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Durability of cement-stabilised rammed earth: A case study in Western Australia

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Abstract

Cement-stabilised rammed earth (CSRE) is a popular building material in Australia due to its natural aesthetic, good thermal properties and environmental appeal. However, little work has been done investigating the effect of long term exposure to environmental conditions on its durability. This paper presents a case study investigating the aged properties of material obtained from a 32-year old CSRE wall in Perth, WA. Core samples were obtained for unconfined compressive strength (UCS) testing and compared to results found for 28-day old specimens, manufactured using the same material and nominal compaction regime, to investigate changes in material strength over time. Sample wall sections were also obtained to determine material volume losses due to erosion. Results found for 32-year and 28-day old material are compared taking into account local climate conditions to comment on the suitability of current laboratory methods for predicting degradation of CSRE materials. Loss of strength due to exposure is found to be significant in this study. This result suggests that, when designing for the longevity of exposed CSRE materials, aging strength is an important factor that should not be neglected.

Keywords: Rammed earth, cement stabilised, durability, erosion, unconfined compressive strength

1. Introduction

Rammed earth (RE) is a construction technique which has gained popularity in Australia thanks to its sustainable and aesthetic qualities. Traditional RE structures are formed through the compaction of raw material (most commonly sandy-loam subsoil) into formwork, which is then removed to allow the material to dry, granting it its considerable strength [16, 19]. The technique is therefore highly environmentally friendly, as the use of natural materials means that little-to-no processing is required prior to construction. The use of thick (typically 300mm) walls also grants RE structures a high thermal mass, enabling them to counteract high diurnal temperature fluctuations, as are common in many regions of Australia, and provide comfortable internal living environments [4]. Several examples of traditional RE structures have survived for hundreds, if not thousands of years in a wide range of climates of varying severity [17].

RE construction methods have changed little since ancient times. However, it is now common to add stabilising agents to the raw soil, the advantages of which are severalfold. Primarily, the use of stabilisers significantly increases material strength. Stabilised material is also far less susceptible to surface wear, reducing or, ideally, eliminating the need for regular maintenance as is required for its unstabilised counterpart [14]. In addition, the

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use of stabilisers also allows a wider range of soil types to be used; for example, soils with lower or higher clay contents than those recommended for unstabilised construction can be used if stabilised with Portland cement or hydrated lime respectively [6].

Although the use of stabilisers for RE construction has been an accepted practice in Australia over the last 30 years, the technique's youth means that there is still a distinct lack of data regarding the long-term durability of these materials. Current Australian RE construction guidelines [19] therefore require very high factors of safety for material strength in order to account for any degradation that may occur, resulting in highly conservative designs and, potentially, unnecessarily high construction costs.

This paper presents a case study conducted on material obtained from a Portland cement-stabilised RE (CSRE) wall, built in 1980 in Cottesloe, Perth (WA) and exposed to weathering for over 30 years. Degradation in terms of both strength (unconfined compressive strength, UCS) and material losses are discussed. Methods used to measure degradation in non-rammed earth materials are then examined in order to determine their suitability and applicability for use with CSRE when compared to results found in the field. Findings are then used to identify key issues pertinent to the understanding of CSRE durability and to provide guidelines for laboratory testing and designers.

2. RE durability: factors and assessment

Durability of construction materials is the ability to withstand the destructive actions of weathering and corrosive substances without degradation. The most obvious visual sign of degradation due to weathering in RE materials is erosion. Erosion of RE materials is caused by the breakdown of interaggregate bonds (cemented or uncemented), generally provoked by moisture ingress or rain/wind pressure.

Moisture ingress affects the environment of the material clay particles producing shrinking and swelling. This is clearly of less concern for cement-stabilised materials, where the clay content is necessarily low, but is a key source of degradation in unstabilised and lime-stabilised structures [15]. Moisture ingress into porous materials can occur either through capillary suction (the migration of water due to the establishment of a pressure differential through the formation of water menisci) or through external pressure differentials arising due to incident wind [13]. The former can be controlled through the use of waterproof layers at the base of walls, for example, or by ensuring that walls remain well ventilated. The use of impermeable renders, however, to counter surface ingress has been demonstrated to result in additional degradation due to the pooling of trapped water within the material [17, 20].

Incident rainfall erodes RE materials both due to the energy released on impact and subsequent wetting. The damage caused by wind driven rain depends on a number of parameters such as the incident angle, drop size, intensity and wall surface roughness. Although intense, rainfall events are generally sufficiently short lived so that water cannot permeate the material to a significant depth; the outermost saturated material prevents additional ingress (the so-called "overcoat effect"). Saturated outer material is weaker, however, and so is prone to damage if rainfall continues at a sufficient intensity [14]. Clearly, the effects of incident rainfall can be guarded against through the proper use of wall protection, for example large overhanging roof eaves [10].

A small number of authors have presented work investigating the durability of RE materials with respect to their erosion characteristics. Guettala et al. [12] compared the erosion of cement and lime-stabilised earth bricks (a similar material to CSRE, although not as compact) subjected to wetting and drying and accelerated erosion testing [19] to that arising from exposure to real climatic conditions (Biskra, Algeria). It was shown that the laboratory tests used were too severe compared to the material aging observed from real conditions, suggesting that alternative testing methods were required. Similarly, Hall [14] investigated erosion of CSRE walls exposed to low and high velocity rainfall, at controlled pressure differentials. Results showed little moisture ingress or erosion after 5 days. Although this research highlighted the strengths of a suitable laboratory procedure, a link between the laboratory test results and real long-term performance was beyond the scope of the investigation.

Bui et al. [5] investigated erosion of unstabilised and hydraulic lime-stabilised (5% by soil mass) RE test walls following exposure to climatic weathering for 20 years. Results showed that lime-stabilised walls presented little erosion (2.0mm average across the surface), whilst unstabilised walls showed deeper, but still shallow erosion (6.4mm average). Results also suggested that the exposure of larger particles (i.e. gravel) during the erosion process served to protect deeper fine material from damage. This research is one of the few available in the literature that provides an order of magnitude of the erosion due to weathering of RE materials. However, any loss in material strength due to aging was not assessed. Instead, it was assumed that the minimal loss of wall thickness due to erosion would result in a subsequently small loss of structural strength due to the wall's reduced cross section.

It is important to note that these studies could not comment on expected changes in *material* strength due to aging. This paper therefore aims to address this issue by determining whether any significant loss of strength occurs due to exposure and to investigate methods by which it can be assessed. As there are few examples of RE materials exposed to prolonged periods of weathering that are able to be studied, this investigation necessarily takes the form of a case study focusing on one specific site. Results found here are therefore also site and material specific, but can be used to inform RE design and construction practices on a larger scale.

3. Aged material testing

3.1. Environment

The investigated CSRE wall was built in Cottesloe, WA in 1980 and demolished in early 2012. Cottesloe is classified as category [Csa] by the Köppen-Geiger Climate Classification (KGCC) system (temperate, dry hot summer) and as category 5 by the Australian Building Codes Board (temperate dry, hot dry subtropical). Climatic information for this area (for Swanbourne, Perth, roughly 4km North of Cottesloe) for the period 1980–2013 is shown in Figure 1. These climatic conditions are comparable to many areas in which RE structures are situated, so that results found here might

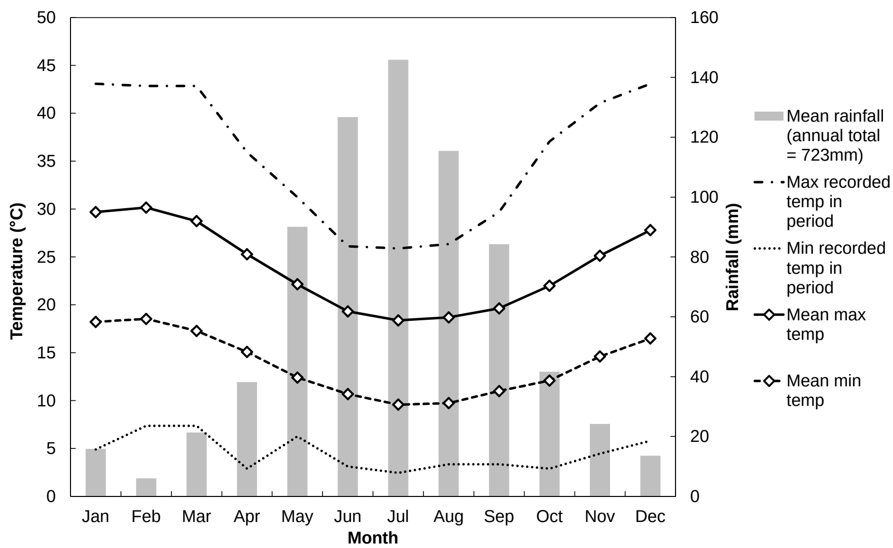

Figure 1: Mean temperature and rainfall data for Cottesloe, Perth, for the period 1980–2013 (Australian Government Bureau of Meteorology)

be extended to other RE sites in Australia and around the world [17, 2]. As the wall was situated roughly 500m from the coast, it is also possible that it was subjected to superficial salt attack; the significance of this observation will be discussed in the following sections.

3.2. Cored samples for UCS determination

A detail sketch (not to scale) showing key features around the investigated wall section is shown in Figure 2. The wall and footing was constructed from CSRE (7.5% Portland cement content by mass) to nominal widths and heights of 200mm×1800mm and 600mm×600mm respectively. A wooden trellis, anchored to the top of the wall, was provided on one side for shade,

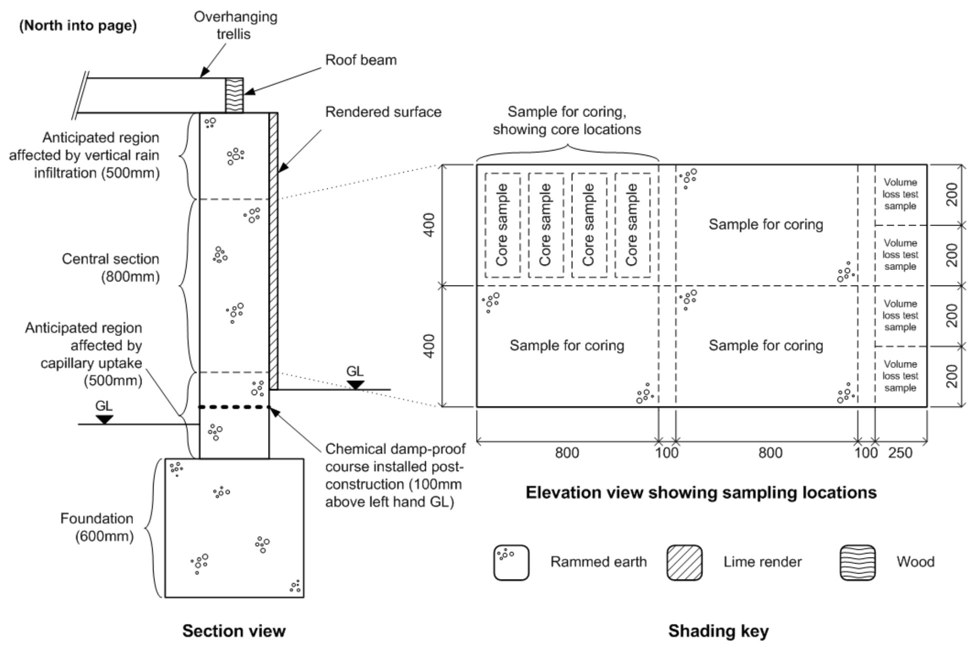

Figure 2: Sketch of key details of investigated wall (dimensions in mm, not to scale)

supported by a wooden roof beam. The wall was otherwise unprotected from incident rainfall. The wall ran north-south along its long axis, perpendicular to the prevalent wind direction, but was protected from direct wind by nearby structures; gusting was, however, still possible. A chemical damp-proof course was installed in the mid 1990s, however this was unsuccessful due to unequal ground levels on either side of the base of the wall (as shown in Figure 2). The lower and upper 500mm portions of the wall were therefore discounted for sampling in order to avoid material too much weakened or damaged by water infiltration.

Four 400mm high, 800mm wide samples were obtained for coring, as shown in Figure 2, with vertical sections of 100mm width left between them to avoid damage during cutting. Four ∅100mm cores of nominal height

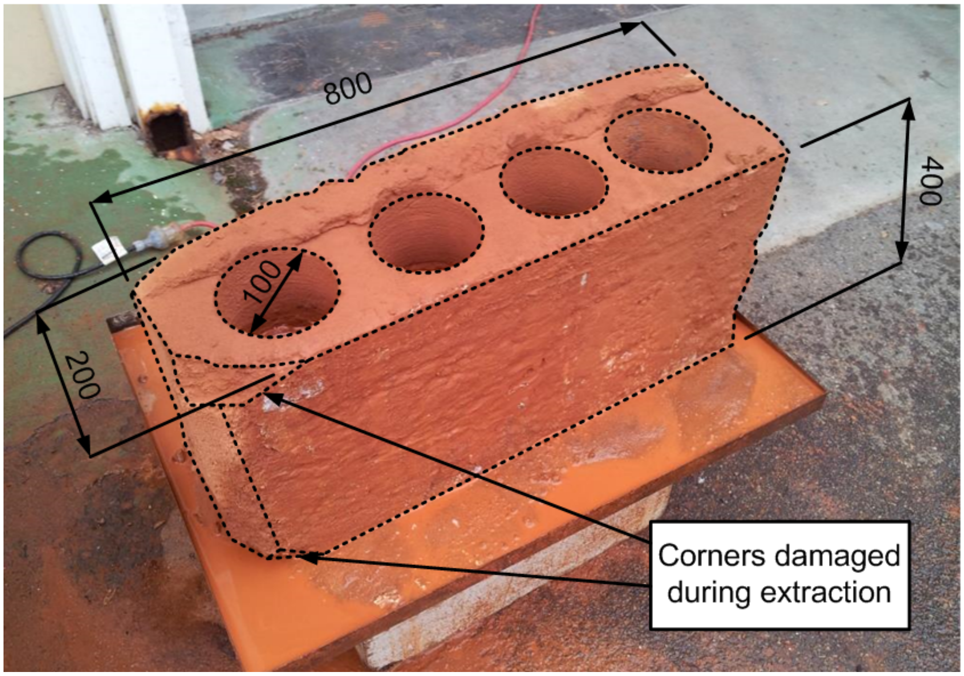

Figure 3: Extraction of cores from sample material. Outlines added for clarity. Dimensions in mm.

300mm were obtained for UCS testing from the central portion of each of these samples, as shown in Figure 2. An example of cored wall sample is shown in Figure 3. Cores were extracted using a water-cooled drill; coolant flow was limited in order to limit scour damage and a nominal border of 50-75mm was left surrounding each core to avoid cracking the larger wall sample. Cores were left to dry to ambient conditions on wire racks and then trimmed using a dry diamond-edged cutting wheel to provide two parallel faces for UCS testing; a dry cutting wheel was used to avoid further damage to the material. Cores were then left to equilibrate to conditions of 94 $\pm$ 2% relative humidity and 21 $\pm$ 1°C for seven days to ensure suction uniformity.

As the wall was constructed using ramming layers of roughly 150mm compacted depth, core samples contained several such layers along their height. Some cores failed along these layer interfaces on extraction, producing shorter sections. Only 8 samples with slenderness ratio > 1.5 were therefore available for UCS testing. UCS was determined by crushing specimens uniaxially at a constant displacement rate of 0.3mm/min until failure. Teflon sheets were placed between the samples and the metal testing platens during testing to reduce size effects due to the slightly different slenderness ratios [7]. Failed material was then crushed, weighed and oven dried at 105°C for a minimum of 48 hours to determine its water content and dry density, ρ_d.

3.3. Samples for volume loss testing

Four (nominally) 250mm wide by 200mm high sample wall sections were taken to determine volume loss due to erosion, as shown in Figure 2. A sand raining technique was used to determine the volume of these irregular samples, in order to determine volume loss due to erosion. Unexposed sample surfaces (i.e. on the plane vertical and perpendicular to the viewing plane in Figure 2) were trimmed to present two parallel surfaces for placing between rigid boards. Additional boards were then used to create a tight-fitting enclosure of known volume, as shown schematically in Figure 4. Fine sand was then rained into the enclosure at a set drop height and travel speed to deposit material at an *a priori* known density. Once complete, the sample was extracted and the sand weighed in order to calculate the sample volume. Volume loss was then calculated as the difference between the original and eroded volumes, where original volume was assumed to equal $b \times h \times t$

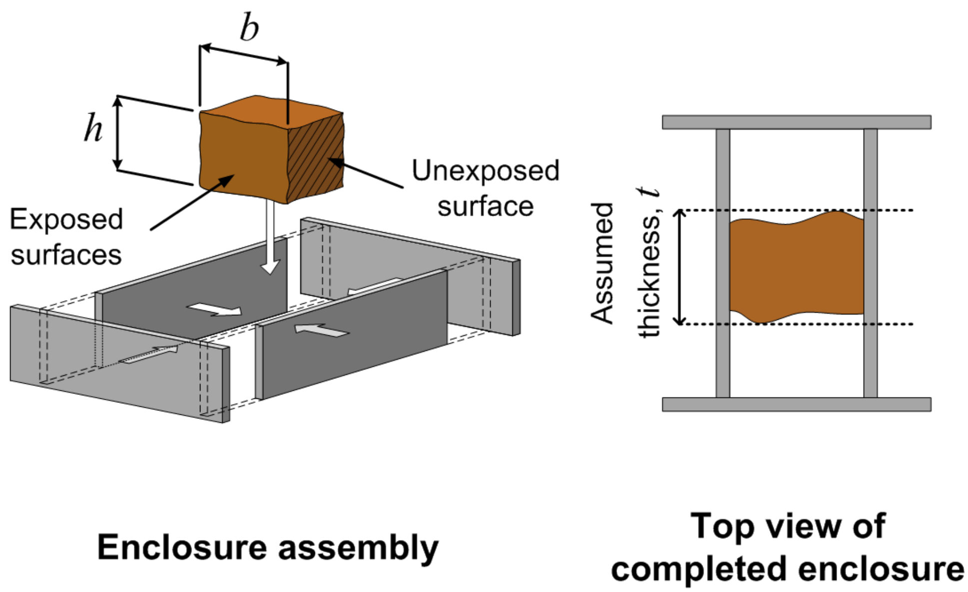

Figure 4: Assembly of enclosure for volume loss testing and principal sample dimensions

(i.e. the volume of the cuboid which bounds the sample's extremities) as shown in Figure 4. This assumption is reasonable as, when the wall was first constructed, the use of rigid formwork would have created smooth, parallel wall surfaces.

4. Results: Aged material testing

4.1. Cored sample UCS

Cored sample UCS results are shown in Figure 5 against dry density, as determined via oven drying. Linear relationships have been included to indicate the rough data trends; whether a linear relationship is the most suitable for this data is not clear, however it is sufficient to demonstrate the major differences between the different tested materials. Cored sample slenderness ratios, given in parentheses in Figure 5, show that there is no discernable relationship between slenderness ratio and UCS, due to the use of Teflon. Results in Figure 5 for non-cored (i.e. early-age) material are discussed in Section 6.

Cored sample UCSs appear to be unchanging with changes in dry density. Other studies (e.g. Ciancio et al. [8]) have shown that the dry density of traditional and CSRE samples are affected by changes in material dry density, albeit for early-age samples (i.e. 28 days for CSRE). The apparently dry density-independent results for the 32-year old material shown in Figure 5 are therefore unusual. A potential cause might be the salt weathering phenomenon due to the proximity of the ocean to the test site; salt weathering removes hardened cement paste, weakening the major source of strength of CSRE. The 32-year old measured dry density does not therefore necessarily correlate to material strength in the same way that it might for early-age CSRE samples.

4.2. Volume loss

Sample dimensions and determined total and average volume losses for two tested wall samples are given in Table 1 (although four samples were obtained for volume loss testing, two were deemed too severely damaged by the demolition process). Average erosion depth is calculated by dividing the total volume lost by the projected exposed surface area (i.e. $b \times h$ as shown in Figure 4). Average erosion depth per year has then been calculated for 49 years (32+17) due to the addition of a protective lime render to one side of the wall 15 years after construction, as shown in Figure 2, which halted

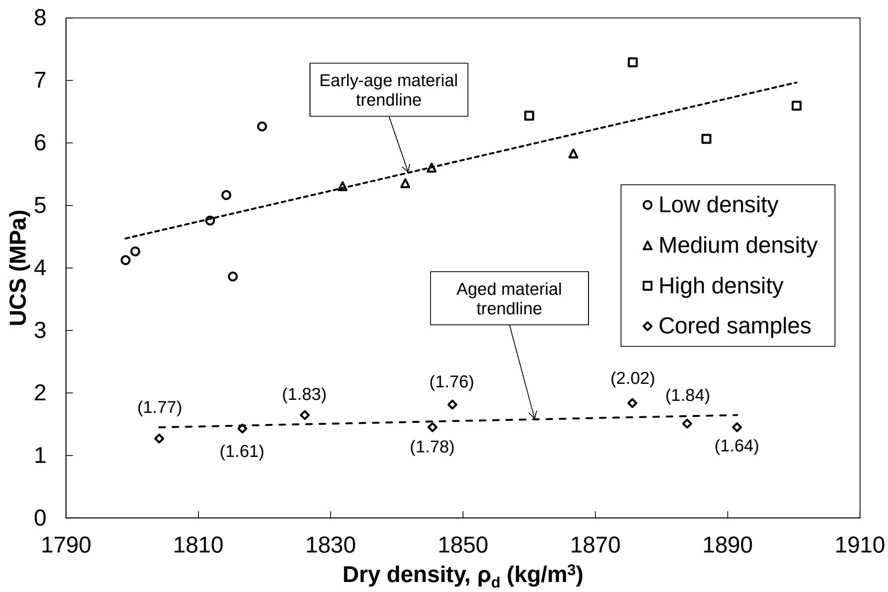

Figure 5: Core and fresh UCS results against dry density (testing and manufacture respectively). Core sample slenderness ratios are given in parentheses.

Table 1: Volume loss test results. Dimensions b, h and t as shown in Figure 4

	Specimen 1	Specimen 2	Average
Max thickness (t) (mm)	204	205	
Width (b) (mm)	320	320	
Height (h) (mm)	178	200	
Volume lost (cm^3)	426	599	
Average erosion depth (mm)	7.5	9.4	
Average erosion per year (mm/year)	0.15	0.19	0.17

erosion (on that side) from then on.

Average erosion depths of 0.15 and 0.19mm/year for the two tested samples given in Table 1 is of the same order of magnitude (0.1mm/year) of that found by Bui et al. [5]. Walls in that work were manufactured from material of similar grading to that used here, stabilised with 5% lime and subjected to a climate of similar severity (KGCC category [Dfb] (cold, warm summer), roughly 350mm rain per annum). In the absence of additional data, erosion losses of roughly 0.1mm/year could therefore offer a preliminary guide for the design of such exposed CSRE materials in mild climates. Values found for wall sample erosion are used in the following sections to calibrate erosion testing of fresh material.

5. Early-age material testing

5.1. UCS specimen manufacture

Original soil dating from the wall's construction, stored dry and unstabilised from that time, was analysed and used to prepare fresh specimens for analysis. The particle grading curve for this material is shown in Figure 6. As is typical for soils used for CSRE construction, the soil contains little clay which would otherwise interfere with the cement hydration process [19].

Specimens for UCS testing were manufactured to reproduce material properties at time of construction. Given the wide range of dry densities found from cored samples (including samples of slenderness ratio < 1.5 not shown in Figure 5), UCS specimens were manufactured to three different target dry densities of 1825, 1875 and 1925 kg/m^3 (hereafter referred to as low, medium and high density specimens respectively). The use of multiple dry densities allows for the unexpected result of no discernable change in compressive strength with increasing dry density found for cored samples to be investigated more fully.

Optimum water contents (OWCs) corresponding to the selected dry density range were determined through a combination of Modified and Standard Proctor testing (MPT and SPT respectively), in accordance with AS 1289.5.2.1 [18]. Dry soil was combined with 7.5% Portland cement by mass to match original manufacturing conditions. Linear regression through the two OWC curve maxima was used to establish a rough relationship between OWC and ρ_d in order to determine OWC values for target testing dry densities, as shown in Figure 7 [11]. Measured and predicted OWC values are given in Table 2. It is noted that the line of optimums is not expected to be linear; however, in the absence of additional data, a linear approximation is considered to be reasonable. It is also noted that significant extrapolation is required from measured results to the lowest OWC values required for testing; unfortunately, lower compactive efforts were not available owing to the use of standardised equipment.

$\varnothing$100, 200mm tall UCS specimens were manufactured at OWC and ρ_d

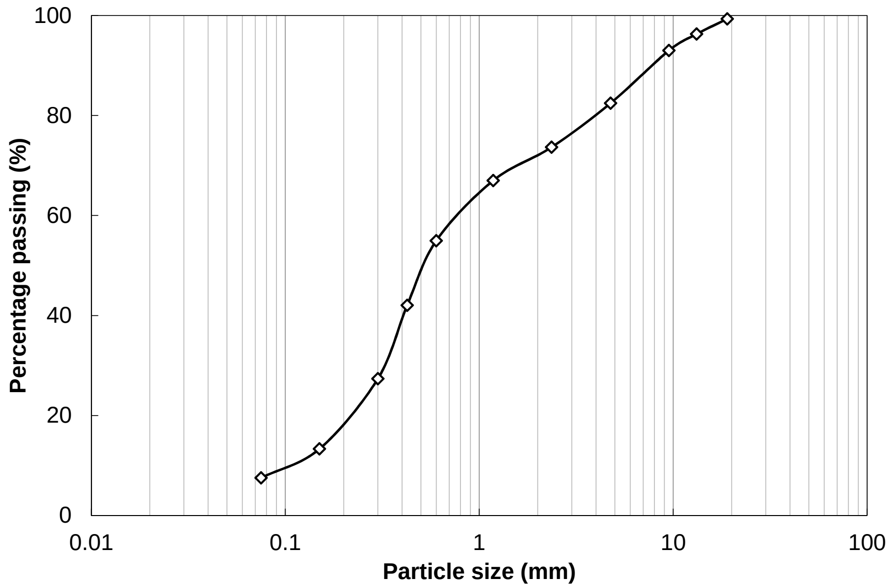

Figure 6: Original soil particle grading curve

Table 2: Measured and extrapolated OWC values

Test	MPT	SPT	1825 kg/m^3	1875 kg/m^3	1925 kg/m^3
OWC (%)	10.4	12.4	15.2	13.6	12.0

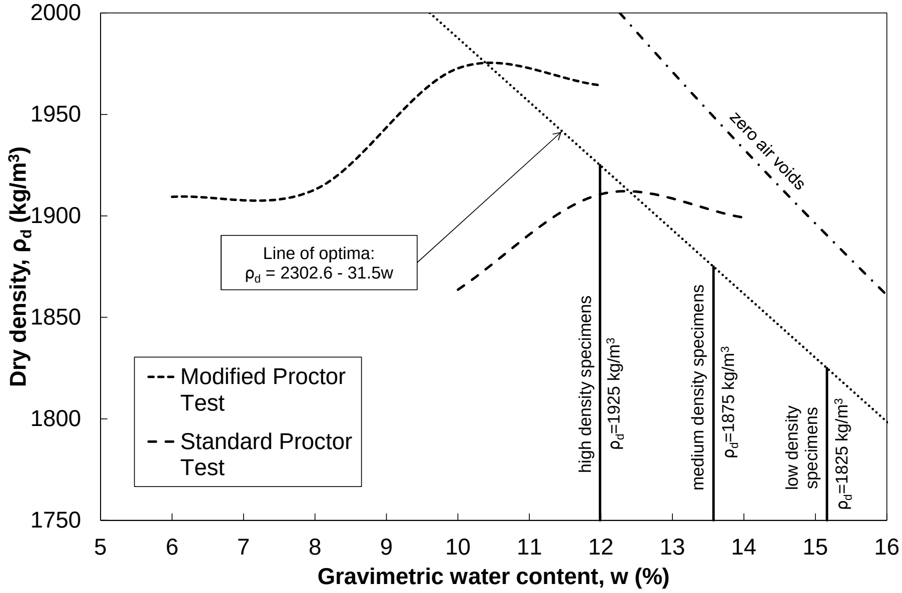

Figure 7: Compaction curves showing assumed relationship between maximum ρ_d and water content, w, and resulting OWC values for selected dry densities

values given in Table 2. Specimens were compacted in five layers of controlled mass and volume to ensure the correct compacted density [3]. A screed of material passing 1.18mm laid over the compacted surface was used to provide parallel specimen faces for testing. Specimens were extracted from the mould immediately following manufacture and cured under conditions of 94 $\pm$ 2% relative humidity and 21 $\pm$ 1°C for 28 days in order to match conditions used for cored sample equilibration. After curing for 28 days, sample UCS was tested following the same procedures used for cored samples. As testing was conducted immediately, it is assumed that specimens remained equilibrated to the curing environment.

5.2. Erosion and strength loss

Five medium density specimens were prepared to investigate erosion and potential strength loss due to weathering; the number of specimens and densities was limited due to the lack of original material. A number of tests were considered, including the Accelerated Erosion Test (AET), the Geelong Drip Test (GDT) (both HB195, Walker and Standards Australia [19]) and wetting and drying testing (ASTM D559 [1]). The suitability of the AET for testing RE materials has recently been questioned by several authors due to its use of unrealistically high pressures [9, 12]. The GDT uses water falling dropwise onto a single spot to assess erodability, resulting in deep pitting as opposed to the more uniform erosion that is seen as a result of incident rainfall. The GDT is therefore also unsuitable to determine volume loss due to rainfall. Wetting and drying testing was therefore selected to investigate the erosion rate of laboratory-manufactured samples.

Although larger than specimens required by ASTM D559, cylindrical specimens for wetting and drying testing were prepared to the same dimensions and cured following the same procedures as used for UCS testing; this was necessary to enable the compressive strengths pre– and post-testing (the former obtained from Figure 5 for medium density specimens) to be fairly compared. Once cured, specimens were subjected to 12 test cycles, each comprising the full immersion of the specimen in room-temperature water for 5 hours followed by oven drying at 71 ± 1°C for 43 hours. After the final cycle was complete, specimens were re-equilibrated to conditions of 94 ± 2% relative humidity and 21 ± 1°C for a period of seven days prior to UCS testing (following the same procedures as described previously).

6. Results: Early-age material testing

6.1. UCS testing

Results for 28-day specimen UCSs are shown in Figure 5, alongside results found for cored samples. Note that manufactured dry densities are slightly lower than their target values; this is due to the need to trim specimens to provide flush surfaces, as discussed above. Final average dry densities for low, medium and high density specimens were therefore 1810 (0.8%), 1846 (1.5%) and 1881 (2.3%) kg/m^3 respectively (relative error from target values in parentheses).

Results shown in Figure 5 suggest a linear correlation between early-age material UCS and dry density. This result is consistent with those found by previous authors (e.g. Ciancio et al. [8]) for stabilised RE materials compacted at their OWC. Figure 5 shows a significant difference (4 to 6 times) between 28-day and cored material UCS values over the range of ρ_d tested. As the same nominal compaction regime (i.e. dry density and water content), stabiliser type and content and equilibration conditions were used for both materials, it is unlikely that these differences are due to inconsistencies in material preparation. It is noted that the use of coring to obtain aged material specimens could have caused damage, however it is also unlikely that this action alone could lead to the large disparity in material strengths. Although it is not possible to say that the observed loss of strength was exclusively due to exposure, it is clear that it is a primary contributor. A loss of strength on exposure is a key result for RE design and conservation as it is clear that RE materials similar to that investigated in this study must be protected from weathering if severe structural weakening is to be avoided.

6.2. Wetting and drying tests

Results for changes in specimen masses during wetting and drying testing (ASTM D559) are shown in Figure 8. A comparison between eroded (i.e. after 12 cycles) and uncycled specimen UCS is shown in Figure 9 where specimen volumes have been calculated by assuming a constant dry density. Average depth of erosion and equivalent number of years for each specimen are given in Table 3. Average depth of erosion has been calculated assuming that degradation of the material occurred on the specimen sides only, as negligible change in specimen height was found after testing. The equivalent number of years has been calculated assuming an average depth of erosion of 0.17mm/year, as determined from volume loss testing for aged material

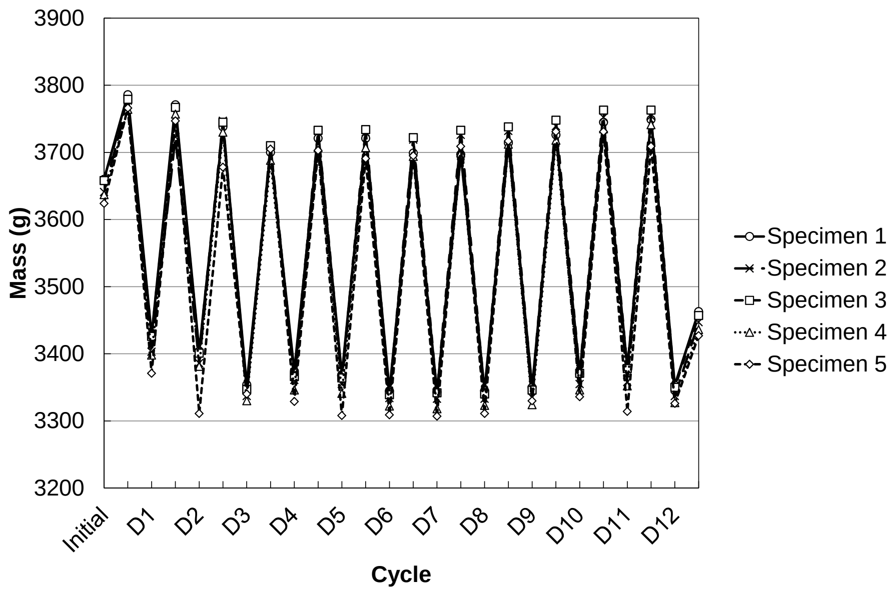

Figure 8: Changes in specimen masses on wetting and drying ("D#" represents drying cycle number)

(as given in Table 1).

Figure 8 shows that all specimens behaved similarly during wetting and drying, with the most significant mass losses occurring during the first few cycles. This is consistent with the findings of Bui et al. [5], who suggested that volume loss due to erosion is most severe on initial exposure due to the loss of poorly-bonded surface particles. Figure 8 therefore suggests that the wetting and drying test is able to reproduce erosion patterns expected of real-world conditions.

Results given in Table 3 suggest that one wetting and drying cycle roughly approximates material losses expected over the course of 1.5 years. This is contrary to results found by Guettala et al. [12], who suggested that

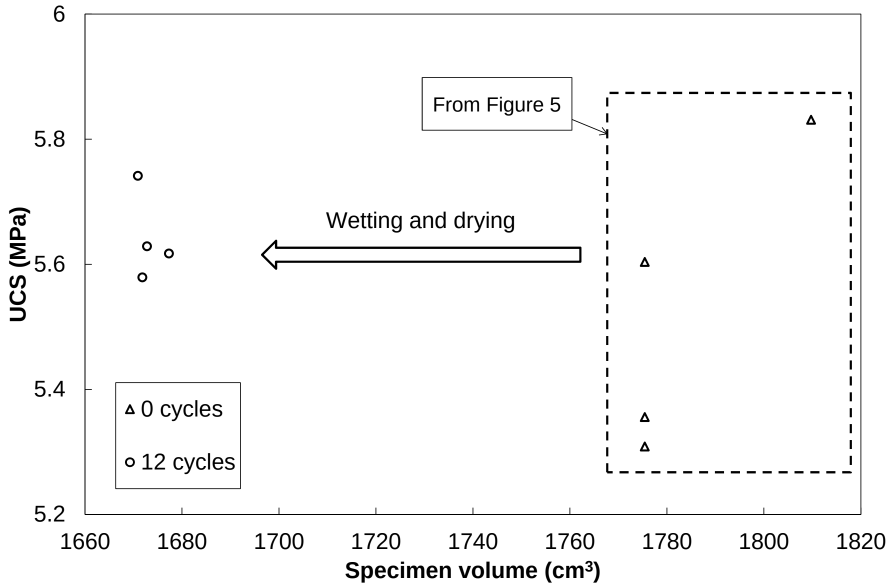

Figure 9: Wetting and drying test results for medium density specimens. The arrow represents the loss of volume associated with wetting and drying testing.

wetting and drying testing was too severe. It is likely, therefore, that wetting and drying testing is better suited to more heavily cemented and compacted materials, as used here, than those used in Guettala et al. [12]. This preliminary result can offer a useful rule-of-thumb for the use of wetting and drying testing for determining volume loss from CSRE materials, but care should clearly be taken if applying this finding to more or less heavily-cemented materials.

Figure 9 shows that the average strengths of cycled and uncycled specimens changed very little as a result of the wetting and drying process. This result lends support to the assumption that dry density does not change with exposure, used to calculate volume from mass losses, as results shown in Figure 5 suggest that a change in dry density would produce a change in specimen strength for early-age materials. Therefore, although the wetting and drying test does result in a loss of volume, Figure 9 shows that it does not adequately reproduce the changes in strength between fresh and aged material seen in Figure 5. This might be due to the fact that cement bonds are not affected by the short-term penetration of water unless *i)* a certain amount of clay is present in the mix or *ii)* corrosive substances, for example sea salt (as mentioned earlier) are contained in the water.

Early-age material testing has therefore demonstrated that, although volume loss due to erosion can be replicated, loss in strength due to prolonged weathering could not be observed using the procedures described here. This is an important result for any test aiming to accelerate the effects of weathering when determining CSRE durability; although aesthetic effects might be accounted for, temporal effects, and subsequent structural

Table 3: Wetting and drying test results

Specimen	Number of cycles	Mass loss (g)	Volume loss (cm^3)	Average depth of erosion (mm)	Equivalent years
1	12	197	95.1	1.42	8.4
2	12	194	94.1	1.40	8.2
3	12	201	97.6	1.45	8.5
4	12	201	98.1	1.46	8.6
5	12	197	96.1	1.43	8.4

implications, are left uncertain. It is clear, then, from this case study that additional work must be conducted to determine the exact cause of, and methods to measure and guard against, degradation of CSRE materials. This is the subject of ongoing research.

7. Conclusions

This paper has discussed factors affecting the strength and durability of CSRE and results found from a case study conducted on 32-year and 28-day old CSRE material. Results from the experimental programme presented here suggested that a considerable loss of strength due to aging can occur in unprotected CSRE materials which had not been observed by previous investigators. It was also shown that changes in strength with time are not detected following accelerated wetting and drying testing. Within the limitations of the materials studied, it is therefore apparent that a weakening of the material must be accounted for when predicting the durability of exposed CSRE materials. Testing on additional materials is required, however, to extend this finding to CSRE in general.

The sand rainer technique provided a simple method to determine eroded depths of aged samples. The average result of volume losses of 0.17mm/year was similar to results found by previous authors (for climates of similar severity), suggesting that the preliminary values of 0.1 to 0.2mm/year represent a rough guide for expected annual erosion losses for exposed CSRE materials.

The wetting and drying test, as described in ASTM D559, has been shown to be feasible for use with the CSRE material tested here for determining volume loss due to erosion. Volume losses equivalent of 1.5 exposed years per cycle were found for medium density specimens, providing a rough rule-of-thumb for designers and conservators. However, comparisons between aged and fresh material showed that losses in strength found between aged and early-age material could not be reproduced, so that this test cannot be used to interpret the structural implications of CSRE weathering. Whether such significant losses of strength are expected of other CSRE materials cannot be commented on, based on the limitations of this case study. However, it is clear that an assessment of expected strength loss must be included in CSRE design and conservation practice; whether other "accelerated" tests can reproduce these losses is the subject of ongoing research.

8. Acknowledgements

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