small and large panels of reinforced adobe and rammed earth walls for seismic resistance. Other tests were also undertaken, including stabilised rammed earth compression and tension, validation of durability tests, bond strength of adobe and pressed earth, and an evaluation of various reinforcement materials (Gurumo, 1992, Morris, 1993, Walker and Morris, 1998).

3. Review of Earth Building Standards

3.1 Setting up the review 2009-2015

By 2009, members of EBANZ had started planning a revision to the standards. Standards are generally reviewed every five to ten years, and although no earth building built in compliance with the 1998 standards had failed, new research and work with a wider range of earthen materials, including better insulating low density earth, had taken place. Other standards and NZBC clauses referenced in the Earth Building Standards had also changed. In 2010 EBANZ began to lobby SNZ about the need to keep the three standards up to date, as well as incorporating amendments made to clauses E2 and H1 of the NZBC pertaining to earth construction back into the standards. In 2011, EBANZ initiated an unofficial revision of the standards with many of the original 1998 standards committee taking part on a voluntary basis. The scope of the standards was widened to include research findings, as well as accommodating a wider range of earthen-based materials.

The Canterbury and Kaikoura earthquakes occurred just before and during the review process, providing real-life testing of the performance of earth buildings built before and after the 1998 standards. EBANZ funded reconnaissance trips by four committee members after the quakes. Their findings, which informed changes and improvements to the revised standards, showed that earth buildings built according to the 1998 standards performed very well, even those very close to the epicentres (Morris et al, 2010, 2011).

In 2013, when the revision drafts were nearing completion, EBANZ approached SNZ to set up an official committee to complete a formal review. At that time SNZ was undergoing a restructuring process, and the outgoing SNZ leaders declined to re-appoint a Technical Committee to adopt and finalise the EBANZ drafts into standards. Under the direction of EBANZ, the voluntary group continued to revise the drafts, which were largely completed by 2015.

3.2 Standards New Zealand (SNZ) and the review 2015-2020

The restructuring process resulted in SNZ becoming a stand-alone business unit within MBIE, with oversight from MBIE's Building Systems Performance unit (BSP), whose role is to oversee building regulations. The BSP has the ultimate say in which building standards receive support and funding for revision. After lobbying by SNZ and EBANZ the three Earth Building Standards were included as part of the upcoming work programme for 2016.

In late 2016, under the auspices of SNZ, the Earth Building Standards Development Committee was formed to take the EBANZ draft revisions through the formal standards process. Under the auspices of SNZ, new committee members were appointed to widen representation beyond SNZ, MBIE, and EBANZ. Representatives were appointed from the New Zealand Institute of Architects (NZIA), Engineering New Zealand (ENZ), Structural Engineering Society (SESOC), Building Officials Institute of New Zealand (BOINZ), Building Consent Authorities (BCA), Universities of New Zealand, Unitec Institute of Technology (UNITEC), New Zealand Certified Builders (NZCB), and the National Association of Women in Construction (NAWIC).

Before the committee was finalised, SNZ took the proposal to the Standards Approval Board for approval. They suggested that the scope of the standards be broadened to include, not only the new low density earthen materials proposed, but also other techniques such as straw bale, and a LEM (Light earth material) section. Draft appendices were quickly assembled and included within the overall drafts EBANZ handed over to SNZ for processing.

Shortly before the inaugural committee meeting in 2017, BSP suspended funding for twelve months. After intense lobbying, the meeting went ahead and the drafts, including new sections on veneer construction, low density earthen materials, straw bale and LEM, were refined with specific tasks assigned to committee members. Drafting and editorial work continued on a voluntary basis for the ensuing twelve months by which time it was made clear that funding through BSP would not be reinstated. In order to keep the project alive, a pilot partnership agreement was negotiated between EBANZ and SNZ, whereby EBANZ would not only provide the administration, but also funding for the necessary SNZ formal functions. EBANZ member Ian Brewer agreed to adopt the role of Development Lead for the standards review process, a role formerly taken by SNZ, and BSP withdrew from the Committee.

Development work continued on the three standards and in July 2019 drafts were released for public comment. The committee deliberated over the more than 400 public comments received, and finalised the content. In December 2019, the Standards Approval Board approved the standards for publication, and in February 2020 the standards were published:

- NZS 4297:2020 *Engineering design of earth buildings*,
- NZS 4298:2020 *Materials and construction for earth buildings*, and
- NZS 4299:2020 *Earth buildings not requiring specific engineering design*.

The revised standards include sections on dense earthen materials such as mud brick, cob, rammed earth and pressed earth brick in the 1400-2200 kg/m³ range, sections on lower density earthen materials such as mud brick and cob 800-1400 kg m³, internal mud brick veneers, earth floors, and earth plasters. Informative appendices are also included on LEM 200-1200 kg/m³ and straw bale over 90kg/m³ in density. For the first time, a range of low carbon materials with density between 90 and 2200 kg/m³ are combined into one set of comprehensive design documents.

3.3 Testing 2000-2019

Testing continued following the publication of the 1998 standards, and leading up to the 2020 standards. Some tests were undertaken to build confidence in the structural capabilities of materials and other tests were undertaken to investigate the performance of new materials and methods, which have subsequently been included in the 2020 standards. Some, but by no means all, of these tests are discussed below.

3.3.1. Internal high density adobe veneer walls

Increased use of high density internal adobe veneers, to provide thermal mass, led to a testing program to validate their use. Typically, 140mm veneer bricks are secured with brick ties fixed to a timber frame and positively screw-fixed to the brick. The tests were to confirm seismic resilience and ensure minimal risk of out-of-plane wall collapse into rooms inside the house.

Figure 2: Adobe veneer wall panel 4m x 3m with lintel, a) tilt test at about 45 degrees, b) highlighted crack pattern following all tests. Photos: Hugh Morris

A novel test approach was taken. In lieu of constructing and then transporting a test wall to a shake table in a distant laboratory, the testing was carried out in a Nelson-based adobe manufacturer's yard. A hinged foundation was constructed on top of a piled foundation and the wall panel was built on top. An initial 1.2m wide x 1.8m high panel performed very well when the wall was tilted at increasing angles backwards and forwards multiple times. The final quasi-static test was near horizontal with the veneer towards the ground, giving approximating 1g equivalent seismic acceleration. A 1.2m x 2.4m wall panel test was also very satisfactory, and was followed by the most critical case, which was a 4.0m x 3.0m wall panel with 1.2m of wall height above a doorway lintel, as shown in Figures 2a and 2b. The side wall panels were of reduced height to maximise the height of wall above the lintel, similar to a higher wall overall (Morris et al, 2017). The quasi-static test of tilting the lintel wall of adobe backwards and forwards was expected to cause moderate damage or collapse, but again performed very well, with cracks of minor structural significance in the mortar joints. The excavator then lifted the wall and dropped the boom, in order to increase the loading and simulate dynamic effects, reaching 2.6g. The wall damage after these tests is marked to highlight the damage pattern, this is satisfactory and would be repairable post-earthquake.

3.3.2. Low density adobe walls

Figure 3: a) Lightweight adobe 230mm thick out-of-plane tilt test, b) Bond wrench test measuring mortar adhesion. Photos: Hugh Morris

In order to improve the thermal performance of earthen walls, lower density adobe bricks for full thickness house walls have been developed. The proposed seismic design system was also tested at the Nelson brickyard and in the University of Auckland engineering laboratories. Out-of-plane tilt tests and in-plane wall tests were undertaken. The out-of-plane tests are shown below.

The same rig was used to undertake low density wall tests on a 1.2m x 2.4m and a 1.2m x 3m high panel. These full thickness walls were reinforced to the proposed requirements of the 2020 standards: deformed threaded “reidbar” vertical mild steel with hand-tightened post-tensioning and horizontal polypropylene geogrid. As shown in figure 3a, the wall was tilted backwards and forwards in a similar manner, but again had only minor cracks, with no bricks falling out. The wall was then tilted down to near horizontal and loaded with sandbags, equivalent in additional mass to the original wall, making an equivalent seismic load of 2g. The cracks visible in the figure show the damage after this additional loading, and give confidence for life safety (Shi, 2017).

3.3.3. Density, flexural and compressive strength validation tests

The mix and shape of low density adobe bricks was consistently achieved by one manufacturer but required validation to determine realistic mix proportions. Appropriate size measurement approaches to take account of the variation of typical shape for accurate density definition was also validated by an architect, engineer and builder on the standards committee as shown in figure 4a. The lever arm test rig for simplified testing was checked for the additional tensile strength of the more fibrous lightweight adobe as shown in figure 4b.

Figure 4. a) Low density adobe bricks b) Simple lever arm test setup using measured water for mass) c) detail of the load point after a flexural tension failure, Auckland 2019 Photos: Min Hall

4. Discussion and conclusion

This paper set out to discuss issues surrounding the regulation of low carbon building materials in Aotearoa New Zealand, using the recently completed review of the NZ Earth Building Standards as a case study. Aotearoa has a long history of building with unfired earth, and a current earth building fraternity with significant skills developed over the last fifty years. It also has a suite of Earth Building Standards, first published in 1998. Experts from backgrounds including architecture, engineering, building and consenting, supported by EBANZ, have collaborated in developing the recently updated and expanded 2020 NZS Earth Building Standards.

Any standards development work requires the input of a range of stakeholders as was the case in the Earth Building Standards committee. The viewpoints of each were essential in drafting the revised standards and ensuring that, as with the 1998 standards, the end result was a usable and useful document for all end-users, including owner-builders. For instance, the testing method described in NZS 4298 and shown in Figure 4 for tensile strength does not require a specialist laboratory; it can be carried out by anyone with the skills and equipment to set it up. Enabling owner-builders and minimizing material evaluation costs were key motivating factors for the committee members, who recognized that as well as offering a mitigating potential in terms of GHG emissions, low carbon materials are often also relatively low-tech, making them innately suitable for use by beginners. Empowering those who wish to be involved in the construction of their own houses has obvious value when addressing the current nationwide housing shortage.

Another key requirement for standards development is financial support. Over the past twenty years successive New Zealand governments have stepped away from active participation in rule-making affecting the construction industry, focusing instead on process and oversight. SNZ, once a stand-alone government agency has been trimmed down to a small team within MBIE, “the over-arching regulator of New Zealand’s building system” (MBIE, 2020). This has meant that the ability to keep the regulatory system up to date relies heavily on industry funding. Such a situation was not ideal even for large scale construction materials such as steel, concrete and timber, which have recently had some government relief and now seriously disadvantages most other low carbon materials. The struggle to complete the revision of the 1998 Earth Building Standards is a case in point. Timber, whose production and processing is big business in Aotearoa, is the only truly low carbon material that has serious industry backing. Timber research is funded by both government and industry at institutions such as Scion, BRANZ and universities, and designers, engineers, builders, and building consent officers are trained in timber construction as a matter of course. For the low carbon materials covered in the Earth Building Standards, however, it has been left up to individuals and organisations, like EBANZ, who have been at the forefront of developing sustainable building practices for decades, to take responsibility for ensuring that the standards are updated.

By the time SNZ became involved in the Earth Building Standards review in 2016, EBANZ had spent $42,000 on developing the review, and the expert volunteers had devoted thousands of unpaid hours. This required a major additional time commitment and perseverance especially from those taking the lead in what is already a complex process. Thousands more hours were spent over four years and, in the end, a crowdfunding campaign was necessary to raise the funds to complete the process.

It is clear that, at a time when there is an urgent need to reduce the impact of the built environment on climate change, but also an equally urgent need to meet housing demand, a change of attitude to regulating the construction industry is necessary. In the words of US building code writer David Eisenberg, “It is possible and reasonable to look for ways to discourage practices with the greatest large- scale impacts and encourage better practices that reduce them” (Eisenberg, 2016). Such a change requires government to take responsibility for the support and development of a range of building practices that employ low carbon materials and techniques. Twenty-five years ago, the 1998 Earth Building Standards were developed, with support that existed in the form of SNZ, who took the lead development role and covered the administrative, editorial and publication costs. This enabled the multi-disciplinary committee members to focus on the content. The incidence of building with unfired earth, straw bale and other low carbon materials, excluding timber, is not high in Aotearoa. However, if used at scale they have the potential to significantly reduce the carbon footprint of a ballooning built environment. But in order for these materials to be developed and used at the scale necessary to make a difference, there needs to be an internationally supported effort to lobby governments to provide support for research and experimentation, coupled with a commitment to a forward-looking regulatory environment that is not dependent on a very small (but growing) industry. Regulations need to be regularly updated and expanded to respond to innovations based on practical experience in low carbon materials and techniques are essential to harnessing their potential as low-cost, low-impact housing solutions.

The New Zealand example of continuing changes to the government agencies responsible for regulating construction has resulted in a reliance on industry to fund regulation development, leaving most low carbon materials out in the cold. Natural materials require minimal processing, cost either very little or nothing, are difficult to monetize, and thus of little commercial interest but regulations are needed to allow use of an even wider range of low carbon materials, at a time when the construction industry needs to significantly reduce GHG emissions. Perseverance has just got the NZ Standards over the line. We need to raise the profile, gain international support, and in parallel with others around the world, undertake coordinated local lobbying to achieve vital on-going government support.

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References

Alcorn, A. (2010) *Global sustainability and the New Zealand house,* PhD thesis, Architecture, Victoria University of Wellington, Wellington.

Buckett, N. (2014) A code to build by, *BUILD, Issue142, June/July 2014,* New Zealand.

Drupsteen, T. and North, G. (1989). *Guidelines to aspects of earth building in New Zealand.* Northland Craft Trust

Eisenberg, D.A. (2016) Transforming building regulatory systems to address climate change, *Building Research & Information, 44:5-6,* 468-473, DOI: 10.1080/09613218.2016.1126943

Gurumo, Shabani R, (1992). *Diagonal Compression Strength of Adobe Wall Panels*, Master of Engineering Project D Report, The University of Auckland, Auckland.

Hall, M. (2012) *Earth and straw bale: an investigation of their performance and potential as building materials in New Zealand*, M.Arch thesis, Architecture, Victoria University of Wellington, Wellington.

Hall, M. (2019) Back to earth: earth building in Aotearoa New Zealand 1945-65. In Andrew Leach and Lee Stickells (Ed.), *SAHANZ - Distance Looks Back*, Vol. 36. 205-216Hodder, G. (1991) *Non-specific design guidelines for earth buildings.* EBANZ, New Zealand

Isaacs, N. (2011) Early building legislation, *BUILD Issue 122 February/March 2011*, New Zealand.

King, M. (2003) *The Penguin History of New Zealand*, Auckland, Penguin

Middleton, G. (1987) Bulletin no 5 Earth-wall Construction. National Building Technology Centre, Commonwealth of Australia, Fourth edition

MBIE. (2020) https://www.building.govt.nz/about-building-performance/ (accessed 19 July,2020)

Morris H.W. (1993) The Strength of Engineered Earth Buildings, Proceedings, *IPENZ Annual Conference, Sustainable Development*, Hamilton, Pages 660-671

Morris, H.W. and Walker, R. (2000) 'Aseismic Design and Design and Construction of Earth Buildings in New Zealand', 12th World Conference on Earthquake Engineering, Auckland, 30 Jan-4 Feb 2000, Proceedings Paper number 2193.

Morris, H.W, Walker, R., & Drupsteen, T. (2010). Observations of the performance of earth buildings following the September 2010 Darfield earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, 43 (4), 393-403.

Morris, H. and Walker, R. (2011) Observations of the performance of earth buildings following the February 2011 Christchurch earthquake, *Bulletin New Zealand Society for Earthquake Engineering,* 44, p.358-367.

Morris, H. W., Brooking, J., & Walker, R. (2017). Out-of-plane adobe wall veneer performance from a novel quasi-static and dynamic tilt test. In Next Generation of Low Damage and Resilient Structures (pp. 8 pages). Wellington. Retrieved from http://db.nzsee.org.nz/2017/O6A.4_Morris.pdf

New Zealand Government. (2019) Climate Change Response (Zero Carbon) Amendment Act 2019, Wellington.

Phillipps, W.J. (1952) *Maori Houses and Food Stores,* Wellington, Government Printer.

Shi, Y., Xiao, M (2017) *Part 4 Student Project Reports*, University of Auckland: Department of Civil and Environmental Engineering, Auckland, unpublished.

Standards New Zealand. (1998) *NZS 4297: Engineering Design of Earth Buildings*, *NZS 4298: Materials and Workmanship for Earth Buildings*, *NZS 4299: Earth Buildings Not Requiring Specific Design*, Wellington, NZ, Standards New Zealand.

Standards New Zealand. (2020) *NZS 4297:2020 Engineering design of earth buildings, NZS 4298:2020 Materials and construction for earth buildings, NZS 4299:2020 Earth buildings not requiring specific engineering design.* Wellington, NZ, Standards New Zealand.

Walker, R. and Morris H.W. 1998 "Development of New Performance Based Standards for Earth Building". *Australasian Structural Engineering Conference, Proceedings* Vol 1 pp477 – 484.