Geotech Geol Eng (2020) 38:2403–2425
https://doi.org/10.1007/s10706-020-01208-6

STATE-OF-THE-ART REVIEW

Durability of Stabilized Earthen Constructions: A Review

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Received: 3 April 2019 / Accepted: 23 January 2020 / Published online: 30 January 2020

Abstract It has become general practice to stabilize earthen materials with chemical binders, since one of their main weaknesses is their lack of durability. The most commonly used stabilizer is cement, which reinforces earth by enhancing its strength and water resistance with chemical bonds, while at the same time significantly increases its embodied energy and reduces its sorption capacity. These side-effects greatly reduce the sustainability appeal of earthen materials, leading to a contradiction in this application of cement. Since the researcher community has been aware of this more and more results are published of experiments with alternative stabilizers. This review provides an overview of research about the durability of stabilized earthen walls, the methods used to assess it and parameters that have been shown to affect it. The review features a brief history of this field, but focuses more on recently published data about the water erosion performance of stabilized earthen construction materials. Conclusions about the existing test methods are drawn, with directions for further development suggested.

Keywords Earth constructions · Stabilization · Rammed earth · Durability · Water erosion

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1 Introduction

1.1 Actuality of Durability

Earthen construction materials are usually stabilized for two main reasons. One of these is increasing the cohesion and strength of soils that are otherwise unsuitable for construction purposes. The other is enhancing the material's resistance against water induced erosion, i.e. its durability. In this review we focus on the worldwide research and results of stabilization for enhancing durability. The contradictions discussed are independent of the purpose, consequently they concern any kind of stabilization.

For obvious reasons it is undeniable that durability is paramount for any material used for construction—a life cycle of a building is generally considered 50 years, but usually we use them for much longer. It is common knowledge, supported by numerous existing examples that earth constructions can be durable in a wide range of climate conditions, granted that a suitable soil is used, the appropriate protective measures are taken and sufficient maintenance is provided.

The latter provides the oldest excuse for not building with earth: the cost of maintenance in terms of time and financial cost is considered uneconomical, and the labor it requires drives the choice of material towards more stable materials for those who can afford them. This argument has gained weight in countries where manual labor is expensive and constructions that require any kind of regular maintenance are often seen as obsolete.

Moreover, in light of aesthetic trends of the past decades in architecture high-pitched roofs and roof overhangs for many designers have become undesirable even in temperate climates with considerable rainfall. Appreciation and exposure of the texture of structural materials has also become popular. Both of these trends undermine traditional protective measures of earthen walls, namely big roof overhangs and protective renders or coatings. These trends could be seen as the results of misguided design and the ignorance of the limitations and inherent values of earth construction. From another point of view they are pushing the limits of building with earth.

1.2 The Contradiction of Cement Stabilization

The most frequent solution used is stabilization with the addition of portland cement, usually 4–8% by mass. As Dahmen (2015) pointed out, recent studies have shown that cement stabilization not only negates the reduced carbon footprint and embodied energy of earthen materials (Treloar et al. 2001; Reddy and Kumar 2010; Lax 2010; Arrigoni et al. 2017b), but the recyclability of the material after its service time is also debated. (Pacheco-Torgal and Jalali 2012; Kapfinger and Sauer 2015) Furthermore cement stabilization has a negative effect on the hygric properties as well (Arrigoni et al. 2017a).

These effects create a contradiction, since the sustainability (Melià et al. 2014; Arrigoni et al. 2017a, b) and positive effect on indoor air quality (McGregor et al. 2016) associated with houses built of earth are the competitive advantage compared to conventional materials in face of climate change. To address this contradiction researchers have been investigating alternative methods of stabilization both with traditionally used vernacular materials and with contemporary, mainly synthetic materials. This paper provides a brief review of the results of these investigations touching on the features that are still debated.

To provide a quick overlook of the range of options already tested to some extent by the 1990s we cite Houben and Guillaud (1994), who document quite a wide variety of chemical stabilizing agents. These include but are not limited to: cement, lime, bitumen, resins (both natural and synthetic), a host of natural products (animal blood, casein, vegetable oil, etc.) and a range of other synthetic products (acids like HCl, HNO_3 or HF, sodas, silicates, paraffins, waxes and industrial wastes like blast furnace slag or molasses, etc.).

1.3 Terminology and Content of the Review

1.3.1 Soil

The term soil is quite generally used and refers to a wide variety of soil types. It is and has been used throughout the literature for practical reasons, but we would like to point out that soils used for earth construction are in most cases inorganic subsoils and this is how we apply the term in this review as well.

1.3.2 Durability of Earth Walls

Durability in itself has been given many definitions so far. Concerning construction materials and building constructions in general it is used to refer to the ability of the material or construction to maintain its functionality over time. In earth construction it is used mostly to refer to the materials resistance against water-induced erosion since this is the most common reason leading to the loss of functionality of earthen walls. Of course this is not the only way of deterioration of earthen walls, so a short account is given in Sect. 1.3.3.

1.3.3 Deterioration of Earthen Walls

Deterioration of earthen walls can come about through different processes. Morton and Little (2015) observed seven different decay mechanisms on wall specimens exposed to outdoor conditions: shrinkage, surface erosion, sacrificial erosion, freeze/thaw cycles, organic growth, delamination and dampness. Most of these can be avoided or kept in check by appropriate detailing, but the above mentioned architectural trends leave the walls without traditional measures against the surface erosion caused by driving rain, which provides the focus to this present paper.

1.3.4 Stabilization of Soils Used for Construction

Houben and Guillaud (1994) categorize the methods of stabilization into three main categories: mechanical, physical and chemical. Mechanical stabilization refers to compaction of the material resulting in changes in its density, mechanical strength, compressibility, permeability and porosity. Physical stabilization refers to changing the materials texture. This includes controlled mixing of different grain fractions or natural soils and mixing of fibers into the soil. Chemical stabilization refers to adding other materials and chemicals that change the properties of the soil either by a physico-chemical reaction between the grains and the materials or by creating a matrix which binds or coats the grains.

1.3.5 Categorization of Durability Assessment Methods

The categories used to classify the durability assessment methods were taken from Heathcote (2002). The three categories he used were indirect tests, accelerated tests and simulation tests. Heathcote considered the tests that bore little or no resemblance to the degradation mechanisms to be 'indirect'. Their validity was provided by experience of their reliability to predict performance in in-service conditions. In 'accelerated' tests an attempt is made to model the real degradation process, with their intensity increased for practicality and feasibility. Heathcote classified tests that attempted to model in-service conditions exactly as 'simulation' tests.

This categorization was deemed helpful for managing and presenting the research in this review. Classifying the rainfall simulation test (Ogunye and Boussabaine 2002a) as an accelerated test rather than a simulation test could be seen as a mistake. It was categorized as being rather an accelerated than a simulation because of its close relation to the spray tests, and because this way the 'simulation' category could be reserved to research works where exposure to outdoor conditions was featured, since these were the closest to in-service conditions.

1.3.6 Content of the Review

In the following section (Sect. 2) a brief account is given of the research done before the previous comprehensive study in the field (Heathcote 2002). The consequent sections review the research done by and since Heathcote categorized by the above mentioned test types: accelerated erosion tests (Sect. 3), indirect tests (Sect. 4) and outdoor experiments (Sect. 5). In general the test types that were used the most are discussed, but research works that were notable for a unique contribution to the field were also incorporated in the study. An overview of the encountered research is given in Table 1. In the last sections the methods and results found are discussed (Sect. 6) and conclusions for future research drawn (Sect. 7).

2 A Brief History of Durability Assessment Methods

2.1 Previous Reviews in the Field

Although an excellent review of earthen construction was published recently by Gallipoli et al. (2017), it had a much broader scope and the topic of durability was only indirectly touched upon.

Ogunye and Boussabaine (2002a) did a rigorous analysis of the durability test methods resulting in a diagnosis of their shortcomings and a development of a refined test method that counterbalances them (Ogunye and Boussabaine (2002b). While this modified spray test can replicate natural rainfall parameters much more closely than previous spray tests its application has not become widespread. This can be seen by the types of tests applied by researchers since as shown in Table 1, and a review of the durability test methods that has been done by Morel et al. (2012). While this book chapter features all the test types mentioned in our review, their focus was more on the description of the methods and not so much on the results. This and the fact, that a lot of research has been done since results in the need for this review.

The only comprehensive review of this field found was the review presented in the 2002 doctoral thesis of Kevan E. Heathcote (2002). In this section we will cite Heathcote's review categorized by test types to provide a list of references and topics that were covered until 2002. We recommend those interested in these earlier results to refer to the original sources for specific data or the thesis of Heathcote for an extract.

Table 1 Overview of reviewed literature

Study data		Base soil		Stabilization type		
Reference	Technique	**USDA** class	**USCS** class	Physical yes/no/both	Chemical yes/no/both	Mechanical yes/no/both
Heathcote (2002)	A, CEB, RE	Multiple		2	1	0
Ogunye and Boussabaine (2002a, b)	CEB	Multiple		1	1	0
Kerali and Thomas (2004)	CEB	Sandy loam	Clayey sand	1	1	0
Walker (2004)	CEB	Multiple	Clayey sand	2	2	0
Guettala et al. (2006)	CEB	Sandy loam	Clayey sand	1	1	0
Krisnaiah and Suryanarayana Reddy (2008)	CEB	Sandy loam	Clayey sand	1	1	0
Forster et al. (2008)	C	Sandy clay loam	Clayey sand	2	0	0
Hall and Djerbib (2006)	RE	Multiple		1	2	0
Bui et al. (2009)	RE	Multiple		2	2	0
Reddy and Kumar (2011)	RE	Multiple		2	2	2
Alavéz-Ramírez et al. (2012)	CEB	Loamy sand	Silty sand	0	2	0
Cid-Falceto et al. (2012)	CEB	Loamy sand	Clayey sand	0	2	0
Erkal et al. (2012)	RE	n/a	n/a	0	0	0
Dahmen (2015)	RE	Multiple		1	0	0
Danso et al. (2015)	CEB	Sandy clay	Highly plastic clay	2	0	0
Morton and Little (2015)	All	Multiple		2	2	0
Narloch et al. (2015)	RE	Sandy loam	Clayey sand	1	2	0
Aguilar et al. (2016)	n/a	Clay loam	Low-plasticity clay	0	2	0
Kariyawasam and Jayasinghe (2016)	RE	Sandy loam/sandy clay loam	n/a	0	1	0
Stazi et al. (2016)	P, C, RE	Silty clay loam	Low-plasticity clay	1	2	0
Arrigoni et al. (2017)	RE	Multiple		2	2	0
Eires et al. (2017)	CEB, RE	Loamy sand	Clayey sand	0	2	0
Nakamatsu et al. (2017)	n/a	Clay loam	Low-plasticity clay	0	2	0
Seco et al. (2017)	CEB	n/a	Low-plasticity clay	2	1	0
Suresh and Anand (2017)	RE	Sandy clay loam	Clayey sand	0	1	0
Raj et al. (2018)	RE	Sand	Well graded sand	1	1	0

Table 1 continued

Study data		Test types										
		Accelerated				Indirect						Simulation
Reference	Technique	Spray test	Drip test	Rainfall test	Slake test	Wire brush test	Wet-dry strength ratio	Capillary water absorption test	Total water absorption test	Water absorption test under static pressure	Freeze–thaw cycle test	Location
Heathcote (2002)	A, CEB, RE	X										Syndey, Australia
Ogunye and Boussabaine (2002a, b)	CEB			X								
Kerali and Thomas (2004)	CEB				X							
Walker (2004)	CEB	X				X	X					
Guettala et al. (2006)	CEB	X				X	X	X	X		X	Biskra, Algeria
Krisnaiah and Suryanarayana Reddy (2008)	CEB						X					
Forster et al. (2008)	C								X[a]			
Hall and Djerbib (2006)	RE							X	X	X		
Bui et al. (2009)	RE											Grenoble, France
Reddy and Kumar (2011)	RE						X					
Alavéz-Ramírez et al. (2012)	CEB						X					
Cid-Falceto et al. (2012)	CEB	X	X									
Erkal et al. (2012)	RE		X									
Dahmen (2015)	RE											Boston, USA
Danso et al. (2015)	CEB	X				X		X				
Morton and Little (2015)	All											Multiple, UK
Narloch et al. (2015)	RE	X										
Aguilar et al. (2016)	n/a		X									
Kariyawasam and Jayasinghe (2016)	RE	X					X	X				
Stazi et al. (2016)	P, C, RE	X	X							X		
Arrigoni et al. (2017)	RE	X				X						
Eires et al. (2017)	CEB, RE	X					X	X				
Nakamatsu et al. (2017)	n/a		X									Lima, Peru
Seco et al. (2017)	CEB		X					X	X		X	Pamplona, Spain
Suresh and Anand (2017)	RE	X										

Table 1 continued

Study data		Test types											
		Accelerated				Indirect						Simulation	
Reference	Technique	Spray test	Drip test	Rainfall test	Slake test	Wire brush test	Wet-dry strength ratio	Capillary water absorption test	Total water absorption test	Water absorption test under static pressure	Freeze–thaw cycle test	Location	
Raj et al. (2018)	RE	X											

A adobe, *C* cob, *CEB* compressed earth brick, *M* mudwall, *RE* rammed earth, *P* plaster, *T* turfwall, *WBT* wire brush test, *C-ab* Capillary water absorption, *T-ab* Total water absorption, *St-ab* water absorption under static pressure, *W-D* wet to dry strength ratio, *F-T* freeze–thaw test, 0 no, 1 yes, 2 both (yes and no)

[a]Flood test not total immersion

2.2 Early Wire-Brush Test

To our knowledge the ASTM D559 standard (1944) was the first standardized durability test for soils used in construction, but it was developed specifically for soil–cement. It described the test the literature refers to as the wire-brush test. This test was employed by Webb et al. (1950), in comparing the durability performance of stabilized pressed bricks to those of fired clay bricks. The Portland Cement Association (1956) realized an extensive experimental program based on the wire-brush test to determine weight loss limits for different soil types acceptable for road construction. After assessing the condition of existing earth buildings Fitzmaurice (1958) suggested climate specific limits for weight-loss in the wire-brush test.

2.3 Development of the Spray Tests

In 1952 the first edition of 'Bulletin 5—Earthwall construction' (Middleton 1952) was published in Australia. It dedicated a lot to soil stabilization methods, also featured a sub-section on durability and an appendix describing an accelerated erosion test. Middleton's test walls at the Commonwealth Experimental Building Station in Sydney, built in 1949 are the longest standing field experiments to the author's knowledge. These walls have demonstrated the dominance of driving-rain in the erosion process of earth walls (Heathcote 2002).

Cytryn (1955) developed a laboratory test that simulates the forces of driving rain. It constituted of spraying samples from a height of 250 mm, with a pressure of 50 kPa fro 33 min. The only parameter intentionally related to natural rainfall parameters was the amount of water released throughout the test. The measurement of the resulting erosion and consequent evaluation criteria were not described by Cytryn.

Another spray test was developed by Wolfskill (2005), with climate-specific evaluation criteria added by Norton and Oliver (1997). This procedure was adapted by Reddy and Jagadish (1987) in India who established the notion of relative erosion with an erosion ratio. This related average depth of erosion per minute to precipitation per minute. After analyzing 5 soil samples through laboratory testing one soil was chosen and a test wall was built outdoors. Erosion ratio of the field sample was around 30% of the laboratory results, indicating that total amount of rainfall per year in itself is inadequate to express the climatic parameters of erosion.

Monayem-Dad (1985) also developed a spray test for cement stabilized soil and used it to simulate annual rainfall in Bangladesh. Dad experimented with different variables of the test: cement content, compaction pressure, angle of impact and face of the brick tested. His results indicated that the most important variables were cement content and compaction pressure, that spraying at an angle of 90° produced around 30% more erosion than at 30° and that there was small difference between erosion of the horizontal and side faces of the brick.

Heredia Zavoni et al. (1988) studied stucco compositions applied to adobe structures in Peru. They applied a simple lawn sprinkler to simulate rain on test panels, with different intervals and intensities. Their results are noted by Heathcote (2002) because they show a decrease in erosion rate over time, where the amount of eroded material plotted against the elapsed time can be fitted to an MMF growth curve.

Ola and Mbata (1990) conducted spray tests as well, experimenting with the parameters of spray pressure, compaction force and amount of cement content. They concluded that weight loss is positively correlated with spray pressure and negatively correlated to compaction force and cement content. Analyzing their results Heathcote (2002) observed a linear relationship between the erosion per unit volume of water and the inverse of the square root of the spray velocity.

The spray test described in the revised Bulletin 5 (Schneider 1981) has become the standard spray test incorporated into normative documents of Australia, New Zealand and the United States as well (Cid-Falceto et al. 2012). In extension of specifying the geometry of the setup and the spraying pressure it also specifies the nozzle. This way the jet velocity and drop size is uniform providing a consistent level of kinetic energy. This is important because it provides a basis on which to compare the erosive effects of the laboratory test with the climatic effects that can be measured in the field.

Ogunye (2019) continued the work of Dad similarly using a spraying chamber for simulating a specific rainfall intensity. He experimented with various pressures and drop heights, finding that for a rainfall intensity of 150 mm/h he had to spray at 50 kPa from 2000 mm above the specimens. Ogunye and Boussabaine (2002b) made a case for their rainfall test rig, discussed in Sect. 3.3.1.

2.4 Development of the Drip Tests

Yttrup et al. (1981) developed the first drip test to provide owner-builders with a simple test to determine the suitability of soils for adobe construction. The test was extended by Frencham (1982) with a classification of erodability based on the correlation of drip test results of bricks taken from 20 existing buildings with the performance of the source buildings, that have existed for at least 60 years. Frencham also proposed the use of two simple factors influencing the field performance namely the exposure and rainfall factors. Furthermore he suggested that erodability indexes as a sum of the classification from the drip test and the two factors could be related to the expected loss of wall thickness.

A few years later, in 1987 students at the Swinburne University of Technology developed an alternate version of the drip test. They found that the pitting depths produced by the Yttrup drip test were often too small to measure accurately. The resulting test known as the Swinburne Accelerated Erosion Test increased the drop height and featured a continuous jet instead of individual drops of water. A classification for the results of this test used for evaluating mud bricks was suggested by Weisz et al. (1995). Since then this modified drip test has been incorporated into several normative documents, for example the Spanish UNE 41410 (AENOR 2008).

2.5 Establishing the Permeability and Slake Tests

Webb et al. (1950) measured the water absorption of soil cement blocks immersed in water for 24 h and specified the acceptable limit for weight gain as 12%.

Apart from spraying the samples Cytryn (1956) also conducted slake tests—immersing stabilized samples in water and measuring their weight gain after 24 h. He observed that the samples which passed the accelerated erosion test usually also passed the slake tests. He reported a reduction of compressive strength of 60% for loess soils and of 40% for sandy soils when comparing saturated samples to dry ones. The ratio of wet to dry strength has since become a popular measure of resistance to water induced erosion as is noted in Sects. 2.6 and 4.1.

2.6 Relating Compressive Strength to Durability Performance

The list of institutes and researchers that have studied the wet to dry strength ratio of stabilized soils include the Portland Cement Association (1956), Chadda (1956), Cytryn (1956), Wolfskill (1970), Lunt (1980), Walker (2004), Heathcote (1995) and Doat (1998). Many suggestions have been made as to the acceptable limit of this ratio. Lunt (1980), Reddy and Jagadish (1984) reported ratios between 0.25 and 0.35 for existing walls, Heathcote (1995) also considered a ratio of 0.33 acceptable. Heathcote (1995) has found a good correlation between the wet to dry strength ratios of compressed earth blocks stabilized with cement contents between 2.5 - 7.5% and their field performance.

For the comparability of the ratios obtained from different sources one has to make sure the 'wet' and 'dry' states are defined correctly in the sources.

The present review focuses on results with chemical stabilizing agents published from 2002 onward and touches on open questions concerning the assessment methods.

3 Recent Accelerated Erosion Testing

The research done by and since Heathcote (2002) constitutes the subject of the remainder of this review. An overview of the research done, with the targeted construction technique, type of soils, type of stabilization and applied test methods is presented in Table 1.

3.1 Spray Erosion tests

The data extracted from the articles featuring spray erosion test is presented in Table 2.

3.1.1 Spray Testing by K.A. Heathcote, Sydney, Australia

Heathcote conducted a thorough investigation into the erodability of stabilized earthen materials (Heathcote, 2002). He studied the variables of volume of impacting water, time of exposure, impact velocity, angle of impact of drops, drop diameter and antecedent moisture content. Heathcote found that the volume of impacting water in the spray test can be related to the driving rain index as a product of the hourly rainfall intensity and the wind speed. Relating the volume of impacting water to erosion he assumed a linear relationship between the two. Based on the experimental work done under his supervision he concluded that the rate of erosion (the amount of material eroded in a unit of time, expressed in mm/min) decreases with time of exposure (min), and the shape of the erosion curve is very similar to an MMF (Morgan—Mercer—Flodin) growth curve. This result was obtained with compressed earth blocks made from a sandy loam stabilized with 3% of cement.

Regarding impact velocity Heathcote concluded that erosion was proportional to velocity raised to the power of 2.5, although there was a great variance in the results, with the 95% confidence limits being 1.9 and 3.1, and values as high as 5.5 and low as 1.0 were also recorded. The effect of velocity was investigated in seven series of tests that were performed on compressed earth blocks made from three different soils stabilized with 3–5% cement. The effect of drop size was investigated by spraying the same specimens on different faces with two different nozzles.

The specimens were made from sandy clay soils stabilized with 3% cement. Heathcote concluded, that erosion was inversely proportional to the mean drop diameter raised to the power of 1.2. It should be noted however that the two different nozzles produced jets with significantly different pressures (75 and 110 kPa) which is the parameter that was used to vary the impact velocities mentioned above. Regarding antecedent moisture content Heathcote showed that a sequential wetting and drying of specimens increased erosion by 20% in the spray test over a 2-h period for a sandy clay soil stabilized with 3% cement. On the contrary sandy loam samples that were originally dry prior to spraying eroded 30–50% more over a 1-h period compared to identical samples that were saturated beforehand.

3.1.2 Spray Testing by P. Walker, Bath, UK

Walker (2004) studied the effects of specimen geometry of compressed earth bricks on erosion performance in the spray test according to the Australian earth building handbook (HB 195, Walker and Standards Association of Australia 2002). He tested five different brick sizes and three different soil

Table 2 Extract of data from the spray tests

Reference	Sample data							Test procedure					
	Sample size			Sample shape	Curing conditions								
	Width (mm)	Length (mm)	Height (mm)	Shape	Temperature (°C)	RH (%)	Time (days)	Reference	Nozzle diameter (mm)	Water pressure at nozzle (kPa)	Distance of rose from sample (mm)	Diameter of sprayed area (mm)	Test duration (min)
Guettala et al. (2006)	100	100	200	Prismatic	20	> 70	27	Doat et al. (1979)	n/a	0.016	180	–	120
Suresh and Anand (2017)	150	150	150	Prismatic	Room	High	28	IS 1725	100	140	180	–	120
Raj et al. (2018)	150	150	150	Prismatic	Room	High	28						
Walker (2004)	140	295	45	Prismatic	Room	> 70	28	HB 195	–	50	470	150	60
Kariyawasam and Jayasinghe (2016)	240*	240*	140*	Prismatic	n/a	n/a	n/a						
Arrigoni et al. (2017)	180	180	160	Prismatic	21 ± 1	96 ± 2	28						
Heathcote (2002)	150	150	120	Cylindrical	Room	Room	28	Mod. Bulletin 5	153	60–130	470	150	60–180
Eires et al. (2017)	200	200	200	Prismatic	Room*	Room*	56	Bulletin 5	153	50	470	150	60
Cid–Falceto et al. (2012)	166	306	103	Prismatic	n/a	n/a	n/a	NZS 4298	153	50	470	150	60
	140	295	90	Prismatic	n/a	n/a	n/a						
Narloch et al. (2015)	300	300	200	Prismatic	20	high	27						
Danso et al. (2015)	140	290	100	Prismatic	27	72	21						
Stazi et al. (2016)	300	1000	1000	Wall	Room	room	90						
	250	250	20	Plaster	Room	room	15						

* Specimen size assumed from standard specimen size used in the reference, since it was unspecified for the spray testing procedure

compositions with cement content varying from 0 to 10%. The soils used were sandy loams and sandy clay loams. During the 1-h spray testing none of the stabilized samples produced any erosion.

3.1.3 Spray Testing by A. Guettala et al. Biskra, Algeria

A study conducted by Guettala et al. in the Biskra region of Algeria investigated stabilization of cement and lime stabilized compacted earth blocks, assessing the performance of mixes by testing under both laboratory and climatic conditions. (Guettala et al. 2006) The base material used was a local sandy loam which was mixed with 30% sand, and was stabilized by three different materials in eight combinations. Cement (5 and 8%), lime (8 and 12%), cement and lime (5 + 3% and 8 + 4%), cement and resin (5% + 50% resin by mass of compacting water). The resin was a commercial latex product. The laboratory spray tests were conducted according to Doat et al. (1979), with the blocks being exposed to a horizontal jet of water with a pressure of 1.6 kg/m^2 ($\sim$ 16 Pa) for 2 h, which can be considered equally low-demanding as the Biskra climate. Due to the softness of the test (compared to the usual 50 kPa pressure spray tests), these results were also satisfactory, with the worst performing samples being the ones produced with 8% lime and suffering a maximum erosion depth of 2.2 mm after the whole duration of the test, followed by the samples with 5% cement, 12% lime and 5% cement with 3% lime all ending up with a maximum erosion depth of 1 mm. The results of the laboratory and outdoor exposure tests were difficult to compare, since the climate of the Biskra region is very mild compared to those simulated by the spray tests.

3.1.4 Spray Testing by J. Cid-Falceto et al. Madrid, Spain

Cid-Falceto et al. (2012) assessed the durability of compressed earth blocks commercially available in Spain according to several international standards. Their intent was two-fold: to assess the performance of the blocks and to assess the differences of the durability tests by comparing their outcomes. Three types of blocks were tested, one unstabilized block, one stabilized by 6% cement and the third type stabilized by 8% cement-quicklime. Unfortunately there wasn't any more detailed information about the type of cement or the ratio of cement-quicklime used in the production of the blocks. All the types were subjected to four different test procedures, three spray erosion tests (specified by the New Zealand Standard NZS 4298 (SNZ, 1998), the Sri Lanka Standard SLS 1282 (SLSI, 2009) and the Indian Standard IS 1725 (BIS, 1982)) and one drip erosion test (specified by the Spanish Standard UNE 41410 (AENOR, 2008)). Both of the stabilized block types passed all four tests without reported erosion in any of the cases. Cid-Falceto et al. concluded that for the blocks tested no measurable difference was found with the different test procedures, but all of them were considered to severe for the assessment of the unstabilized block. Comparing the three spray test procedures they observed that with the different evaluation criteria it is hard to compare results between different procedures and expressed the need for a unified test.

3.1.5 Spray Testing by P. L. Narloch et al. Warsaw, Poland

Narloch et al. (2015) studied the durability of rammed earth specimens fabricated from engineered soil mixes. Four granular mixes (three sandy loams and one sandy clay loam) and three levels of cement stabilization (0, 6 and 9%) were chosen and tested according to the NZS 4298 spray test method.

3.1.6 Spray Testing by K.K.G.K.D. Kariyawasam & C. Jayasinghe, Moratuwa, Sri Lanka

Kariyawasam & Jayasinghe (2016) tested rammed earth specimens made from a sandy laterite soil with cement contents ranging from 2–10%. The test procedure of HB 195 was adapted to suit Sri Lankan conditions, but the specific adjustment were undisclosed. The erosion rates of the specimens were reported to be between 3.25 and 1.25 mm/min, corresponding to the 2 and 10% cement contents respectively.

3.1.7 Spray Testing by F. Stazi et al. Ancona, Italy

Stazi et al. (2016) studied the suitability of earth plasters for the protection of earthen buildings. In their study they investigated the effects of different natural and synthetic admixtures and surface treatments on the durability of a specific soil that can be characterized as a silty clay loam. The durability was assessed according to the spray test and drip erosion test specified by the NZS 4298. The choice of admixtures was controlled for its effect on the bond strength between plaster and substrate, for two substrates constructed with different techniques, an important aspect that was noted by Bui (Bui, 2008) as well. The results of Stazi et al. indicate that there are synthetic admixtures as well as surface treatments that are compatible with earth plasters and their substrates, both in technical and aesthetic terms, and provide an enhancement of durability as measured by the drip test and the accelerated erosion test. The most interesting case in the article is the surface treatment of an aqueous silane-siloxane solution that passed the accelerated erosion test without any erosion at all. All other plaster samples, both surface treated and with admixture generally eroded for their full depth of 20 mm within 15 min during the spray test. One exception was the sample with an admixture of aqueous emulsion of organic derivatives of silicon which endured the spray test for 30 min. Apart from the plasters, two wall samples were constructed as substrates for the testing of plasters. A cob wall and a rammed earth wall without chemical stabilization were built and tested without plaster as well, both of them suffering a mere 12 mm of surface erosion during the 60 min exposure to spraying with a pressure of 50 kPa.

3.1.8 Spray Testing by A. Arrigoni et al. Milano, Italy

Arrigoni et al. (2017a, b) conducted a life cycle analysis of the environmental impacts of stabilization comparing the durability of several mixes through accelerated erosion tests and wire brush tests, also comparing the unconfined compression strengths for reference. They used six different materials in six distinct combinations derived from practice observed in Perth, Australia. Three of the mixes were crushed limestone or recycled concrete aggregates stabilized with 10 or 5% of cement. The other three mixes were based on an engineered local soil that can be characterized as a sandy loam, of which two were stabilized. One was stabilized by 5% portland cement and 5% fly ash (a local industrial waste product) (Mix 4), the other by 6% calcium carbide residue and 25% fly ash (Mix 5). The last mix (Mix 6) was left unstabilized and is not considered in this review. Mixes 1, 3, and 5 were reported to pass the accelerated erosion test according to HB 195 without any quantifiable erosion, Mix 4 also passed the same test with minimal localized erosion, but damage expressible in an average erosion depth was not reported. These results were obtained with specimens cured at 21 ± 1 °C and 96 ± 2% relative humidity for 28 days. Curing was done in a humid environment, to facilitate the chemical reaction of the binders. This might also have resulted in a higher moisture content at the start of the spray tests, which would've been beneficiary to their durability performance according to the results of Heathcote (2002) mentioned above.

3.1.9 Spray Testing by R. Eires et al. Braga, Portugal

Eires et al. (2017) studied the effects of natural admixtures on the durability of rammed earth specimens without plastering or coating measured by wet strength, water absorption and accelerated erosion. They selected a loamy sand soil to represent poor soils and mixed it with quicklime, used cooking soybean oil, sodium-hydroxide and different combinations of these. For reference they also tested specimens mixed with cement and hydrated lime. Their results for the accelerated erosion test according to HB 195 (Walker and SA 2002) show that for the soil tested the use of quicklime significantly decreases the surface erosion rate (to 0.25% of the unstabilized soil), and although vapor permeability was decreased with every natural additive tested, it still remained higher than for any lime plaster mentioned in the state of knowledge. (Eires et al. 2017) The weakness of the original soil is demonstrated by the fact that the rate of erosion even with the chosen natural admixtures (5–11 mm/1 h, Eires et al. 2017) is almost as high as those reported by Stazi et al. for the erosion rate of unplastered rammed earth and cob substrates without any stabilizers (12 mm/h, see above).

3.1.10 Spray Testing by A. Suresh and K.B. Anand, Coimbatore, India

Suresh and Anand (2017) used a sandy clay loam to fabricate 150 mm cubic samples of rammed earth and subjected them to the spray test according to IS-1725. In this severe spray test the spray pressure is 140 kPa, the nozzle is placed only 180 mm from the sample and the duration of the test is 2 h, instead of one. Samples with 0, 3, 5 and 7% cement content were tested. All the stabilized samples easily passed the test, with the maximum depth of erosion 7 mm obtained from the sample with 3% cement.

3.1.11 Spray Testing by S. Raj S. et al. Coimbatore, India

Raj et al. (2018) studied the performance of coal ash stabilized rammed earth from various aspects. The durability performance was assessed by subjecting two mix types based on a sand soil to the spray test according to IS-1725. One mix contained 30% ash and 6% cement, while the other 30% ash and 10% cement. The pitting depths after the 2-h spray period were 5 and 3 mm respectively.

3.2 Drip Erosion Tests

Data extracted from the drip tests concentrated on the procedures applied, their main parameters and the general data of samples used in these tests. An overview of these data is shown in Table 3.

3.2.1 Drip Erosion Tests by J. Cid-Falceto et al. Madrid, Spain

Cid-Falceto et al. in their previously mentioned study (Cid-Falceto et al. 2012) assessed the durability of the compressed earth blocks also by the drip erosion test specified by the Spanish Standard UNE 41410 (AENOR 2008). Both of the stabilized (6% cement and 8% cement-quicklime) block types passed the drip test without reported erosion on any of their faces.

3.2.2 Drip Erosion Tests by Erkal et al. Bath, UK

Erkal et al. (2012) assessed the wind-driven rain related surface erosion of historic building materials. In their investigation they conducted drip tests on unfired clay bricks as well, with two different drop diameters. The mean weight loss produced by surface erosion was 1.02% for a drop diameter of 3.07 mm and 0.82% for a drop diameter of 4.06 mm with fall heights of 4.0 m. More notable than the specific results was the development of a novel methodology for the drip test. The amount of water released the drop size in a specific test are all derived from the climatic data of the site of intended application. The fall height is derived from the rain intensity vector (calculated from terminal velocity of the chosen drop sizes and the wind speeds). Erkal et al. claim that this method is straightforward and globally adaptable because of the parameters being easily adjustable and relatable to on-site measurements or region-specific climate data.

An interesting part of the research of Erkal et al. was the observation of the behavior of water drops in relation to surface roughness, angle of impact and impact velocity. They did a statistical analysis of the effect of these parameters on the drops' behavior by counting the number of instances a drop splashed, bounced off, ran off or adhered to the surface. Of the many conclusions they presented we cite the water collected by wind-driven rain gauges to measure the amount of driving rain from a certain direction could be misleading since a significant number of drops either bounce off or run off upon impact of a solid surface, but are caught by the gauges.

3.2.3 Drip Erosion Tests by F. Stazi et al. Ancona, Italy

Stazi et al. (2016) in their studied of the suitability of earth plasters for the protection of earthen buildings assessed the durability of their mixes with the drip test of NZS 4298 (NZS, 1998) as well. The silty clay loam used to produce the samples passed the test in all combinations with or without chemical stabilizers, with erosion depth ranging from 0 to 11 mm.

3.2.4 Drip Erosion Tests by R. Aguilar et al. Lima. Peru

Aguilar et al. studied the effect of chitosan as a biopolymer additive or a surface treatment on the erosion resistance of earthen construction. They subjected cylindrical specimens of 55 mm radius and 10 mm thickness made from a clay loam to the UNE 41410 drip test. The samples without additive and the one with solution A (0.5%) of chitosan failed, but the ones with 1% solution and above passed the test. The surface treated samples all passed, even with solution A (0.5%). This biopolymer seems capable of enhancing resistance of earthen constructions against water induced erosion.

Table 3 Extract of data from the drip tests

Reference	Sample Data							Drip erosion test					
	Sample size			Sample shape	Curing conditions								
	Width (mm)	Length (mm)	Height (mm)	Shape	Temperature (°C)	RH (%)	Time (days)	Test procedure	Test duration (min)	Fall height (mm)	Water released (ml)	Angle of impact to surface (°)	Weight of dripped water to sample (%)[a]
Erkal et al. (2012)	105	220	67	Prismatic	110	n/a	3	Unique	n/a	3200/4000	400/900	5–45	13/30
Cid-Falceto et al. (2012)	166	306	103	Prismatic	n/a	n/a	n/a	UNE 41410	10	1000	500	63	5
	140	295	90	Prismatic	n/a	n/a	n/a						7
Aguilar et al. (2016)	55	55	10	Cylindrical	20	60	7						826
Nakamatsu et al. (2017)	55	55	10	Cylindrical	20	60	7						826
Seco et al. (2017)	65	65	75	Cylindrical	20	100	28						79
Stazi et al. (2016)	300	1000	1000	Wall	Room	Room	90	NZS 4298	20–60	400	100	63	0
	250	250	20	Plaster	Room	Room	15						4

[a]Assuming a high density of 2000 kg/m^3 for all the samples

3.2.5 Drip Erosion Tests by J. Nakamatsu et al. Lima. Peru

Nakamatsu et al. (2017) continued the work of assessing use of biopolymers with earth by studying the effect of carrageenan as an additive and a surface treatment on the erosion resistance of earthen construction. The methods and sample sizes used were the same as with Aguilar et al. with the incorporation of outdoor weathering periods as well (see Sect. 5.1.2). Carrageenan was tested both as an additive to the mixture as solutions of three different saturations (0.5, 1 and 2%). The same solutions were used to create a surface treatment as well. Carrageenan proved to be an adequate stabilizers, both in terms of strength and durability.

3.2.6 Drip Erosion Tests by A. Seco et al. Pamplona, Spain

Extensive durability testing of unfired clay bricks was conducted by Seco et al. Sixteen soil mixes were prepared for the fabrication of bricks, to assess the effectiveness of four different stabilizers. The stabilizing agents were portland cement, hydraulic lime and ground granulated blastfurnace slag (GGBS) applied with two different activators (calcerous hydrated lime and PC-8). Aside the tests discussed in following sections the samples were subjected to the drip test according to the Spanish standard UNE 41410 as well, but all of them passed without any sign of damage.

3.3 Rainfall Simulation Test

3.3.1 The Experiments of Ogunye & Boussabaine

After analyzing the assessment methods of weatherability of stabilized compressed soil blocks (Ogunye and Boussabaine, 2002b) and concluded that none of the then available methods have been adequately verified by field performance. Ogunye and Boussabaine (2002a) presented a new accelerated erosion method, in which the discharged spectra of rainfall has been shown to be much more closer to natural rainfall characteristics (range of drop sizes, impact velocities and kinetic energy) than previous test methods. They calibrated the rainfall test rig (RTR) for the worst case scenario of a tropical rainfall of 120 h. For this the spray head was hung 2000 mm above the reference plane and a 150 mm/h rainfall intensity was simulated by spraying at a pressure of 50 kPa. Nine specimens are tested simultaneously all of them being placed on an adjustable block holder and shifted every 15 h to compensate for the differences caused by the combination of the specific spray pattern and the location of the samples on the holder. They presented preliminary soil loss results for samples cured at two different temperatures and fabricated from two different soil types (undisclosed) with varying amounts of cement (6, 8, 10%) or lime (6, 10, 15%) or lime and gypsum (6 + 1.8, 10 + 3.0, 15 + 4.5% respectively). The results were reported in average soil loss by weight (%) but the dimensions and weight of the blocks were undisclosed, so comparing it to other results in literature become difficult, since most of the spray test methods measure results in erosion depth (mm).

3.4 Slake Durability Test

3.4.1 A Quick Test Suggested by A. G. Kerali & T. H:Thomas, Kampala, Uganda

A test left unmentioned by Heathcote has been given attention by Kerali and Thomas (2004). Originally developed by Gamble (1971) for the classification of argillaceous rocks and mud-stones and later applied for cement stabilized soil blocks by Franklin and Chandra (1972). It consists of placing 30 × 30 × 30 mm, oven dried samples into a rotating drum, half immersed in water for 10 min and subsequently drying and measuring the weight loss of samples. As a result each sample is assigned a slake durability index (SDI) defined as the ratio of initial and final dry weight. Kerali & Thomas used blocks of sandy loam stabilized with varying cement contents (3–11%).

Their suggestion is given weight by the fact that the rankings obtained from the test were reported to be in good correlation with the rankings of their in-service durability performance, based on 'extensive field observations' in the tropical climate of Uganda. Since these observations were only referred to, but were left undisclosed it is hard to evaluate the realistic nature of these rankings.

3.5 Indirect Tests

From the wide range of indirect test featured in the literature reviewed only the wet to dry strength ratio was selected. This parameter has been considered by many authors to be a good predictor of in-service performance.

3.6 Wet to Dry Strength Ratio

The data extracted from reports on wet to dry strength tests is presented in Table 4. We highlight the differences in the definition of the dry and wet states, and give the average wet to dry strength ratio obtained for stabilized samples in each study.

3.6.1 Wet Strength Tests by Walker in Bath, UK

Walker (2004) investigated the strength and erosion characteristics of earth blocks. The materials tested were different engineered soils, one sandy loam and two types sandy clay loams were tested. All but one reference sample were stabilized with cement contents varying between 2.5 and 10%.

Walker concluded that unit dry compressive strength increased with increasing clay content. He also noted however that blocks containing active clay minerals that show sufficient wet strength initially are at a risk of losing this strength when subjected to cyclic wetting and drying. More importantly Walker confirmed that for the blocks studied erosion requirements of wetting and drying test and the spray test can be indirectly satisfied by the specification of wet compressive strength.

3.6.2 Wet Strength Tests by Guettala et al. in Biskra, Algeria

Guettala et al. (2006) as part of their extensive experimental program conducted wet to dry strength tests as well. The definitions of the dry state was not clear from the article, although a standard (AFNOR XP P13-901) was referred to for the used test procedure. Theirs was the highest average wet to dry strength ratio as shown in Table 4. Guettala et al. noted the severity of these tests, especially in contrast to the desert climate of Biskra.

3.6.3 Wet Strength Tests by Krisnaiah & Suryanarayana Reddy in Anantapur, India

Krishnaiah and Reddy (2008) investigated the effect of clay content on soil cement blocks. They fabricated soil blocks from a sandy loam with clay contents ranging from 7 to 11.9% and stabilized with 3% cement. According to their results the only the mix with a clay content of 9.45% manufactured with 15% water content satisfies the dry compressive strength requirement of 10 kg/cm^2 (1 Mpa), but none of the samples had a wet to dry strength ratio high enough for unprotected exterior application (0.4). The latter was attributed to the low cement content.

3.6.4 Wet Strength Tests by Reddy & Kumar in Bangalore, India

Reddy and Kumar (2011) also experimented with different clay amounts, ranging from 9 to 31.6% stabilized with cement percentages of 5, 8 and 12%. They also tested results for different dry densities. They found that the optimum value of clay content yielding maximum compressive strength for the cement stabilized rammed earth was 16% (for the specific clay minerals used in the test). The increase in density also significantly influenced compressive strength and reduced saturation water content at the same time—these two effects should positively influence wet to dry strength ratios as well (note by authors).

3.6.5 Wet Strength Tests by Alavéz-Ramírez et al. in Oaxaca, Mexico

Alavéz-Ramírez et al. (2012) experimented with sugar can bagasse ash (SCBA) to assess its potential to substitute cement as a stabilizer. As a reference samples stabilized only with lime and cement were also tested. SGBA was found to be a potent stabilizer and compares favorably to cement in terms of environmental impact. They investigated the effect of curing time and age of specimens on their strength, but found that no significant change in strength occurred over time.

Table 4 Data from the assessment of wet to dry strength ratios

Reference	Sample data								Wet to dry strength			
	Sample size			Sample shape	Curing conditions							
	Width (mm)	Length (mm)	Height (mm)	Shape	Temperature (°C)	RH (%)	Time (days)	Age (days)	Test procedure	definition of dry state	definition of wet state	Average ratio for stab. samples
Walker (2004)	Varied			Prismatic	Room	> 70	28	0	HB 195	Oven dry	24 h immersion	0.36
Guettala et al. (2006)	100	100	200	Prismatic	20	> 70	27	0	AFNOR XP P13-901	n/a	24 h immersion	0.67
Krisnaiah and Suryanarayana Reddy (2008)	144	305	100	Prismatic	Room	Room	28	0	n/a	Air dry	48 h immersion	0.20
Reddy and Kumar (2011)	150	150	300	Prismatic	Room	Room	28	28	n/a	Air dry	Saturated	0.46
Alavéz-Ramírez et al. (2012)	150	300	120	Prismatic	Room	90	0–28	3–90	n/a	Air dry	24 h immersion	0.42
Kariyawasam and Jayasinghe (2016)	240	240	140	Prismatic	n/a	n/a	28	0	SLS 1382	n/a	24 h immersion	0.54
Eires et al. (2017)	50	50	55	Cylindrical	n/a	n/a	56	0	ASTM D1633-00	n/a	Saturated	0.16

3.6.6 Wet Strength Tests by Kariyawasam & Jayasinghe in Moratuwa, Sri Lanka

Kariyawasam and Jayasinghe (2016) characterized a sandy laterite soil (sandy loam) available in the tropical regions for use in cement stabilized rammed earth production. For the wet strength test samples were stabilized with three different cement contents (5, 6 and 8%). They concluded that the specific sandy laterite soil can be reliably used as a multipurpose construction material, including external load-bearing walls, retaining walls and road construction with stabilization by a cement content of 6% or higher.

3.6.7 Wet Strength Tests by Eires et al. in Braga, Portugal

Eires et al. (2017) assessed the influence of quicklime and oil on the durability performance of a loamy sand soil. The soil was chosen to represent poor soils, which was reflected in their results as well. While it was demonstrated that a significant increase in both dry and wet strength can be achieved with the stabilizer combinations tested, none of the samples could reach a wet to dry strength ratio of 0.3. The highest achieved was 0.26, with 4% quicklime and 1% oil. Nonetheless they concluded that the use of quicklime and oil with the chosen soil results in a material that is fit to fabricate walls without render or coating even harsh climates.

4 Outdoor Experiments

4.1 Outdoor Testing of Laboratory Samples

4.1.1 Outdoor Tests in Sydney, Australia

Heathcote (2002) conducted eight series of test with samples identical to those used in his laboratory tests. The originally fabricated 150 mm diameter, 120 mm high cylinder samples were split in half to obtain two faces as identical to each other as possible, the split face being always the one subjected to the testing/driving rain. Heathcote's contributions will be discussed in Sect. 6.

4.1.2 Experiments in Lima, Peru

Nakamatsu et al. (2017) experimented with the biopolymer carrageenan both as an additive and a surface treatment for adobe. Since the work was conducted in Lima, low demanding laboratory erosion tests (drip erosion test) were deemed suitable to assess the durability performance for the local climate, which has an extremely low average annual rainfall of 18 mm (weatherbase.com), with average wind speeds around 4 m/s and a maximum of 11 m/s (weatheronline.co.uk). The base soil was a clay soil, and a series of samples were tested after curing at ambient conditions, another series was placed outdoors. Although the samples exposed to outdoor conditions were all intact at the end of the 95 day test, they were afterwards subjected to the same drip erosion test to assess the effects of weathering on the carrageenan treatments. They reported a decrease of durability compared to the initial performance regardless of whether carrageenan solution was used as an additive or a surface treatment. Since there was no rain during the outdoor exposure time and temperatures were far from freezing (between 20 and 30 deg. C) the deterioration of the biopolymer film was attributed to solar radiation. When the solution was used as an admixture in the soil it was protected by the soil particles and the deterioration was much less severe.

4.1.3 Experiments in Pamplona, Spain

Seco et al. (2017) conducted an analysis of the relationship between the main parameters of earth based construction materials' production and their durability to achieve a better understanding of how durability performance can be estimated. They chose a clayey silt base soil which they stabilized with three different materials: portland cement, natural hydraulic lime (NHL-5) and ground granulated blastfurnace slag (GGBS). In the case of the GGBS they experimented with two different activators: calcareous hydrated lime (CL-90-S) and PC-8 a byproduct of the calcination of natural $MgCO_3$ rocks. All four cases were used to produce samples with different percentages of sand added to the base soil (0, 10, 30 and 50%). All the samples passed the laboratory tests specified by the Spanish Standard UNE 41410, but since only 10 of the 32 samples passed the outdoor exposure, the Swinburne accelerated erosion test (drip test) was deemed not demanding enough and incapable of providing a good estimate of the durability performance of the studied mixes in the Spanish climate. The climate in the region of the test site has an average annual rainfall of 1042 mm (weatherbase.com), with an average wind speed around 3 m/s and a maximum of 11 m/s (weatheronline.co.uk). The specific climate data showed, that during the outdoor exposure there were 60 days when temperature dropped below 0 °C. Although the dates of failure for each sample were presented, the failure criterion for the outdoor exposure wasn't discussed in the article. Thus the results of this study are hard to compare with other studies assessing the durability of earthen building materials, because both the laboratory and the outdoor exposure test were conducted by a different method than the others presented in this review, with even the geometry of the specimens being different.

4.2 Outdoor Testing of Wall Samples

4.2.1 Experiments in Biskra, Algeria

Guettala et al. (2006) tested their samples (as described in Sect. 1.3.3) under climatic conditions as well by building eight test walls, 30 cm wide, 90 cm long and 15 cm high. The desert climate of Biskra has an average annual rainfall of 130 mm (weatherbase.com) with average wind speeds around 9.7 m/s and a maximum of 22.2 m/s in winter (Guettala et al. 2006). This climate doesn't pose a threat to earth constructions in general, with a very low amount of rainfall, although the variations in relative humidity (90% in winter to 10% in summer) and the winds might affect the erosion process. The wall specimens were unsheltered (unrendered and without any protection from above) and were observed for 4 years at the end of which no erosion was reported for any of them during this time period. Minimal localized erosion was seen on the sides exposed to the dominant winds of the samples with 8 and 12% lime. An average erosion depth of 1 mm was reported for the former and 0.5 mm for the latter.

4.2.2 Experimental Site Near Grenoble, France

A comprehensive study was started in France in 1985 that was evaluated by Bui et al. after 20 years of natural weathering (Bui et al. 2009) in a climate with 1000 mm average annual rainfall and a maximum wind speed of 21 m/s and an average of 3.3 m/s (timeanddate.com). The original setup contains 104 wall units built with four different construction techniques and portraying a wide variety of coatings and renders. The walls were relatively small (1000 mm × 400 mm × 1100 mm) compared to buildings and all of them had a roof overhang that was scaled based on their height to model an average overhang to wall height ratio (1/15). Bui and Morel presented the results for three rammed earth wall units, two from unstabilized soils, one from stabilized. They chose the three reference units that were left without any render or surface treatment. In this review we only cite the uncovered reference wall for the lime stabilized rammed earth. They reported an average erosion depth of 2 mm for this wall, with a maximum erosion depth of 7 mm, although determination of the original surface is somewhat debateable since there were no reference points placed during construction to determine the location of the initial surface.

4.2.3 Experiments in Scotland, United Kingdom (Morton and Little 2015)

Morton and Little wrote the report of a vast experimental project focused on gaining a deeper understanding of traditional earth building techniques of Scotland, the locally available materials and their interaction with other materials (straw, lime, animal blood and urine, etc.). The aim of the experimental program was to evaluate the traditional techniques from a contemporary point of view, i.e. what can be developed into modern earth building techniques, but also to assess the suitability of a range of repair methods. Here we only cite the cement stabilized rammed earth test wall for reference, but otherwise encourage the reader to explore the report of this rich program first hand. The wall was constructed from a silty clay loam stabilized with 10% of cement. A manual rammer was used during fabrication, but a mechanical digger was needed for its deconstruction after a 7 year exposure period. During this period the wall was inspected ten times, but it suffered very little visible damage apart from a small patch at the base of the wall.

Morton and Little noted that this mix should rather be considered as a weak cement, than an earth wall, as they found that the inclusion of cement at this ratio fundamentally changed the characteristics of the material.

4.2.4 Measurements in Fujian Province, China

Luo et al. (2019) presented the results of an extensive field measurement program with an erosion model for predicting the erosion rate of unrendered rammed earth walls. This work stands apart from the previous research presented since the data was obtained from existing buildings rather than test walls or samples and the rammed earth walls observed were unstabilized. Nonetheless it features a durability assessment method that could provide a fourth category: 'in-situ' performance measurements and is therefore briefly discussed as well.

Luo et al. measured the erosion of existing rammed earth walls similar to the ones in the Fujian region that are part of the World Heritage List. Monthly measurements were made for 6 years with the help of narrow stainless steel erosion pins (5 mm diameter, 100 mm length) fixed into the walls in a 1.5 by 1.5 m grid. The measuring tool was a digital depth gauge with a precision of 0.02 mm. Values were obtained for seven walls, with different orientations, roof protection and slightly different composition, these values were than statistically analyzed. The average annual erosion was between 0.54 and 2.43 mm, with the lowest value obtained from a wall that was well protected by a roof and in an orientation with low exposure to wind-driven rain, and the highest obtained from a wall without eaves overhang and high exposure. The erosion model was developed from the rainfall soil-loss theory supplemented with the results of the field measurements. This takes into account the amount of roof protection as well, but seems to lack the connection between wind and rain events.

5 Discussion

5.1 Remarks on the Assessment Methods

5.1.1 Validity of the Standardized Test Methods

Current knowledge deems driving rain as the most dominant factor in the erosion of earthen walls. This resulted in the utilization of spray tests as the most common tool in assessing the durability of earth materials, but the drip tests, wet to dry strength ratios and wire brush tests were also quite common among the encountered research. These tests are utilized the most in spite the fact that many authors have questioned their reliability in predicting in-service performance of the materials. (Ogunye and Boussabaine 2002b; Erkal et al. 2012) This could be attributed to the fact, that most of the test were incorporated into standards before the publication of their critiques.

Ogunye and Boussabaine proposed a new test method (2002a), the rainfall simulation test (discussed in Sect. 3.3.1) which has been demonstrated by them to simulate the characteristics of natural rainfall much more closely. This is one possible way of providing more reliable results.

Heathcote (2002) after extensive study of rainfall parameters made a small modification to the Bulletin-5 spray test, namely using a nozzle that produces individual droplets of water rather than a continuous jet, thus better simulating natural rainfall characteristics. Heathcote also managed to develop a numerical method to correlate the results obtained from this modified test to field measurements. He took care that the method be adaptable to any climate, but to the author's knowledge no one has followed up on this.

5.1.2 Problematic Variance in Test Parameters Among Authors

Although most of them being standardized tests described in national normatives there is still a lot of variance among authors in test parameters. The parameters of sample size, antecedent moisture content and measurement/expression of results are discussed below.

Sample size has been shown to matter a great deal, as noted by Cid-Falceto et al. (2012). A more extreme example is illustrated in Table 3 by the ratio of released water to sample weight in a drip test expressed in percentages. The original purpose of the drip test was to assess the erosion performance of soil blocks, but the test done in Lima used 1 cm high cylindrical samples. This seems to alter the severity of the test quite extremely.

Heathcote (2002) has demonstrated that different moisture contents prior to testing can produce results with a difference as high as 50%. Based on this controlling either the curing parameters or the moisture content of the samples before testing should be part of the standards defining the tests.

Concerning the measurement of erosion there is the question whether the maximum or the average erosion depth should be measured during a test, and what basis of reference should be used in a laboratory test and a field experiment. If erosion is expressed in mm, what is the reference plane or point in a test. This question might be answered quite easily for laboratory tests, but is quite hard to tackle in field measurements as seen in the report of Bui et al. (2009). In this matter the application of the erosion pin method by Luo et al. is a much welcome advancement.

If erosion is expressed in weight lost (%), it is the reference weight of a sample that comes into question. Usually dry weight is specified for practical reasons, but as it is noted by Ogunye and Boussabaine (2002a, b) oven dry weight is basically never reached in built-in situations. It would seem suitable to compare the weight lost to the weight of the sample before testing, but this in turn evokes the question of pre-test moisture conditions mentioned above. Expressing in weight lost is always relative to the weight of the sample and the moisture conditions of the reference weight. For this reason it is quite hard to extrapolate these results for a full-sized wall construction with ever changing moisture conditions.

Sometimes erosion is expressed as a reduction in thickness expressed in percentages. This seems practical for structural calculations, but is otherwise quite meaningless in itself. For this reason it is considered inadvisable for expressing erosion test results solely in percentages of thickness, as it can be calculated easily from results expressed in mm or even from ones expressed in percentage of weight lost.

Categorization of measured results are currently relative to each other, but for the most part remain unrelated to expectable in-service performance. The qualitative evaluation of test results should be correlated to measured field performance. Heathcote (2002) has made progress in this matter as mentioned before.

These above mentioned variances make for an inconsistent body of research in the field. A universally accepted definition of durability for earthen constructions, that is independent of the parameters of climate, technique and design would allow to derive evaluation criteria specific to any unique combination of these parameters.

6 Remarks on the Costs of Stabilization

The main appeal of earthen materials, namely their sustainability is called into question with the most commonly used stabilizer: cement. The performance and application of alternative stabilizers is still uncertain in many cases. Synthetic chemical additives like silane-siloxane raise similar problems as those encountered with cement, while biodegradable additives provide sufficient, but potentially short-lived protection.

The cost of achieving an acceptable durability should also be acceptable in terms of environmental impacts and its effects on other properties of the material. For example a study into the recyclability and reusability of soils with these admixtures is needed. Firstly to help alleviate the of the lack of consensus on this matter and secondly to assess its weight in the degree of sustainability of the construction material. There is also potential in the investigation of the application methods for stabilizing agents. The adequate mixing of admixtures often requires extensive preparation, infrastructure and attention manageable in laboratory conditions, but problematic on-site.

Design trends and expensiveness of manual labor are pushing the boundaries of earth construction: if the newly built earth houses keep with recent design trends, then based on the above further investigation is needed into alternative stabilizing agents (other than cement), mainly in terms of outdoor performance and weathering due to climatic factors.

Most of the research encountered reinforces the belief that unstabilized earth is unsuitable to be exposed to outdoor conditions. This is considered misleading by the authors, since the selection of soils in research of stabilized earth construction are dominated or at least highly affected by their suitability for the specific stabilizer investigated (Houben and Guillaud 1994). Stabilized soils also have a different erosion characteristic than unstabilized ones (Heathcote 2002), that is why the durability test methods are usually noted as incapable of assessing the performance of unstabilized soils. There is also a vast heritage of earth buildings that contradict the apparent lack of trust towards unstabilized earth construction (Van Damme and Houben 2018).

Based on the above it would seem worthwhile to investigate the performance of unstabilized earthen materials.

7 Conclusions

- In spite of the difficulty in comparing the results of research and experience of practice, the data collected reinforce that the durability performance of stabilized earth constructions is adequate for widespread use.
- Durability test parameters of sample size, pre-test moisture conditions and measurement methods should be incorporated into the relevant standards. Earth building practice worldwide would benefit from a unified assessment system, that can take into account these parameters.
- A long awaited validation of durability assessment methods should be done:
  - Either by developing a new test method that reliably simulates in-service conditions and its parameters are adaptable to different climates,
  - Or by defining a numerical relationship between the results of existing test and in-service conditions, that is capable of taking into account specific climate characteristics.
- An investigation of alternative stabilizers with low environmental impact is needed, mostly regarding their weathering due to climatic factors.
- Assessment of existing strategies aiming to provide durability for earth constructions other than stabilization (i.e. renders, coatings, white-washes, roof overhangs, structural inserts) is needed, that quantifies at least the relative performance of these approaches.
- The erosion mechanisms and the durability performance of unstabilized earth materials merits a comprehensive investigation.

Acknowledgements Open access funding provided by Budapest University of Technology and Economics (BME). The authors would like to thank the help of Dániel Bakonyi PhD for his comments and advice in the proofreading stage.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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