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Weathering the storm: A framework to assess the resistance of earthen structures to water damage

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Abstract

Earth building is experiencing a renaissance due to the emerging recognition of the damage the construction industry is doing to the global environment. Research over the past three decades has identified the hygroscopic nature of these materials, and our understanding of the factors governing their hydromechanical properties is now mature. However, little work has been done to unify methods to assess material durability: namely, how exposure to degrading agents, predominantly water, impacts a structure's service life. Although strength is usually of primary concern to engineers, it is undeniable that earthen structures usually fail due to durability, rather than strength, issues. As earthen architecture and demands made of the material become more ambitious, the need for robust guidelines on how to predict the longevity of these structures becomes paramount.

This paper presents a framework for assessing the durability of earthen materials based on perceived routes of exposure to water. The framework is built upon the findings of a review of nearly 60 articles discussing original durability testing programmes, comprising 118 investigations and almost 700 soil and stabiliser combinations. From these works, 12 assessment methodologies were

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identified, encompassing a range of earthen construction techniques, e.g. mud brick, compressed earth blocks and rammed earth. Each method is described and its suitability for assessing the real world durability of a range of earthen construction techniques appraised. From this, the efficacy of each test was determined and a shortlist of suitable tests created. The derived framework provides assessors with a method to determine likely exposure routes for an earthen construction element (e.g. an internal or external wall) and, from the shortlisted methods, to specify the range of tests necessary to ensure suitable durability given the construction and environmental conditions. This work forms part of the update to the Standards Australia Earth Building Handbook: SA HB 195.

Keywords: Review, Durability, Testing, Earthen construction, Moisture

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1. Introduction

Emerging understanding of the detrimental effects of human activities on the global climate has prompted scientific interest in low-embodied energy building techniques, for example earthen construction. This interest, coupled with improved characterisation techniques, prompted a proliferation of written material over the past three decades, as shown in Figure 1 for search term returns from the Science Direct repository relating to earthen construction. The majority or these works concern themselves with material hydromechanical properties (strength and stiffness), usually with a view to identify suitable raw materials for construction based on some accepted mechanical benchmark, e.g. minimum compressive strengths as specified in New Zealand Standard NZS 4298:1998 [68]. However, while strength is a major factor in structural design, it must be acknowledged that the failure of earthen buildings is predominantly due to durability, rather than strength, issues [60, 29].

Durability can be defined as the ability of a structural element to resist environmental or anthropogenic wear, damage or decay. In the case of earthen

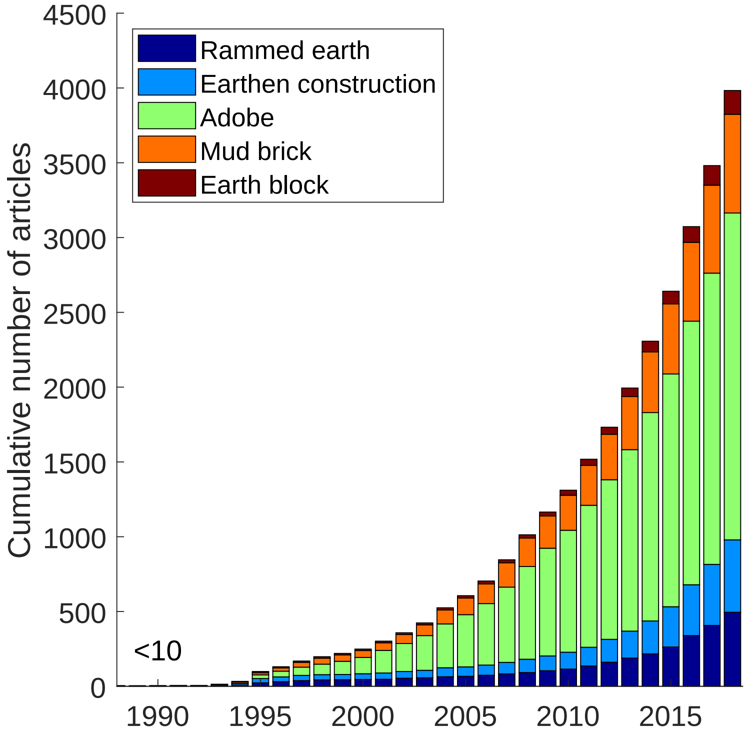


Figure 1: Cumulative number of research and review articles discussing earthen construction techniques recorded per year as indicated by Science Direct keyword searches. Some terms, for example “adobe” and “mud brick” are interchangeable and so some duplication in the returns is expected. “Adobe” was combined with “soil” to remove results relating to software

structures, durability is predominantly associated with resistance to water (although insect/animal, chemical and thermal attack may also impact a structure's longevity [44, 29]). Widespread concern regarding the moisture-resistance of earth buildings is generally well founded and multiple examples exist of structures where poor protection against attacking moisture has led to severe degradation or failure. For example, Figure 2 shows how the surface of a rammed earth wall in the Loire Department, France, has severely degraded due to prolonged exposure to direct rain and freezing temperatures.

Broadly speaking, moisture ingress occurs primarily from wind-driven rainfall, condensation, infiltration, absorption from the surrounding ground, and from general building use. Examples of potential exposure routes are shown in Figure 3. Moisture alone is not particularly damaging if it is able to evaporate before significantly penetrating the earthen material [43]. However, if it is allowed to build up, it can cause material deterioration due to hydromechanical weakening (the reader is referred to Jaquin et al. [49], Gerard et al. [38], Beckett et al. [10], Xu et al. [98] for a detailed explanation of this phenomenon) or the establishment of differential hydraulic, thermal and expansion gradients [35, 76]. Intense wind-driven rainfall during violent storms can also cause significant erosion damage as energies are sufficient to remove particles mechanically [67]. Although many or all of these risk factors can be minimised with appropriate architectural design, it is those cases where such design is poor or absent that place durability demands on the materials themselves. These demands will become critical as earthen structures become architecturally more ambitious, e.g. the recent 40 m high SIREWALL tower at the Telenor '345' head office complex near Islamabad, Pakistan.

Durability mitigation has, for the most part, been associated with strength; high strengths are specified to provide the prerequisite resistance against dam-

Figure 2: Damage (loss of surface material) to a pisé wall in Précieux in the Loire Department, France, due to exposure to direct rainfall. Photograph: Nicolas Meunier

age, rather than to resist structural loads. This is in part due to the lack of universally accepted testing methodologies for material durability and part due to the ease and widespread accessibility of strength testing methods and facilities. We must also accept that the perception that modern building materials (concrete, fired masonry, steel and glass) are 'durable' with regards to their design lifespan, at least as far as domestic use is concerned, has reduced the perceived importance of regular maintenance or durability assessment [52]. However, the assumption that greater strengths impart greater durability places an emphasis and preference on stabilised construction methods (i.e. using cemetitious products to bind soil particles) [40, 23]. Such methods exhibit higher embodied energies due to the manufacture, use and transport of these agents and so counter the aim of reducing embodied energy [5]. Furthermore, stabilisation may not protect the earthen element against all forms of degradation; stabilised

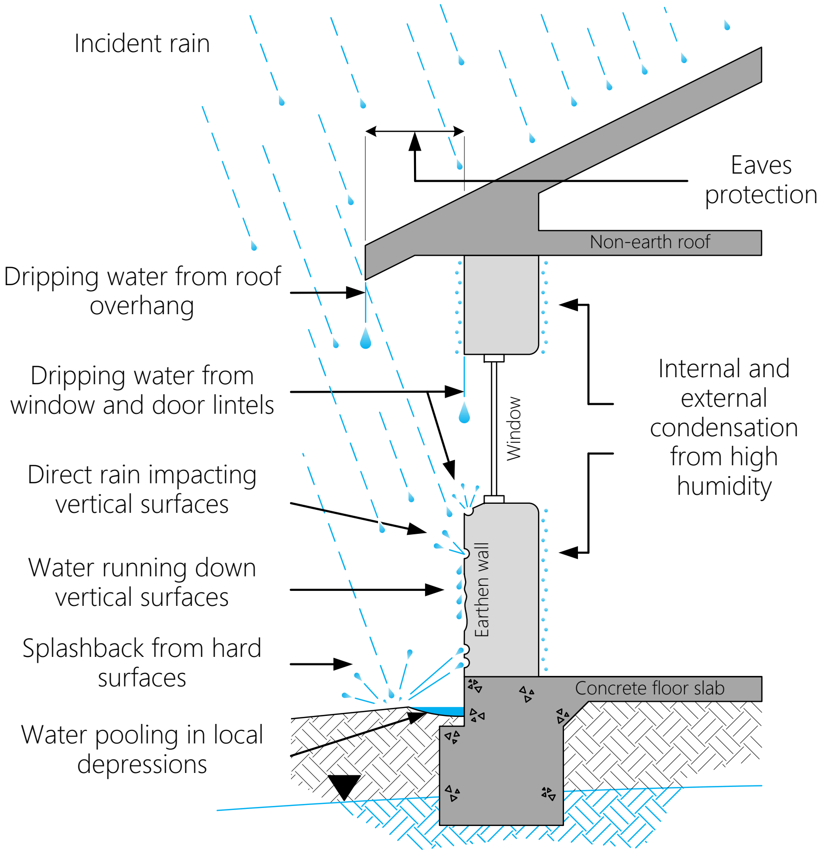


Figure 3: Possible moisture exposure routes for earthen walls

materials, for example, may resist direct rainfall but can degrade under repeated wetting/drying or freeze/thaw cycles or long-term exposure to moisture [13]. This disparity has fuelled the opinion that existing tests are too aggressive or do not reproduce observed *in situ* performance [28], so that different tests are often specified for stabilised or unstabilised materials. Such a situation is detrimental to assessment standardisation; the desired position is, rather, one where all tests are applicable to all materials and the passing or failing of those tests reflects the material's suitability or lack thereof.

In this paper, we review past literature discussing earthen material durability assessment to identify which methods are currently in use and for which materials. We examine how those results were interpreted and how they could be related to real performance. Based on this, we suggest a condensed list of durability tests that reflect likely exposure scenarios and can assess their impact on a structure's longevity quantitatively. We note, however, that methods used to mitigate erosion, for example inserting erosion breaks in rammed earth walls (e.g. Minke [58]) are outwith the scope of this article. This work formed part of the activities of Standards Australia Technical Committee BD-083, of which the authors are part, to identify and update durability testing methods for use in Australian earthen construction (Standards Australia HB 195, [97]).

2. Literature

59 articles (listed in Appendix A) were identified which presented original experimental programmes examining earthen material durability. Between them, these articles discuss results for 118 investigations and 686 different soil and stabiliser combinations. Twelve testing methodologies were identified:

i. accelerated erosion testing (AET);

ii. modified AET;

iii. drip tests;

iv. wire brush testing (WBT);

v. immersion testings;

vi. absorption testing;

vii. rain simulation;

viii. strength testing;

ix. natural exposure;

x. freeze/thaw testing;

xi. Atterberg limit testing; and

xii. shrinkage testing.

The breakdown of these articles by year is shown in Figure 4. Construction techniques examined within the articles and their number of testing instances are shown in Figure 5. Clearly, this is a small subset (roughly 3%) of the overall available literature (Figure 1), which serves to highlight how infrequently durability concerns are examined as opposed to other, more traditional parameters. We cannot, however, claim to have catalogued every instance of durability testing; rather, only those research articles where original tests were discussed were included, with a publication cutoff date of the end of 2018.

As shown in Figure 5, the majority of the identified articles examined the behaviour of stabilised compressed earth blocks (SCEB), rammed earth (RE) and mud brick (which includes adobe), which reflects these materials' popularity above other available techniques when it comes to academic research [48]. Here, we distinguish between earth blocks which gain their integrity only through compression (CEBs) and those which are also stabilised (SCEB). However, we

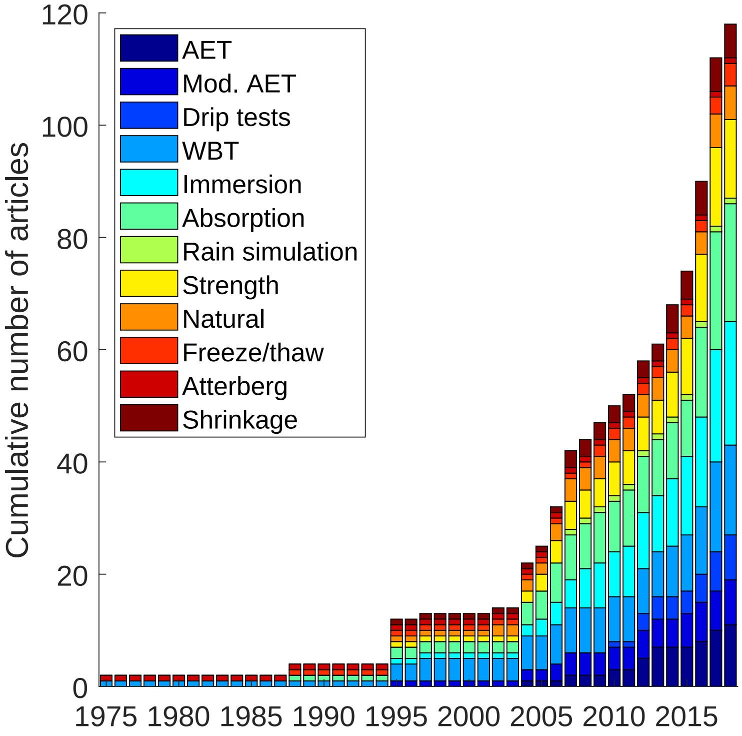


Figure 4: Cumulative number of identified research articles reporting results for given durability testing methods. Abbreviations are listed in Appendix A. Note: best viewed in colour

have grouped together adobe and mud brick to highlight the similarities between these materials (they may be considered synonymous). A rigorous classification of earthen material typologies is beyond the scope of this article; however the reader is referred to, for example, Minke [58]. Brief definitions for each of the identified construction techniques are given in Appendix B. Despite the predictable focus on popular techniques, we believe that the range of techniques and testing methods identified is sufficient to draw general conclusions regarding the efficacy of durability testing methods across the earthen material spectrum. The individual assessment methodologies are described and discussed below.

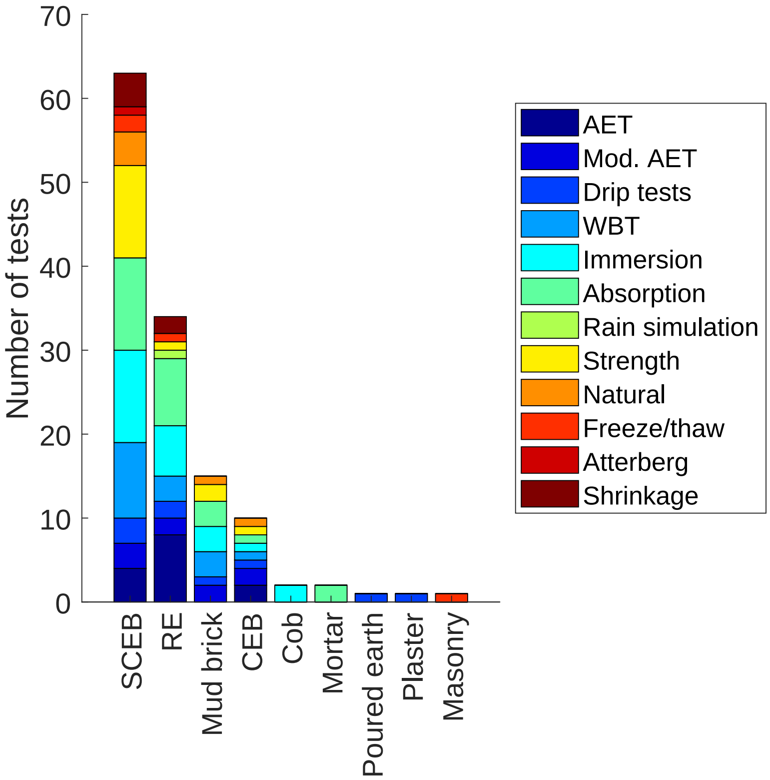
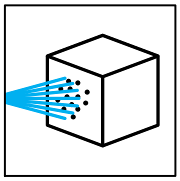


Figure 5: Earthen construction techniques and number of testing instances in reviewed literature. Abbreviations are listed in Appendix A. Note: best viewed in colour

2.1. *Accelerated erosion test (AET)*

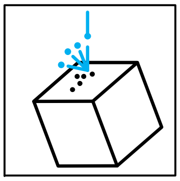


The AET was originally specified in Middleton [56] and appears under NZS 4298:1998 [68] and HB-195 [97]. In it, a 70 or 150 mm diameter section of exposed specimen face is subjected to a water spray at 50 kPa from a distance of 470 mm for 60 minutes. The test is passed if erosion, measured intermittently with a blunt 10 mm diameter steel rod, progresses at less than 1 mm/min. Several variations of this test exist, comprising different spray pressures, delivery distances or exposed areas; here, we classify all of these variations as “modified” AETs (mAET). It should be noted, however, that the Swinburne “accelerated erosion test”, which uses dripping water to simulate indirect rainfall, falls outwith this category (that test is discussed under “drip tests”). 11 of the identified articles presented results for the AET and 8 for mAET methods.

The objective of using water at elevated pressure is to compress the effect of direct rainfall over a structure’s lifetime into a realistic timescale for testing. Given the test’s consequent severity, a common assumption is that if a material can pass the AET then it is sufficiently durable to resist any form of environmental attack (e.g. as implicitly specified in New Zealand Standards NZS 4298:1998). Combined with the test’s relatively long heritage and popularity, this assumption has promoted the use of stabilisers to ensure sufficient durability. The consequent notion that unstabilised materials cannot pass the AET is well grounded; from those 19 articles which used AET or mAET methods, no unstabilised specimens survived intact. Contrariwise, all stabilised materials passed; however, specimens stabilised with hydraulic/carbide lime or fly ash (with activators) performed more poorly than those utilising Portland cement [5]. This result correlates well with expected strength improvement; for suitable soil types and similar stabiliser amounts, greater strengths are found for cement stabilisation than for lime, FA or GGBS [25]. This outcome may seem to reinforce the original postulate that only stabilised materials can pass the AET. However, it should be noted that, beyond a certain stabiliser content, all stabilised materials will be sufficiently resistant to high pressure water [9, 5]. Therefore, although we cannot conclusively say that no unstabilised material could pass the AET, results reviewed here indicate that the AET (or mAET) is more a test of stabiliser effectiveness rather than a predictor of erosion rates likely to be encountered in the field.

Guettala et al. [40] and Heathcote [45, 46] used degradation observed under natural exposure (4 and 3 years respectively) to modify the AET to better match *in situ* erosion over a given time, either by reducing the delivered pressure or modifying the spray distance. However, Ogunye and Boussabaine [71], and later Van Damme and Houben [90], noted that natural exposure generally does not comprise extreme events, so that observed degradation arises due to alternative mechanisms, e.g. prolonged wetting and drying cycles. Given the aforementioned extremity of the AET, it is therefore questionable whether matching it to long-term degradation is appropriate.

2.2. Drip tests

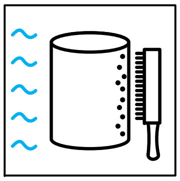


Drip testing predominantly comprises the Geelong Drip Test (NZS 4298 [68] and HB-195 [97]) and the Swinburne Accelerated Erosion Test (HB-195 and Spanish Standards UNE 41410 [1]). In the Geelong test, 100 mL of water under an initial head of 60 mm drips onto the face of an inclined specimen from a wick suspended 400 mm above the impact site. The specimen is inclined at 27 degrees (a slope of 1:2) to the horizontal and the test must be completed within 20 to 60 minutes. Pitting cannot exceed 15 mm as measured using a blunt 3 mm diameter rod. In the Swinburne test, a continuous 5 mm diameter stream of water of constant 1.5 m head falls vertically onto the face of the specimen for 10 minutes. Pitting cannot exceed 30 mm as measured using a blunt 3 mm diameter rod. For both tests, moisture penetration at the impact point should not exceed 120 mm. 8 articles presented results for drip testing.

Drip tests were originally developed for mud bricks to simulate less severe, indirect rainfall impacting material surfaces. Stabilised and unstabilised materials were therefore able to pass these tests in 6 out of the 8 identified investigations; failures were associated with unstabilised materials with lower density (poured earth [2] and adobes coated with Carrageenan (a natural polymer [65]). Unstabilised specimens with applied surface coatings [2, 65], those containing fibres [7] and those with low or non-hydraulic stabilisation (biopolymers [65, 61] and fly ash with activators [83]) also passed, although with greater erosion depths than for more heavily stabilised specimens (e.g. hydraulic lime or cement).

Nakamatsu et al. [65] and Seco et al. [81] compared drip test results to materials exposed to natural conditions for 3 (summer only) and 18 months (starting in winter) respectively. Nakamatsu et al. [65], testing adobe bricks mixed or coated with Carrageenan, did not find any degradation after the relatively short exposure but noted that no rainfall occurred during that period. However, exposed materials performed poorly on subsequent drip testing compared to non-exposed counterparts. Seco et al. [81], testing CEBs comprising 11% Portland cement stabilised, lime (hydraulic and calcareous hydrated) stabilised or GGBS with activators, found little correlation between the drip test and natural exposure; all materials passed the drip test but showed unacceptable degradation on exposure. Based on this limited evidence, drip tests can seemingly indicate likely short term resilience to erosion but cannot indicate long term performance encapsulating multiple environmental factors.

2.3. Wire brush test (WBT)



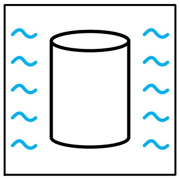
16 articles presented results for tests identified under this category. 13 articles presented results for wire brush testing codified under ASTM D559 and two [82, 86] under Bureau of Indian Standards IS 1725 and IS 4332-4 [17, 14]. Both ASTM D559 and IS 4332-4 specify cylindrical specimens of 101 mm diameter, 116 mm height (i.e. 1 litre), however Arrigoni et al. [6] used 200 mm high specimens to permit subsequent unconfined compressive strength testing. In these tests, cylindrical specimens are immersed in room-temperature water for 5 hours and dried at 71°C for 42 hours. The cylindrical surfaces are then brushed with a wire brush “with a firm stroke” (a notional applied force of 1.5 kg), covering the entire surface area twice (up to 25 brush strokes). This sequence is repeated for a total of 12 cycles. Specimens pass the test if mass lost is <14% for well-graded soils or <7% for clayey soils (United States Department of Agriculture soil definitions). Fitzmaurice [36] extended these recommendations to consider local climate, suggesting that mass loss should be limited to 5% in regions with >500 mm rainfall and ≤10% for regions with <500 mm rainfall; however, these requirements are considered to be quite severe [96].

Two articles presented results examining mass loss after wetting and drying cycles but without intermittent brushing: Ren and Kagi [77] (German Institute for Standardisation DIN 52617E, [32]); and Seco et al. [81] (UNE 41410, [1]). Ngowi [66] carried out another variation of the WBT; specimens were submerged for 24 hours and then sun-dried for 3 days prior to brushing, with only one wetting and drying cycle applied. Also included here is the slake test used by Kerali and Thomas [52]. The slake test involves repeated inversion of 30×30×30 mm prismatic samples in an abrasive drum, rather than the use of a brush.

Hence, it does not permit subsequent strength analysis and larger particles must be removed from the parent material prior to testing. However, both tests share the quantification of durability via mass loss due to repeated wetting.

No unstabilised materials were able to pass the test, regardless of construction technique: all disintegrated during immersion. "Sun dried bricks" (classified here under mud brick) stabilised with cow dung or bitumen [66] also failed. All stabilised specimens passed; of those, mud bricks stabilised with 2.5% Portland cement [82] performed the most poorly, as did cement-stabilised materials with high clay contents (around 10% mass loss, [93, 5]) or low compacted densities [52]. The majority of stabilised specimens comprised cement (or combinations of cement and hydraulic lime) contents in excess of 5%: above 10%, specimens showed little degradation throughout testing. The WBT can therefore identify minimum stabiliser efficacy (as affected by soil type and stabiliser content) to survive immersion and, provided that requirement is met, distinguish between stabiliser contents up to a given limit. This observation agrees well with previous assessments; PCA [74], reported in Heathcote [45], noted that stabilised soils achieving unconfined compressive strengths of over 5 MPa (for cylindrical specimens of aspect ratio 1.25) after curing for 7 days were also able to pass the ASTM mass loss criteria, i.e. stabilisation is an implicit part of WBT interpretation.

2.4. Immersion testing



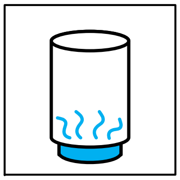
22 articles presented results for immersion testing. Note that this test is referred to as "total absorption" in the Bureau of Indian Standards literature (IS 1725 [17] and IS 3495 [15]) and so should not be confused with "absorption testing", which is discussed in the following section. In immersion testing, specimens are dried to a constant mass (usually under ambient

conditions), with or without curing, and then fully immersed in room temperature water with their mass being recorded periodically over a prescribed period (usually 48 hours) or until reaching a constant value. The test differs from the WBT as specimens are not brushed and are only exposed to one wetting stage. In general, specimens fail if more than 15% water is absorbed however higher limits may be set (e.g. 20% in da Silva Milani and Freire [30] and da Silva Milani and Labaki [31]). Given its simplicity, it is unsurprising that immersion testing was the most frequently performed test out of those identified.

As for the WBT, no unstabilised materials (or unstabilised cob with fibres [37, 54]) survived immersion. Gypsum-stabilised mud brick also failed [3]. All other tested materials survived intact, however Bahar et al. [9] noted that material stabilised with 4% cement performed more poorly than those with higher stabiliser contents.

Guettala et al. [40] compared the outcomes of immersion and WBT testing to erosion observed due to natural exposure. Based on that comparison, they deemed the immersion test (and, by extension, the WBT) too severe for materials tested in that work. However, it should be noted that exposed materials were not subjected to inundation and so a direct comparison cannot be drawn. Rather, it is likely that the immersion and WBT tests provide a good reflection of stabiliser efficacy and short-term material performance in the event of prolonged contact with pooling water [54].

2.5. Absorption testing



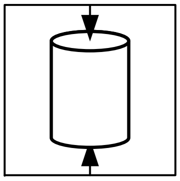
21 articles presented results for absorption testing. This category covers a family of tests, including "Capillary Absorption" (e.g. Eires et al. [33]), "Water Absorption" (IS 4332-10 [16]), "Initial Rate of Suction" [41], "Initial Rate of Absorption" (AS/NZS 4456.17 [78]) and "Wet/dry ap-

praisal" (HB 195 [97] and NZS 4298 [68]): all methods are similar. A saturated, absorbent material (usually florists' foam but Eires et al. [33] used, for example, wet sand) is placed in a tray of water so that its topmost surface is just above that of the water (distance varies). Specimens to be tested are dried under ambient or oven conditions, depending on the test (earthen materials are usually dried to ambient). Specimens are weighed prior to testing and then one face is placed in contact with the saturated material. Specimen weight is then recorded at set intervals; in most processes, weighing is carried out several times within the first 5 minutes of testing, to examine initial sorption rates. Unlike for previous tests, no specific pass or fail criteria have been specified. Rather, the test is usually comparative; the lower the absorption rate, the better the performance. In the absence of a specified target, results from Hall and Djerbib [41] indicate that 0.4 $\mathrm{kg/m^2min^{1/2}}$ is a suitable upper limit for unstabilised rammed earth. Stabilised materials can be sufficiently durable at higher values, e.g. 4.5 $\mathrm{kg/m^2min^{1/2}}$ for RE stabilised with 4% Portland Cement [92]. Alternatively, Guettala et al. [40] specified a stricter failure criterion for stabilised CEBs as absorbing >2.5% water (by mass) after being in contact with the absorbent material for 7 days.

Like immersion, adsorption testing is technologically simple and so its popularity is warranted. Furthermore, it is far less severe than the AET, WBT or immersion test and so is suitable for testing unstabilised materials. As expected, processes associated with decreasing hydraulic conductivity (stabilisation, increased clay content or increased density) improved performance (i.e. decreased the absorption rate); CEBs stabilised with cement and lime (combinations greater than 5%) in Guettala et al. [40] were sufficiently durable to survive contact with the absorbent surface for 7 days. Contrariwise, unstabilised materials with higher sand contents or lower dry densities [42, 18] were susceptible to degradation (failing the limits specified by Hall and Djerbib [41]).

Guettala et al. [40] and Seco et al. [81] compared absorption test results to degradation observed for specimens exposed to natural conditions. In both cases, those materials showing faster final absorption rates or greater absorbed masses also performed the worst under natural exposure. Agreement between the absorption test and natural exposure is reasonable, as rainfall can be expected to wet predominantly only one side of an exposed material, rather than all sides as is the case during the immersion test or WBT. Hall and Djerbib [41] also noted that evaporation at the dry surfaces establishes a hygrothermal gradient across the specimen, prompting salt dissolution or deposition and efflorescence which cannot be examined when specimens are submerged. Meek et al. [55] also demonstrated a good (but negative) correlation between adsorption and corrosion potential; the faster a material is able to absorb (and by extension, desorb) water, the better it is as protecting embedded steel against waterborne attack. Somewhat contradictorily, then, the adsorption test is better suited to reveal long-term performance than the (longer) WBT or immersion tests.

2.6. Wet/dry strength testing

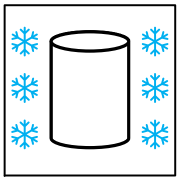


Recent scholarship has demonstrated that earthen materials derive their behaviour from hygrothermal interactions and that strength, stiffness, thermal conductivity etc. are all governed by the amount of water trapped within the material and its distribution [49, 24, 12, 38, 11]. Strength testing for durability assessment contrasts the material's unconfined compressive strength when dried under ambient conditions or in an oven (at 60 to 70°C) to that after the specimen has been submerged in water for 24 to 48 hours (IS 3495 and HB-195 [15, 97]). Different minimum ratios between the wet and dry strength ratios are recommended for a material to be considered sufficiently durable; the

CRAterre organisation (reported in Heathcote [45]) recommend a ratio >0.5 for CEBs, whilst Heathcote [45] suggested a more relaxed 0.33–0.5. No limits have been suggested for other earthen construction types however 0.5 is generally accepted as a suitable target (e.g. [40]).

14 articles presented results relating wet strengths or strength ratios to durability; given the near-ubiquitous nature of compression testing apparatus in engineering laboratories, the relative popularity of this test is to be expected. As for the WBT and immersion test, poorly stabilised adobe (incorporating saw dust and cow dung [94]), CEB and CS-CEB disintegrated during the immersion stage (granting a wet/dry strength ratio of zero). Stabilised specimens were able to survive immersion with the best performance achieved by the heaviest stabilisation regimes. The wet/dry strength ratio could therefore be considered a parallel metric to the outcomes of the WBT or immersion tests: it better represents stabiliser effectiveness against immersion than likely long term performance when exposed to water. This observation is supported by Heathcote [45], whose wet/dry strength ratio of 0.33 was recommended as the minimum performance required to pass the AET, rather than to provide long-term durability.

2.7. Freeze/thaw testing

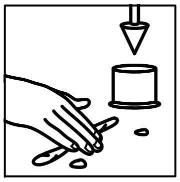


Freeze/thaw testing requires that specimens be subjected to multiple temperature cycles from above to below 0°C. Several variations exist, however the majority cycle between -15°C to +20°C over 24 hours. Specimens may be saturated for 24 hours prior to testing (e.g. PD CEN/TS 13286-54:2014 [22]) or tested from an air-dry condition. However, Bryan [19] notes that a sufficiently high initial degree of saturation is necessary before frost damage will occur; what that saturation is depends, in turn, on the material porosity, permeability and time spent within the icing damage window (the reader is referred to Rempel and Rempel [76] for a comprehensive description of freeze/thaw damage mechanisms in earthen materials). Cycles are repeated up to 100 times and specimen unconfined compressive strength may be tested after cycling has been completed; performance is either assessed visually, by mass loss after testing or by means of a strength ratio. In the absence of pass/fail criteria, mass losses after testing (without brushing) of greater than 2% may be considered poor performance [73].

Specialised equipment is required to deliver the required heating and cooling rates; consequently, only 4 articles presented results for freeze/thaw testing on CEB [73, 81], RE [19] and fired masonry [89]. Furthermore, those tests that have been reported assessed several material qualities; hence, the condition of the specimen at the beginning of the test (e.g. dry, cured etc.) varied significantly, as did specimen performance. Overall, poorly stabilised materials (e.g. 5% cement in the presence of clay in Bryan [19]) degraded during testing. Tang et al. [89] also showed that higher initial degrees of saturation reduced performance.

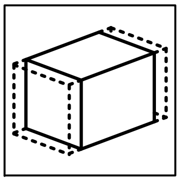
Seco et al. [81] found good agreement between freeze/thaw testing and degradation arising due to natural exposure. Greater research is required, however, to establish the nature of the correlation; it may be, for example, that degradation due to freeze/thaw testing matched that arising outdoors in that work as specimens were exposed to wintry conditions (regularly <0°C) over months 1–3 and 12–16 of testing. Pending that information, however, freeze/thaw testing may offer a realistic option to estimate long-term degradation over an accelerated timeframe.

2.8. Atterberg limits



Only one of the identified articles [84] examined using changes in the Atterberg limits (i.e. material plastic and liquid limits) before and after durability testing to predict material durability. The rationale behind this was that sandy soils are best suited to cement stabilisation and so a minimum plastic or liquid index (or change in those indices) might be expected to delineate suitable materials. However, no correlation was found between material Atterberg limits and their performance under the WBT. This was likely due to the tests being carried out on remoulded fine material (i.e. that passing the 425μm sieve); as the WBT does not impart mineralogical changes, it is unlikely that any changes would be detected in the liquid or plastic limits. Although only one article is available for discussion it is nevertheless unlikely that Atterberg limit testing represents a useful method to assess material durability.

2.9. Drying shrinkage



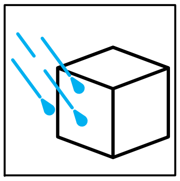
Shrinkage testing for durability assessment refers to the shrinkage of the entire specimen when dried to ambient (or otherwise specified) conditions from manufacturing conditions. Earthen literature commonly refers to this as the "drying shrinkage"; this is not to be confused with "linear shrinkage" (e.g. BS 1377-2 [21]), which only uses the soil fine fraction (i.e. passing the 425μm sieve).

Unlike the other tests identified in this review, drying shrinkage does not expose specimens to water; rather, it examines material performance as water is removed. Shrinkage is an important durability concern as cracking on drying can create preferential seepage paths (and so degradation). Material is placed into a long mould (usually $\geq$10 times as long as it is wide) at the required water content and compacted, as necessary, to the required density.

The specimen is then released from the mould and shrinkage (assumed to be one-dimensional) observed until completion. According to NZS 4298:1998 [68] and HB-195 [97], >10% shrinkage in the long dimension is unsuitable for most techniques. Greater shrinkage is acceptable for mud brick. <2.5% shrinkage is unsuitable for mud brick making but suitable for stabilised rammed earth. Alternatively, the Kenya Bureau of Standards KS02-1070 [51], reported in Salim et al. [79], accepts specimens if crack lengths are <50% of the dimension parallel to the crack and <0.5 mm wide upon reaching constant mass.

6 articles presented results for drying shrinkage and all materials passed the shrinkage criteria discussed above for their respective techniques. Shrinkage was affected by variations in cementitious additives (sugarcane bagasse ash [79], and Portland Cement [88, 92]), fibres [88] and clay contents [92]. Shrinkage was unaffected when the same soil was stabilised with non-cementitious additives (pumice, glass, polyfoam and Kenaf fibres, Maniatidis et al. [53]). Kariyawasam and Jayasinghe [50] noted good agreement between shrinkage specimens and shrinkage observed *in situ* (judged by the size of shrinkage cracks for given panel sizes). The shrinkage test as defined above therefore appears to provide a useful assessment of real shrinkage in earthen structures.

2.10. Rain simulation



Rain simulation subjects specimens to low or high pressure water sprays of characteristics similar to natural rainfall. Ogunye and Boussabaine [70] developed a method to test multiple brick-sized specimens against low pressure rain. Hall [43] presented results for exposing full-sized walls to simulated wind-driven rainfall within a climatic chamber.

Hall [43] exposed cement-stabilised (6% by mass) RE walls of three base soil types to static pressure-driven moisture ingress for 5 days. No erosion was found for either low (equivalent to 0.225 L/min) or high velocity (equivalent to 0.65L/min) rain; this result may have been expected, as similar materials were able to pass the AET (e.g. Bahar et al. [9]), which is more severe, with no damage. Furthermore, no signs of moisture penetration from the wet to the dry side were found; rather, moisture ingress was restricted to a thin (roughly 20 mm) layer of material on the wet side: the so-called "overcoat" effect. Notably, the four test walls shared similar absorption rates (as determined from measured runoff quantities) during rainfall simulation, which was contrary to results from absorption testing. It was suggested that this was due to the use of a dynamic water source during rain simulation, unlike the static source used in the absorption test. Unfortunately, Ogunye and Boussabaine [70] did not compare specimen performance to other testing methodologies or *in situ* conditions, however most specimens showed less than 1% mass loss. Rain simulation may therefore be considered, from the information that is available, to occupy a position between absorption and accelerated erosion testing; it neither captures extreme erosion episodes, as can the AET, nor moisture penetration as observed in the absorption test. The specialised nature of the rain simulation equipment already precludes its use by most laboratories; however, in light of the issues discussed above, it does not seem to be a useful method to assess durability.

3. Durability assessment framework

Prior to evaluating the merits of the testing methods discussed above, it must be noted that none of the reviewed articles examined the performance of *in situ* structures; merely isolated material specimens. This is in part due to the method used to select the reviewed articles but also to the difficulty in determining the causes for observed degradation and in obtaining samples from existing structures. In building the assessment framework, the danger is therefore that the approach is founded upon presupposed degradation mechanisms as examined by the laboratory tests, rather than those that might be present *in situ*. However, it is clear that relating degradation to only one mechanism would not be appropriate [23, 71, 13]. The framework must therefore provide a route to assess multiple exposure scenarios, based on the anticipated conditions affecting a given structural component.

A key observation to emerge from the review is the perception that surviving immersion is synonymous with long-term durability. From the discussion presented in the previous section, it is clear that this is not the case. Rather, the WBT, immersion, wet/dry strength and drip tests could be interpreted as assessments of short-term stabiliser efficacy (although that is not to say that unstabilised materials can never pass these tests, merely that the reviewed results suggest that is it unlikely). Long-term durability (as assessed by available exposure data) was, instead, better reflected by the absorption, shrinkage and freeze/thaw tests (although more information is required in the latter case). Accelerated erosion testing stood alone in this regard; although it was also considered to be a test of short-term stabiliser efficacy, it provided information on likely performance in extreme environments, e.g. under cyclonic conditions. The outcomes of the assessments of the individual testing methods are summarised in Table 1.

The assessment framework for different perceived exposure routes was built upon these derived functions and is presented in Table 2. Several of the reviewed works precluded certain testing methods from their analyses (e.g. the AET) under the assumption that the material in question could not pass that test. The advantage of Table 2 is that it is independent of the earthen construction techniques and stabilisation methods; as demonstrated in the previous discussion, this is because stabilisation alone (for example) may not provide sufficient protection against water damage depending on its efficacy, as well as the element's location within the structure and how that element was formed. Key material risks due to the different exposure routes are suggested but it would be simple for an assessor to add more risks (and associated testing methods) as required. A further advantage is that the majority of the recommended tests can be performed with simple equipment using similarly-sized specimens (e.g. 100 mm diameter, 200 mm high cylinders), which makes them more accessible to practitioners. Note that shrinkage testing does not feature in Table 2; this is because a material cannot be 'exposed' to shrinkage. Rather, all earthen materials should be tested after manufacture (either as individual units, e.g. mud bricks, or after construction, e.g. rammed earth) to show that the product satisfies the shrinkage requirements.

A critical consideration not explicitly included in the assessment framework in Table 2 is that exposure routes may vary or evolve during an element's lifespan. Examples of ways in which exposure routes may vary are suggested in Table 3. Clearly, however, such evolution depends on the specific construction plan, conditions and setting of the structure in question. It is the implied role of the assessor to determine the principal exposure routes governing the specific structure at all stages of use. Examples of such a process may be as follows:

A single-storey house comprises a north-facing lime-stabilised mud brick wall with little roof protection. The wall is not guarded from direct rain by any nearby vegetation. Construction began in the spring but the mud bricks, once manufactured, were stored outdoors over the winter. Assessors determine that the wall is likely to be exposed to direct rain, dripping water and wetting and drying cycles when in service. The mud bricks were also subjected to freezing temperatures when in storage, prior to construction. From Table 2, the mud bricks must therefore pass the following tests: AET; WBT; Geelong Drip Test or

Swinburne Accelerated Erosion Test; absorption test; wet/dry strength testing; freeze/thaw testing. As mud bricks are manufactured at a high water content, shrinkage testing should also be passed. Based on the outcomes of the test, stabilisation (or other) regimes meeting the minimum performance requirements can be recommended as required.

An internal, two-storey unstabilised rammed earth wall is to be constructed on a concrete slab as part of a dwelling. Construction necessitates that it be built before the external walls and roof are in place, due to the large formwork. Assessors determine that the flat top of the wall will be exposed to direct rain and pooling water. The vertical wall sides will be exposed to direct rain, indirect rain and pooling at the base around the floor slab. However, the wall will be protected once the building envelope is in place and will be maintained at a reasonable temperature and humidity. The soil stockpile is not under threat of erosion as the material is not in a final condition. From Table 2, the rammed earth must therefore pass the following tests: AET; WBT; Geelong Drip Test or Swinburne Accelerated Erosion Test; absorption test. Given that the unstabilised rammed earth is unlikely to pass the AET, the assessors may recommend a modification to the material (e.g. stabilisation, in whole or in part) or the construction schedule (e.g. adding a temporary cover) to ensure adequate protection. The wall must also satisfy the shrinkage test requirements once constructed.

Note that, in these examples, some tests (e.g. the WBT) appear under multiple exposure routes; in these cases, the test must only be completed and passed once.

Table 3: Example exposure routes for earthen construction elements for different construction stages

Exposure type	**Construction phase**	**Example exposure scenario**
Direct rain	Storage & handling	Direct rainfall striking mud brick stockpile causes damage prior to construction
	Construction	Rainfall incident on exposed walls prior to roof placement causes erosion of exposed wall portions
	Maturity	Rainfall incident on sections of walls not protected by roof overhangs leads to erosion of exposed material
Indirect rain or dripping water	Storage & handling	Splashback from hard surfaces around mud brick stockpile erodes bricks prior to construction
	Construction	Splashback from hard surfaces and water dripping from overhead erodes material prior to any protection being in place (e.g. roof eaves)
	Maturity	Splashback from external hard surfaces, e.g. ground slab or soil causing erosion of wall lower portions. Internal activities e.g. washing or dripping from plumbing may erode material not otherwise exposed to external water.

Pooling water	Storage & handling	Poor drainage around CEB stockpile causes inundation and potential weakening of the CEB supply prior to construction
	Construction	Standing water on hard surfaces absorbed by walls
	Maturity	Standing water on hard surfaces and flooding absorbed by walls
Prolonged contact with ground water	Storage & handling	Poor drainage around the stockpile allows CEBs to absorb water, potentially weakening them
	Construction	Groundwater penetration into footings and earth floor slabs in direct contact with surrounding soil
	Maturity	Build-up of debris near walls and footings may prevent moisture evaporation and alter groundwater flow paths, exposing additional material to groundwater permeation
Wetting and drying cycles	Storage & handling	Mud bricks exposed to rain due to poor moisture protection on the stockpile
	Construction	Walls exposed to short-term rain events e.g. showers or storms prior to weather protection being in place (e.g. roof overhangs)

	Maturity	Unprotected sections of walls exposed to short-term rain events e.g. showers or storms or changes in humidity due to seasonal changes
Freezing and thawing	Storage & handling	Poor thermal protection on the mud brick stockpile exposes material to thermal extremes
	Construction	Heating and cooling cycles during wall construction; construction interruption due to poor weather
	Maturity	Prolonged exposure to wintery conditions

4. Conclusions

Durability assessment forms a small part of the overall earthen construction literature and yet durability concerns are foremost when designing a new (or appraising an existing) earthen building or structure. This paper presented a review of 59 articles discussing original results from 118 separate durability assessments for 686 different earthen materials. Twelve assessment methodology categories were identified and each was discussed and judged in terms of examined materials, their performance and, where possible, how degradation reflected that observed *in situ*. The review demonstrated that no unified method to assess material durability exists and that different methods are adopted for different materials, based on the presumed ability to pass the test in question. Of those methods, immersion, absorption wire brush and strength testing were

Table 1: Durability test functionalities

Test	**Function**	**Timeframe**
Absorption/IRS	Durability in non-extreme environments	Long term
Immersion	Stabiliser efficacy	Short term
WBT	Stabiliser efficacy	Short term
Strength	Stabiliser efficacy	Short term
AET	Stabiliser efficacy; durability in extreme environments	Short term
Modified AET	Stabiliser efficacy; durability in extreme environments	Short term
Drip test	Durability in non-extreme environments	Short term
Shrinkage	Crack formation	Long term
Freeze/Thaw	Durability in non-extreme environments	Long term
Rain simulation	– – Not a useful representation of durability – –	
Atterberg limits	– – Not a useful representation of durability – –	

the most popular, likely due to the ease with which these tests can be completed in a modestly equipped laboratory.

The review indicated that assessment methods could be divided into two categories: short–; and long-term durability. Short-term tests (AET, WBT, immersion, wet/dry strength and drip testing) focused on stabiliser efficacy against immersion and were largely unable to provide insight into likely *in situ* performance. Long-term tests (absorption, shrinkage and freeze/thaw testing) showed good correlation between testing outcomes and degradation due to natural exposure, albeit with limited evidence in some cases. Notably, unstabilised materials were more likely to survive the long-term tests but none passed the short term tests; this is not to say that unstabilised materials can never pass these tests, however it highlights the issue of unstabilised material survivability when exposed to immersion. Rain simulation and Atterberg limit testing, from the information available, were deemed not to be useful representations of

Table 2: Durability assessment framework: exposure types and risks for earthen buildings and structures and corresponding material durability testing methods

Exposure type	**Material performance risks**	**Testing method**
Direct rain	Material removal due to high energy rain impact	Accelerated Erosion Test
	Material weakening due to increased water content	Wire brush test
Indirect rain or dripping water	Material removal and pitting due to repetitive low energy impact	Geelong Drip Test *or* Swinburne Accelerated Erosion Test
	Material weakening due to increased water content	Absorption test
Pooling water	Gradual weakening of material due to water absorption;	Absorption test
	Material weakening and erosion due to water absorption	Wire brush test
Prolonged contact with ground water	Gradual weakening of material due to water absorption	Absorption test
Wetting and drying cycles	Fretting/spalling of material due to protracted wetting and drying cycles	Wire brush test
	Gradual weakening of material due to water absorption	Wet/dry strength test
Freezing and thawing	Cracking of material due to ice expansion ("onion peel effect")	Freeze-thaw testing
	Fretting/spalling of material due to protracted wetting and drying cycles	Wire brush test
	Gradual weakening of material due to water absorption	Absorption test

durability.

Building upon the review, a framework to assess material durability was developed and examples of its use presented. The advantage of the proposed approach is that it is independent of the material, construction technique or stabilisation regime in question. Rather, the framework relates testing methods to a range of exposure scenarios, each arising from and dependent upon the construction environment. In so doing, it makes the explicit statement that results from one testing method cannot be used to predict those from another, unless both fall within the same exposure scenario. Formalising each testing method was outwith this paper's scope; however this will be completed as part of the upcoming updated release of the Standards Australia HB 195.

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Appendix A

Table 4: Reviewed articles, giving material types and tests performed

Authors	Material	AET	mAET	Drip test	WBT	Immersion	Absorption	Rain simulation	Strength	Natural exposure	Freeze/Thaw	Atterberg limits	Shrinkage
Aguilar et al. [2]	Poured earth			✓									
Alam et al. [3]	Abode block		✓			✓							
Araiza et al. [4]	LS-CEB						✓						
Arrigoni et al. [5]	CS-RE	✓			✓								
Arrigoni et al. [6]	CS-RE				✓								
Ashour and Wu [7]	Earth plaster			✓									
Bahar et al. [9]	CS-RE		✓			✓	✓						
Beckett and Ciancio [13]	CS-RE				✓				✓				
Bruno et al. [18]	Hypercompacted RE					✓	✓						
Bryan [20]	Soil/cement, similar to CS-RE						✓				✓		
Ciancio and Boulter [26]	U- and CS-RE	✓											
Ciancio et al. [27]	U- and CS-RE	✓											
Cid-Falceto et al. [28]	CEB and CS-CEB	✓	✓	✓									
Eires et al. [33]	CEB and U-, CS- and LS- RE and CEB	✓					✓						
Erkal et al. [34]	Historic mud brick and LS mortar			✓									
Forster et al. [37]	Cob					✓							
Gomes et al. [39]	U-RE, U-, CS- and LS-mortar						✓						
Guettala et al. [40]	CS- and LS-CEB		✓		✓	✓	✓		✓	✓			
Hall [43]	CS-RE							✓					
Hall and Djerbib [41]	U-RE						✓						
Hall and Djerbib [42]	U- and CSRE						✓						
Heathcote [45]	CS-CEB		✓						✓	✓			
Heathcote and Moor [47]	CEB		✓							✓			
Kariyawasam and Jayasinghe [50]	CS-RE	✓					✓						✓
Kerali and Thomas [52]	CS-CEB				✓*								
Maniatidis et al. [53]	U-RE (with F)	✓											✓
Medero et al. [54]	Cob (with F)					✓							
da Silva Milani and Freire [30]	CS-RE					✓							
da Silva Milani and Labaki [31]	CS-RE					✓							
Millogo et al. [57]	Adobe						✓						
Miranda et al. [59]	Interlocking FA-CEB and mortar with activators						✓						
Muguda et al. [61]	Biopolymer SRE			✓		✓							
Muntohar [62]	CS-CEB						✓						
Nagaraj et al. [63]	CS-CEB				✓	✓	✓		✓				
Nagaraj and Shreyasvi [64]	CS- and LS-CEB					✓			✓				
Nakamatsu et al. [65]	Adobe			✓						✓			

Ngowi [66]	U- adobe and CS-, LS- and OS- adobe ("sun-dried bricks")				✓								
Obonyo et al. [69]	CS- (+GGBS) and LS-CEB	✓											
Ogunye and Boussabaine [70]	CEB									✓			
Oti et al. [72]	CS- and LS-CEB					✓					✓		
Porter et al. [75]	U- and CS-RE (with rubber chips)	✓				✓							
Ren and Kagi [77]	Adobe (with surface treatments)				✓	✓	✓						
Salim et al. [79]	OS-CEB (sugarcane bagasse ash)												✓
Saranya Raj et al. [80]	CS-RE (with FA)		✓										
Seco et al. [81]	CS- and LS-CEB (with GGBS)			✓	✓	✓	✓			✓	✓		
Silva et al. [83]	U- and FA-RE + activators	✓		✓									
Sharma et al. [82]	U- and CS abode (with F)		✓		✓	✓	✓	✓	✓				
Spence [84]	CS-CEB				✓							✓	
Sravan and Nagaraj [85]	U- and C+LS CEB (with enzymes)					✓			✓				
Sravan and Nagaraj [86]	U- and C+LS CEB (with enzymes)				✓	✓	✓		✓				
Taallah et al. [88]	CS-CEB (with F)					✓			✓				✓
Taallah and Guettala [87]	LS-CEB (with F and activators)						✓						
Tang et al. [89]	Fired masonry										✓		
Venkatarama Reddy and Gupta [91]	CS-CEB					✓	✓		✓				
Venkatarama Reddy et al. [92]	CS-CEB				✓	✓	✓		✓				✓
Venkatarama Reddy and Latha [93]	CS-CEB				✓	✓			✓				
Vilane [94]	U-, CS- and OS adobe								✓				
Walker [95]	CS-CEB				✓								✓
Walker [96]	CS-CEB	✓			✓				✓				
	Total	11	8	8	17	22	21	2	14	6	4	1	6

Construction techniques: CEB - compressed earth block; RE - rammed earth

Stabilisation regimes: CS - cement-stabilised; LS - lime-stabilised; OS - other-stabilised (e.g. bitumen); U - unstabilised

Materials: F - fibres; FA - fly ash; GGBS - ground granulated blastfurnace slag

Test methods: AET - accelerated erosion test; mAET - modified AET; WBT - wire brush test

*Tests assigned to category due to similarity

Appendix B

Construction technique definitions adopted in this study:

Technique	Soil contents				Definition
	Silty clay	Sand	Gravel	Water	
Cob	Medium	Medium	Medium	Medium	Soil is compressed into place to form a freestanding wall. Commonly contains plant fibres e.g. straw and may be placed within formwork.
Compressed earth block (CEB)	Low	High	Low	Low	Cuboidal blocks formed through the dynamic or static compression of earth.
Masonry	High	Low	None	High	Fired brick masonry
Mortar	Medium	High	Low	Medium	Soil used to bind mud bricks. Commonly comprises the same soil as the surrounding mud bricks but may have a reduced coarse fraction. Can be stabilised (lime stabilisation is common).
Mud brick	Medium	High	Low	Medium	Soil formed into brick-shaped units via moulds. Often air or sun dried. May contain fibres (e.g. straw) and can be stabilised. This category also includes adobe.
Plaster	High	Low	None	Medium	A mixture of finer soil particles, used as an external render for other earthen materials. Can be stabilised (lime is common)
Poured earth	High	Medium	Low	High	Soil is poured into formwork as a slurry and consolidates under self weight. Can be stabilised.

Rammed earth	Low	High	Medium	Low	Soil which is compacted into formwork to form freestanding walls. Commonly comprises stabilising agents and may contain fibres.
Stabilised CEB	Low	High	Low	Low	Similar to CEB but comprises stabilising agents (e.g. cement or lime)