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Cow-dung stabilised compressed earth blocks: a mechanistic approach to understand its water resistance behaviour

Yask Kulshreshtha · Philip J. Vardon · Gabrie M. H. Meesters ·
Mark C. M. van Loosdrecht · Nelson J. A. Mota · Henk M. Jonkers 

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Abstract Cow-dung is a widely used stabiliser applied in traditional earthen buildings with one objective to improve water resistance. However, most research has focused on explaining its mechanical strength, with only one study suggesting water resistance mechanism via formation of insoluble compounds at high pH, a phenomenon uncommon in natural cow dung and soil mixtures. This article investigates the water-resistance behaviour of cow-dung stabilised compressed earthen blocks (CD-CEBs) through an extensive experimental programme to understand the influence of cow-dung and soil related factors and to characterise the components of cow-dung responsible for its water resistance. It was found that the small-sized microbial aggregates (SSMA) present in cow-dung, which are negatively charged hydrophobic aggregates of low specific surface area, are responsible for enhanced water resistance of CD-CEBs. The insights gained from experiments are compiled to recommend the following

strategies for improved performance of CD-CEBs: (i) The use of wet cow-dung is advised over dry cow-dung as it provided over 80 times better water resistance; (ii) Adopting a higher compaction liquid content (by 3%) improved the water resistance by over 40 times; (iii) The water resistance of CD-CEBs was improved over 30 times by using soils rich in low-swelling clay minerals such as kaolinite. A case study applying these findings demonstrates the successful scaleup from the lab to field showcasing potential of cow-dung and soil in low-carbon construction.

Keywords Cow-dung · Earthen construction · Water-resistance · Immersion · Microbial aggregates

1 Introduction

Building with unfired earth (mud) is a practice over 10000 years old that is regaining its popularity due to the rising concern of the impact of the construction sector on the climate. Earthen buildings offer several advantages over standard practices such as improved indoor thermal comfort, reduced operational and embodied energy use, and the potential of the materials to be reused. The raw material for earthen construction, ‘soil’, is generally excavated from the building site but may not always be suitable for construction. Hence, one or more binders or stabilisers are often added to the soil to improve its strength and durability characteristics.

Y. Kulshreshtha · P. J. Vardon · H. M. Jonkers (✉)
Faculty of Civil Engineering and Geosciences, Delft
University of Technology, Delft, The Netherlands
e-mail: H.M.Jonkers@tudelft.nl

G. M. H. Meesters · M. C. M. van Loosdrecht
Faculty of Applied Sciences, Delft University
of Technology, Delft, The Netherlands

N. J. A. Mota
Faculty of Architecture and the Built Environment, Delft
University of Technology, Delft, The Netherlands



Cow-dung is a commonly available natural and biological stabiliser that is widely used across Asian and African countries [1, 2], whose use in traditional earthen construction is primarily motivated by its water resistance characteristics [3–7]. For example, globally there are over 1 billion cows [8] with each producing an estimated 9–68 kg of dung per day [9–11]. Cow-dung is known to be composed of undigested plant fibres (consisting of cellulose, hemicellulose and lignin), microorganisms, fatty acids, esters, polysaccharides, aldehydes, amine, alkylhalides, fragments of intestinal tissues and traces of sulphur, calcium, iron, magnesium, and manganese [5, 11–14]. While there are multiple scientific studies showing the positive impact of cow-dung on water resistance and strength of earthen materials [4–7, 15–18], none provides a comprehensive investigation on the mechanism responsible for improved water resistance or strength.

In their study, Millogo et al. [5] proposed that the chemical reaction between cow-dung and soil under alkaline condition results in the formation of an insoluble compound that binds the soil aggregates together, simultaneously improving strength and water resistance. However, this compound remained undetected in their characterisation study. Moreover, the alkaline condition reported (pH of 12) and presumed in the study of Millogo et al. [5] to result from the fermentation of cow-dung is significantly higher than the pH range of 6.5–9.5 reported for cow-dung in other studies [19–22]. Thus, there remains a need to verify their hypothesis. Water resistance of cow-dung is also anecdotally attributed to the fibres present in cow-dung, however, the mechanism of how fibres cause increase of the water resistance is unclear [23]. Therefore, a thorough investigation into the role of various components of cow-dung is needed to provide new insights into the mechanism(s) responsible for the water-resistance improvement of cow-dung stabilised earthen blocks.

This article investigates the water-resistance behaviour of cow-dung stabilised compressed earth blocks (CD-CEBs) through an extensive experimental programme to (a) Identify and characterise the components of cow dung responsible for its water-resistance, (b) Assess the impact of cow-dung and soil related parameters on water resistance and compressive strength relationship, and (c) Understand the mechanism responsible for the disintegration of

CD-CEBs upon water ingress. The insights obtained in this research are used to lay out practical recommendations for the efficient use of cow-dung in earthen structures.

2 Experimental design

The parameters and variables selected for experimental investigation were developed through a series of three preliminary studies conducted to characterise cow-dung stabilised earthen materials. Key outputs of these studies were: (a). Use of wet-dung gives better water resistance and (b). Optimal cow-dung content in CD-CEBs was found to be equivalent to 2% mass of dry dung in dried soil.

Table 1 provides an overview of the experimental programme of this study, including the objective of the test series and the variables involved. It should be noted that Test series A-E was conducted with cow-dung collected in a single batch; a different batch was used for Test series F.

3 Materials and methods

3.1 Soil

The soil used in the experiments was supplied by Oskam V/F (Netherlands). The soil was excavated from a tunnelling site and it is used in commercial production of compressed stabilised earth blocks (CSEB) in the Netherlands. The soil characterisation is presented in Table 2. In addition to natural soil, ‘manufactured or artificial soil’ for test series F were prepared with commercially available kaolinite (Sigma-Aldrich), bentonite clay (Sigma-Aldrich) and river sand (0.125–0.25 mm). Soils were prepared by adding 14.8% mass of kaolinite or bentonite (equivalent to clay content in the natural soil) to sand (0.125–0.25 mm).

3.2 Cow-dung and its components

Fresh (wet) cow-dung was collected from a biological cow farm located in Delfgauw, the Netherlands. The dung was collected in plastic buckets with airtight lids and stored at room temperature until its usage (up to 30 days). The solid content in the freshly collected



Table 1 Summary of experimental design

Objective	Test series code	Variable	Definition
To evaluate the improvement in water resistance with cow-dung stabilisation	A	cow-dung content	Mass of cow-dung relative to the mass of dry soil. Note: samples prepared with and without cow-dung
To evaluate the factors influencing strength and water resistance of cow-dung stabilised earthen blocks (CD-CEBs)	B1	Ageing of cow-dung	Duration of storage after collection of fresh cow-dung (1, 8, 15, 30 days)
	B2	Ageing of soil and cow-dung mixture	Duration of storage after mixing soil and dung (1, 5, 14, 28 days)
To identify and characterise the component of cow-dung which makes CD-CEBs water resistant	B3	Compaction liquid content	Liquid content in the earthen block immediately after compaction (12.1% - 15.6%)
	B4	Compaction pressure	Amount of pressure applied during compaction of soil cow-dung mixture into CD-CEBs (1.25 MPa and 2.5 MPa per block)
To optimise the CD-CEBs for better water resistance	C	Components of cow-dung	Various components separated from cow-dung: fibres, small-sized microbial aggregates (SSMA) and medium-sized microbial aggregates (MSMA). Amount of each component mixed with soil is given in Sect. 3.3.1
	D	Components of cow-dung (their combinations)	Combinations available in Table 3
To understand the variation between dry cow-dung or wet cow-dung stabilised CEBs	E	Wet and dry cow-dung	Wet dung refers to fresh cow-dung in its natural liquid state, while dry dung was obtained by drying wet cow-dung in a well-ventilated fume hood at 21 °C for a week
To understand the role of soil type on performance of CD-CEBs	F	Soil type	Natural and artificially created soil Natural soil was collected from a tunnel excavation, while artificial soil was prepared by mixing sand (0.125–0.25 mm) with kaolinite or bentonite clay (see Sect. 3.1 for more details)



Table 2 Summary of properties of the soil natural Dutch soil used in this study

Properties	Value	Method	Standard/Reference
Predominant clay minerals [wt%]	Smectite (37.2), illite/smectite (35.1)	XRD (<0.002 mm)	In-house protocol, Qmineral
Grain size distribution			
Clay (<0.002 mm) [wt.%]	14.8	<i>Hydrometer</i>	ISO 17892-4 [24]
Silt (0.002–0.074 mm) [wt.%]	16.5	<i>Wet sieving</i>	
Sand (0.075–4.74 mm) [wt.%]	68.5	<i>Wet sieving</i>	
Fine gravel (4.75–6.74 mm) [wt.%]	0.2	<i>Wet sieving</i>	
Atterberg limits			
Liquid Limit [%]	28.8	<i>Falling cone</i>	ISO 17892-6 [25]
Plastic Limit [%]	15.2	<i>Thread</i>	ISO 17892-12 [26]
Plasticity Index [LL-PL]	13.6		
Unified soil classification system	CL (inorganic clay of low to medium plasticity)		
Natural water content [%]	3.5	<i>Oven drying at 105 °C</i>	ISO 17892-1 [27]
Compaction characteristics			
Maximum dry density [kg/m ³]	1980		
Optimum Moisture content [%]	11.1		
Specific Gravity	2.6887	<i>Ultrapycnometer</i>	ISO 17892-3 [29]
pH	7.36 (21 °C)	<i>pH meter</i>	*
Cation exchange capacity (meq/100 g)		<i>Co (III)-hexamine</i>	Bardon et al. [30]
Bulk			
Clay (<0.002 mm)	78.7		
Loss on ignition [%]	1.15	<i>Heating at 550 °C</i>	BS EN 15935 [31]

*1 part of soil was mixed with 5 parts of demineralised water (accounting for 3.5% water content in the soil), stirred magnetically for 5 min, and the pH measured after 10 s

cow-dung (mass of oven dried dung relative to the mass of wet dung) was measured to be 10.8%, and the pH was 7.5. The solid content in various batches of cow-dung was measured in the range of 9.5–12.2%.

The fresh cow-dung was separated into fibres and microbial biomass (or microbial aggregates) through wet sieving followed by centrifugation at 5000 rpm for 10 min (Model: Heraerus megafuge 16, ThermoFisher, Germany). Microbial biomass was separated by washing fresh cow-dung on a sieve, either directly (in case of block preparation) or with tap water (in case of component analysis, 90 g of cow-dung was washed with tap water until the filtrate was clear, requiring ~1 L). The filtrate containing microbial aggregates was collected and centrifuged at 5000 rpm for 10 min. The centrifugation process resulted in settling of heavier microbial biomass, termed medium-sized microbial aggregates (MSMA), leaving supernatant liquid termed

small-sized microbial aggregates (SSMA), as shown in Fig. 1. The solid mass of fibres, MSMA and SSMA were found to be 42%, 24% and 34% respectively. The particle size distribution of MSMA and SSMA were determined with the laser particle size analyser (DIPA 2000, Donner technologies / Ankersmid, Netherlands) giving a range and mean size of 1–63 µm and 19.8 µm respectively for MSMA and 0.5–7 µm and 2.7 µm for SSMA.

3.3 Production of cow-dung stabilised compressed earth blocks (CD-CEBs)

3.3.1 Preparation and storage of soil cow-dung (soil-CD) mixtures

Soil and cow dung (and components) mixtures were prepared using a mix design and standard mixing procedure and its slight variations, as shown in Table 3.



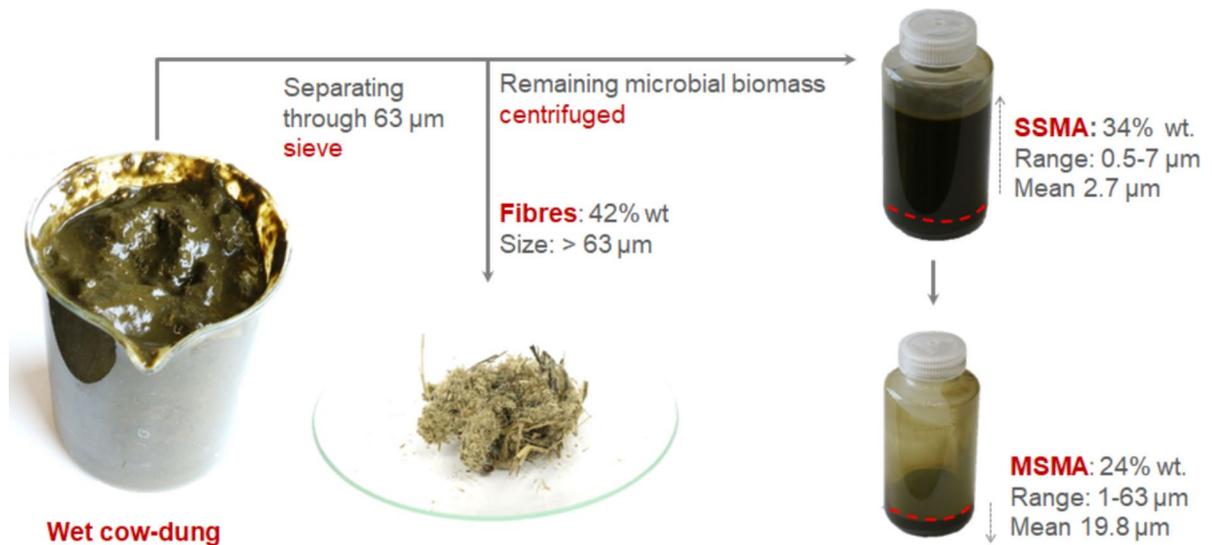


Fig. 1 Separation of components from wet cow-dung

In the standard mixing procedure, wet cow-dung was added to soil gradually and mixed manually for a duration of 5–10 min. The amount of cow-dung added to soil was equivalent to 2% dry cow-dung in dried soil (by weight), as per the results from a preliminary study. The solid content in cow-dung and natural water content in soil was determined prior to the mixing by heating the materials at 105 °C for 24 h in an oven, and accordingly wet cow-dung (naturally occurring only) and soil were mixed to ensure 2% dry cow-dung in dried soil. The age of cow-dung used in most mixtures was 1 day.

After preparation of the soil cow-dung mixtures, they were stored in a metal container tightly sealed with plastic film for a duration of 5 days at room temperature. It was observed that storing soil-CD for over 3 days eliminates odour.

For the test series on components of cow-dung (C), the amount of separated components of cow-dung (Fibres, MSMA and SSMA) added to the soil was determined by their respective proportions in cow-dung. For example, SSMA represents 34% of the solid mass of cow-dung. Therefore, the corresponding amount of SSMA added in soil was equivalent to 0.68% (34% of 2%) dry mass of SSMA. Similarly, mixtures were prepared with 0.84% fibres and 0.48% MSMA. Adding these specific dried mass to the block ensured a fair comparison with soil mixed with 2% cow-dung dried mass.

Details on the specific variations on mixture design for each test series is summarised in Table 3.

3.3.2 Casting and drying of CD-CEBs

CD-CEBs were produced using a custom-made assembly capable of casting 9 blocks of 40 mm × 40 mm × 40 (± 1) mm simultaneously (video available at <https://youtu.be/yc37SiTrFM>). A pre-determined amount of mixture was filled based on the information obtained from the Harvard miniature compaction apparatus for the desired block size (details available in [32]). Initial liquid content of all the mixes were determined before casting (refer Table 3). No releasing agent (e.g. oil) was used and all CEBs were prepared with a compaction pressure of 2.5 MPa per block, with the exception of Test series B4, F4 and F5. In B4, mixture was compressed with 1.25 MPa to study the influence of lower compaction pressure on characteristics of CD-CEBs, whereas machine compaction was found infeasible for F4 and F5, as preliminary trials on compacting sand specific mixes resulted in damage to the mould. Hence, these were hand compacted with a hand-held metal rammer. Unlike other CD-CEBs which were removed from the mould immediately after casting, CD-CEBs of Test series F4 and F5 were removed from the mould only after 14 days. The compaction process in most mixes resulted in release of liquid and

Table 3 Summary of mix design, mixing procedure and mixture storage

Test series code	Variable	Soil	Stabiliser	Initial liquid content (ILC)	Mixing procedure and variations	Mixture Storage and variations	Compaction Liquid content (CLC)	Note
A	Cow-dung content (Base design)	Natural Dutch soil—NDS (ref. Table 2)	Cow-dung—CD (2%)	18.9% (naturally occurring)	Standard	Standard	15.6%	
B	Cow-dung and soil related parameters	NDS	None	15.1% (water)	Standard	Stored for a day before use	12.7%	
B1	Ageing of cow-dung	NDS	CD (2%)—stored for 1, 8, 15, 30 days before mixing with soil	8.2 ± 0.7% (natural)	Standard	Standard	15.2 ± 0.4%	Variation in ILC due to ageing related consistency changes in CD
B2	Ageing of soil and cow-dung mixture	NDS	CD (2%)	18.8 ± 0.9 (natural)	Standard	CD- soil mixture stored for 1,5,14, 28 days after mixing	15.6 ± 0.5%	Variation in ILC due to natural ageing
B3	Compaction liquid content	NDS	CD (2%)	12.3%, 13.6%, 14.9%, 18.9%	Drying of mixtures (with a temperature-controlled air blower set at 60 °C) was necessary to reach the desired liquid contents (12–19%)	Standard	12.1%, 13.1%, 14.2%, 15.6%	
B4	Compaction pressure	NDS	CD (2%)	17.9% (natural)	Standard	CD- soil mixture stored for 20 days	17.1%	

Table 3 (continued)

Test series code	Variable	Soil	Stabiliser	Initial liquid content (ILC)	Mixing procedure and variations	Mixture Storage and variations	Compaction Liquid content (CLC)	Note
C	Components of cow-dung (Fibre, MSMA, SSMA)				Two sets of samples were prepared for mixtures with components of cow-dung: at optimum liquid content (10–13%) and at wetter liquid content (14–19%)			Optimum liquid content is defined as liquid content corresponding to maximum dry density. CD stored for 13 days before separating components
C1	Fibre	NDS	Fibres (0.84%) –Extracted from cow-dung and oven dried at 60 °C for 24 h	11%, 18.7%	Fibres were mixed with soil, and tap water was added to reach the desired ILC	Mixture was stored for 1 day before casting	10.9%, 17.1%	Based on the cow's diet of ryegrass, hay, and silage (fermented grass), the extracted fibres are expected to be their digested form
C2	MSMA	NDS	MSMA (0.48%) –Extracted in form of a thick paste (~23% solid content) as per the process (without tap water) explained in Sect. 3.2	10.5%, 19%	MSMA paste mixed with soil to achieve 0.48% dry MSMA mass in dried soil. Tap water was added to reach the desired ILC	Standard	10.2%, 16.8%	No sample remained for ILC measurement; therefore, the exact water added to soil and MSMA paste mixture is reported (accounting for liquid content in the paste)

Table 3 (continued)

Test series code	Variable	Soil	Stabiliser	Initial liquid content (ILC)	Mixing procedure and variations	Mixture Storage and variations	Compaction Liquid content (CLC)	Note
C3	SSMA	NDS	SSMA (0.68%)— extracted in form of suspension (~6% solid content) as per the process (without tap water) explained in Sect. 3.2	12.3%, 20.8%	SSMA liquid mixed with soil to achieve 0.68% dry SSMA mass in dried soil. Mixture was dried with a temperature-con- trolled air blower set at 60 °C to achieve desired ILC	Standard	11.9%, 18.9%	
D	Components of cow-dung (their combinations)							
D1	Microbial aggre- gates (cow-dung without fibres)	NDS	SSMA + MSMA (1.16%)— extracted in form of a suspension (~13% solid content) as per the process (without tap water) explained in Sect. 3.2	16%	Similar to proce- dure used in C3	Standard	13%	Stabiliser content of 1.16% based on % of SSMA (0.68%) & MSMA (0.48%) in CD CD stored for 20 days before separating compo- nents
D2	Excess microbial aggregates	NDS	SSMA + MSMA (2.32%)— extracted in form of a suspension (~13% solid content)	13.6%	Similar to proce- dure used in C3	Mixture stored for 24 h before casting due to appearance of fungus in mix- ture in 2 days	13.6%	Stabiliser content was double that of D1 CD stored for 27 days before separating compo- nents

Table 3 (continued)

Test series code	Variable	Soil	Stabiliser	Initial liquid content (ILC)	Mixing procedure and variations	Mixture Storage and variations	Compaction Liquid content (CLC)	Note
E	Wet and dry cow-dung	NDS	Dry Cow-dung (2%) – Obtained by drying wet cow-dung in a well-ventilated fume hood at 21 °C for a week	15.4%	2% dry cow-dung soaked in a pre-determined amount of water and mixed with soil	Similar to procedure used in D2	13.9%	
F	Soil type							CD from another batch
F1	Soil 1: Natural Dutch soil	NDS	CD (2%)	20.4% (natural)	Standard	Standard	17.8%	
F2	Mix 2: Kaolinite rich soil + CD	Kaolinite (14.8%) + Sand: 0.125–0.25 mm (85.2%)	CD (2%)	20.2% (natural)	Standard	Standard	19.7%	
F3	Mix 3: Bentonite rich soil + CD	Bentonite (14.8%) + Sand: 0.125–0.25 mm (85.2%)	CD (2%)	33.6%	Water was added to reach the desired liquid content close to their plastic limit (34%)		30.5%	
F4	Mix 4: Sand (0.125–0.25 mm) + CD	Sand (0.125–0.25 mm)	CD (2%)	20.4% (natural)	Standard	Standard	20.4%	Dry sand mixed with cow-dung, and hand compacted in 3 layers. Blocks were demoulded only after 14 days, as they were too soft to handle

Table 3 (continued)

Test series code	Variable	Soil	Stabiliser	Initial liquid content (ILC)	Mixing procedure and variations	Mixture Storage and variations	Compaction Liquid content (CLC)	Note
F5	Mix 5: Sand + SSMA	Sand (0.125–0.25)	SSMA (0.68%)— extracted in form of a thin suspen- sion (~6% solid content)	23%	Similar to proce- dure used in C3	Standard	-	Dry sand mixed with cow-dung, and hand compacted in 3 layers. Blocks were demoulded only after 14 days, as they were too soft to handle

therefore, compaction liquid content (liquid content immediately after compaction) was also determined (details in Sect. 3.4). The measured compaction liquid content for each mixture is indicated in Table 3.

After determination of mass and dimensions of freshly casted blocks, they were dried for 14 days at $19 (\pm 1) ^\circ\text{C}$ and $55 (\pm 2)\%$ relative humidity, with the exception of Test series F, where CD-CEBs F2 and F3 were dried for 21 days, and CD-CEBs F4 and F5 were dried for 28 days. A longer drying duration was required for CD-CEBs F2 and F3, as they were made with manufactured soil and were still slightly wet after 14 days. CD-CEBs F4 and F5 were demoulded after 14 days as they were too soft to demould earlier, and were therefore left for an additional 14 days to allow complete drying. The mass and dimensions of all blocks were determined after their respective drying period.

3.4 Water resistance and compressive strength tests

Out of every 9 blocks prepared from each mixture, 6 blocks were selected for water resistance tests, and remaining 3 for compressive strength. To evaluate the water resistance, the immersion test and drip erosion test were chosen due to their reliability in assessing the efficacy of stabilisers [33].

The immersion test was carried out by placing CD-CEBs in a glass jar filled with water and images were captured with a digital camera (Canon 70D) at different time intervals spread over 24 h (1–5 min (video), 10 min, 15 min, 20 min, 30 min, 1, 2, 4, 6, 9, 12 and 24 h). In exceptional scenarios when the earthen blocks were significantly water resistant, images were also captured in 2, 3, 5, 7 and 10 days.

The drip erosion test assembly consists of water dripping from a showerhead (placed at a height of 30 cm) above the block, which is oriented at 27° to horizontal. The rate of flow of water was adjusted to be 50 ml/min based on a study by Nakamatsu et al. [34] and the mass loss (%) was calculated at 2 and/or 10 and 60 min based on the resistance of the individual blocks. For the shorter duration (2/10 min), the mass was measured from the material collected in a tray placed below the sample, whereas for the longer duration (10/60 min), it was determined by removing the block, drying it in an oven and weighing it.

The compressive strength of CD-CEBs was tested in a compression testing machine (Model:

E161PN114, Matest, Italy) set with the following loading parameters: loading rate=0.5 kN/s with a starting load=0.5 kN. After testing each block, the residual liquid content was determined by oven drying and along with information on mass loss upon drying, used in the re-calculation of compaction liquid content.

3.5 Advanced characterisation tests

Physical and chemical characterisation tests were performed on microbial aggregates (specifically the ones responsible for water-resistance) and stabilised CEBs to gain insights on their response to water ingress. Zeta potential measurement was conducted on microbial aggregates using Zetasizer Nano ZS (Malvern, UK) to find the net charge and the influence of pH on it (at solid concentration of 0.07%). The microstructure of the cow-dung, its components and their composites with various soil minerals, were characterised using a Quanta F650 environmental scanning electron microscope (ThermoFisher, Germany). ESEM equipped with a concentric back scattered (CBS) detector was used to capture images at 10 or 15 kV under vacuum at magnifications ranging from 125 \times to 20000 \times . The specific surface area of microbial aggregates was measured using Gemini VII 2390 gas adsorption analyser (Micrometrics, US). Mercury Intrusion Porosimetry (MIP) was conducted on selected CD-CEBs using Autopore IV equipment (Micromeritics, US) to understand the role of pore-structure on water-ingress. The freeze-drying process used by Bruno et al. [35] was followed to prepare the samples. Pyrolysis Gas chromatography-mass spectrometry (Py-GC-MS) was conducted to characterise

the compounds in the microbial aggregates. Contact angle measurements were performed on microbial aggregates and CD-CEBs to study their hydrophilic and hydrophobic behaviour using two approaches: (a) Dropping 50 μ L of a water droplet and recording the video with a digital camera (Canon 70D). (b) Dropping 15 μ L droplets and measuring the contact angle using a vhx-7000 digital microscope (Keyence, Belgium). The sample preparation process for characterisation test is available in [32].

4 Results

4.1 Water resistance of cow-dung stabilised compressed earth blocks (CD-CEBs)

The addition of cow-dung results in significant improvement of water resistance. In the immersion test (Test series A) shown in Fig. 2, unstabilised CEBs disintegrate completely within 20 min of immersion, whereas the CD-CEBs with the base design disintegrate partially after 24 h of immersion, with first cracks appearing after 2 h. This observation was congruent with drip erosion test (see Sect. 3.4) results where the best performing unstabilised CEBs showed erosion of 14.7% after 10 min of the drip erosion test, compared to 0.03% and 0.28% erosion of CD-CEBs after 10 min and 60 min respectively. The drip erosion test indicates that the addition of cow-dung (2%) results in an improvement in water resistance of over 500 times. It should be noted that the value obtained in lab results may not reflect the performance of these materials in outdoor climate. Experiments conducted on unstabilised CEBs and

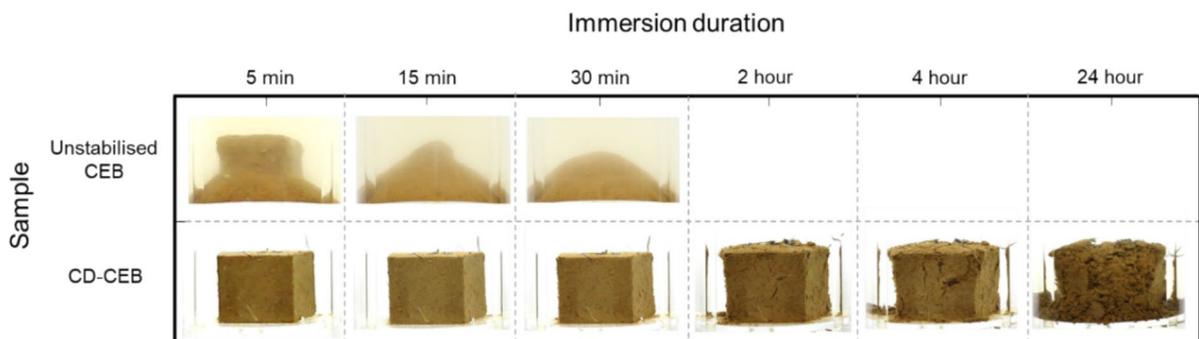


Fig. 2 Time-lapse showing disintegration of unstabilised CEB and CD-CEB– Test Series A

CD-CEBs exposed to 134 days of outdoor climate resulted in improvement of merely 8 times.

Variables influencing water resistance of cow-dung stabilised compressed earth blocks (Test series B) such as ageing of cow-dung, ageing of soil and cow-dung mixture, compaction liquid content and compaction pressure were investigated and results are presented in Figs. 3 and 4.

The water resistance of CD-CEBs is concluded to be substantially unaffected by the cow-dung ageing duration (Test series B1). The ageing of soil and cow-dung mixture (Test series B2) had a positive influence on water resistance, with improvement notable in immersion test, particularly for 14 days ageing duration as shown in Fig. 3. However, the improvement was not reflected in drip erosion test where erosion

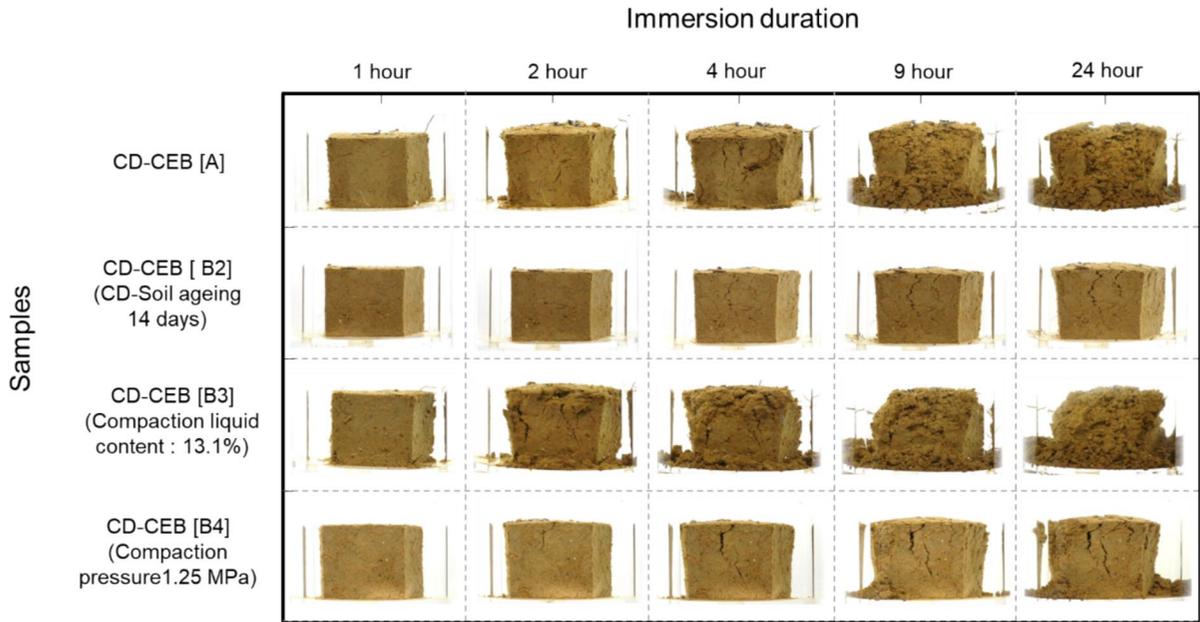


Fig. 3 Time-lapse showing the disintegration of selected CD-CEBs produced with varying mix design: ageing of soil and cow-dung mixture (Test series B2), compaction liquid content (Test series B3) and compaction pressure (B4)

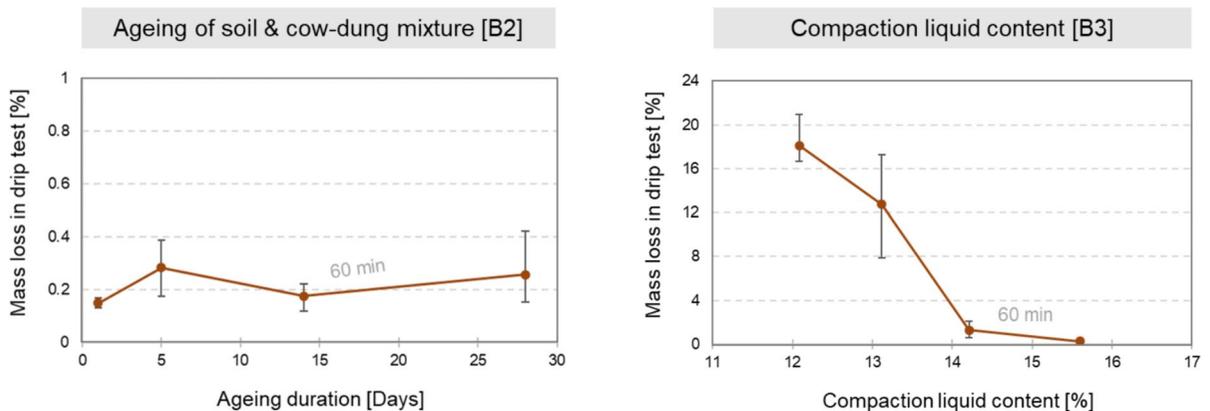


Fig. 4 Influence of soil and cow-dung ageing (left) and compaction liquid content (right) on drip erosion test conducted for a duration of 60 min



of all CD-CEBs was restricted to a narrow range of 0.1–0.3% (Fig. 4).

The water resistance characteristics of CD-CEBs improved with an increasing compaction liquid content (Test series B3), as measured through the immersion test (Fig. 3) and the drip erosion test (Fig. 4). The mass loss in drip erosion test decreased drastically from 18% to 1.3% by increasing the compaction liquid content from 12.1% to 14.2%. With a further rise in compaction liquid content to 16.1%, the mass loss decreases again slightly and reaches a value of 0.3%. A similar trend was also found in the immersion test where the CD-CEBs with a compaction liquid content of 13.1% show a significant level of disintegration beyond 1 h. With a further rise in compaction water liquid, the CD-CEBs were more stable in water. The water resistance characteristics reaches a plateau at higher liquid contents and a further increase in compaction liquid content has a minimal impact on the water resistance characteristics.

The influence of compaction force on the characteristics of CD-CEBs (Test series B4) was investigated by comparing the CD-CEBs prepared with compaction pressures of 2.5 MPa (as in Test Series A) and 1.25 MPa. The result of the immersion and drip erosion test reveal that the compaction force has an insignificant impact on the water resistance of CD-CEBs. The immersion test results illustrated in Fig. 3 show similar performance for CD-CEBs compressed with 1.25 MPa compaction force and 2.5 MPa compaction force. Similarly, the drip erosion test revealed a mass loss of 0.2% in both the CD-CEBs.

4.2 Components in cow-dung responsible for water resistance of cow-dung stabilised earthen blocks (CD-CEBs)

To understand the reason behind water resistance of CD-CEBs, the components of cow-dung were separated and further analysed in order to find evidence of which one contributes most for the water resistance of CD-CEBs (Test series C).

The drip erosion test results of earthen blocks stabilised with the components separated from cow-dung (separation explained in 3.2) is shown in Fig. 5. Irrespective of compaction liquid content, the addition of fibres and MSMA increased the water resistance characteristics substantially in comparison to unstabilised specimens (Fig. 5). However, it was the CEBs stabilised with small-sized microbial aggregates (SSMA) which shows most significant improvement of water resistance performance, even exceeding that of cow-dung stabilised CEBs. The mass loss recorded in SSMA stabilised CEBs was less than 0.3%

The observations in the drip erosion test are also confirmed in the immersion test results of samples prepared at optimum liquid content as shown in Fig. 6. Unstabilised CEBs and CEBs with MSMA or fibres could not survive the immersion beyond 15 min. However, SSMA stabilised CEBs could resist 24 h immersion with minimal disintegration, also performing significantly better than CD-CEBs. The results of test performed on stabilised CEBs prepared at higher compaction liquid content are available in [36].

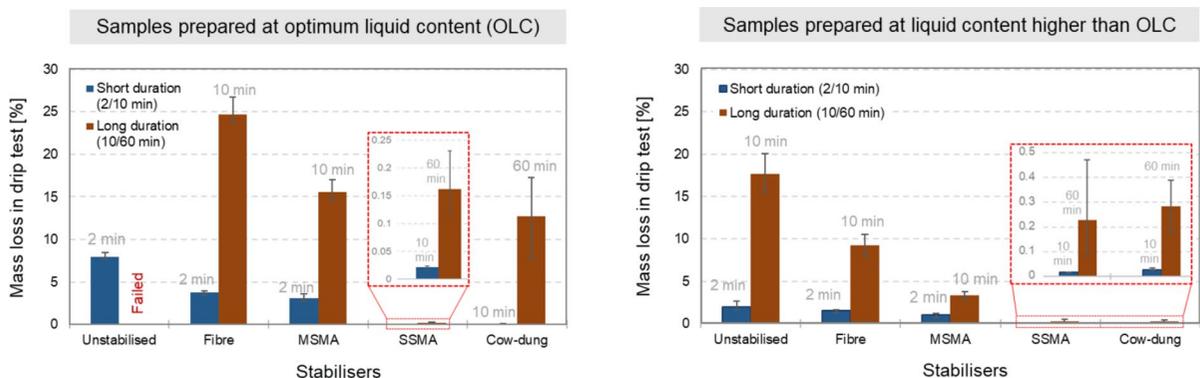


Fig. 5 Results of drip erosion test performed on stabilised CEBs prepared with individual components of cow-dung (Test series C) and compared to cow-dung stabilised CEBs and unstabilised CEBs (Test series A)

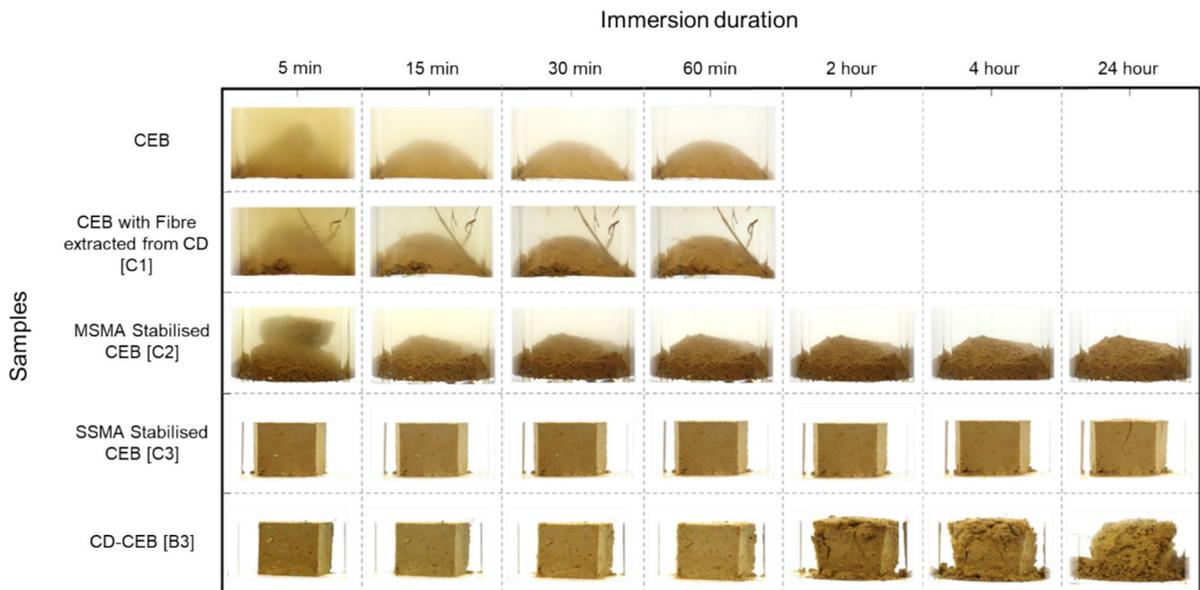


Fig. 6 Time-lapse showing disintegration of CEBs prepared with individual components extracted from cow-dung (test series C) and compared to CD-CEBs and unstabilised CEBs

The results presented in Figs. 5 and 6 conclude that SSMA, which constitute approximately one-third of the solid mass of cow-dung, are entirely responsible for water-resistance of cow-dung and CD-CEBs in this study. These results go against of the established perception that fibres present in cow-dung are mainly responsible for water resistance.

Due to their significant impact on water resistance of CD-CEBs, Small-sized microbial aggregates (SSMA) were extracted from cow-dung used in this study as per the process available in Sect. 3.2, and were characterised thoroughly. The results are summarised in Table 4, with further information available in [36].

Small-sized microbial aggregates (SSMA) can be considered in soil mechanics terms as organic hydrophobic non-layered clays with a low specific surface area, i.e. based on the particle size. Their small quantity of 0.68% in the soil is enough to provide the water resistance to the compressed blocks. Studies have also identified bacteria in cow-dung that are capable of producing extracellular polymeric substance (EPS) which could facilitate interaction with each other and the soil [14, 38]. The interaction of SSMA and cow-dung with soil will be discussed in Sect. 5 in detail using the additional insights gained in the next section.

4.3 Optimisation and evaluating factors influencing water resistance performance of CD-CEBs

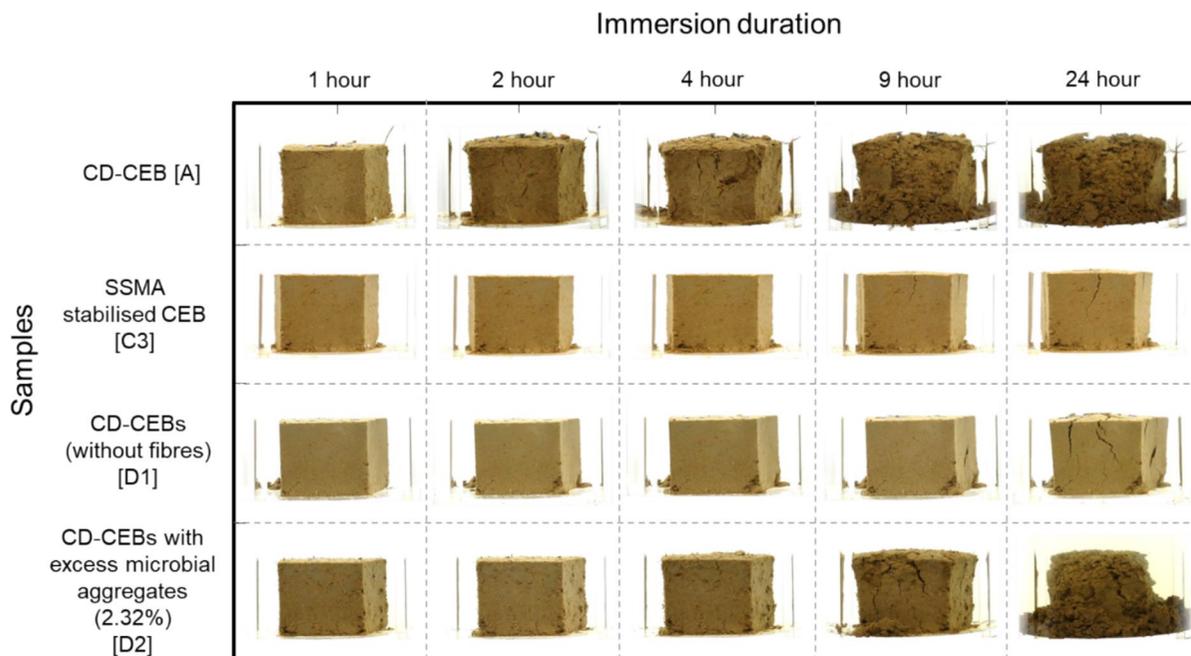
Various routes to improve the efficiency of cow-dung stabilised CEBs are discussed in this section, in particular optimising CD-CEBs using components of cow-dung and their combinations, understanding the variation between dry cow-dung or wet cow-dung stabilised CEBs and role of soil type on performance of CD-CEBs.

4.3.1 Impact of removing the fibres or increasing microbial aggregate quantity on water resistance of stabilised earthen blocks

The CEBs produced with SSMA have shown better water resistance than all CD-CEBs. The extraction of SSMA from cow-dung on site is both time consuming and expensive whereas extracting microbial aggregates (SSMA + MSMA) from fibres using a sieve of 63 μm is relatively feasible. Therefore, experiments were also conducted by adding the microbial aggregates solution (extracted from cow-dung using sieve) to the soil, making CD-CEBs but with no fibres (Test series D1). Removal of fibres from cow-dung has a positive influence on the water resistance characteristics, as shown in Fig. 7. Considering the reported diet

Table 4 Characteristics of the extracted small-sized microbial aggregates (SSMA)

Characteristics	Test	Results	Comment
Size	Laser particle size analyser	Range: 0.5–7 μm Mean: 2.7 μm	–
Morphology	ESEM	Spherical and rod-shaped structures of about 1 μm	–
Elemental composition	ESEM—EDS	Predominately carbon, oxygen and silica elements, with traces of magnesium, phosphorous, sulphur, chlorine and calcium	Widely reported elements in cow-dung research [5, 11–13]
Chemical composition	Pyrolysis–gas chromatography mass spectrometry	Over 150+ compounds detected. The dominant compound (55% of the total composition) identified were acetic acid, butanoic acid (butyric acid), octadecanoic acid (stearic acid), n-Tetracosanol-1, n-Hexadecanoic acid (palmitic acid) and propanoic acid	SSMA are rich in volatile fatty acids that are responsible pungent smell and hydrophobicity. Octadecanoic acid has been used with silica nanoparticles to prepare water-resistant superhydrophobic coatings [37]
Specific surface area	Gas adsorption analyser	1.7–2.2 m^2/g	Non-layered structure and low cation exchange capacity. For example, the clay minerals of natural Dutch soil have a specific surface of 52 m^2/g
Surface charge	Zeta potential measurement	Negatively (-ve) charged above pH 2	
Surface affinity/energy	Contact angle	120°–130°	Hydrophobic, droplet does not percolate into the material hence, SSMA acts as a barrier to water ingress

**Fig. 7** Time-lapse showing disintegration of stabilised CEBs with SSMA (0.68%), and cow-dung without fibres-SSMA+MSMA (1.16%) and SSMA +MSMA (2.32%)

of the cows, the fibres present in the cow-dung are likely derived from a mixture of ryegrass, hay, and silage. However, detailed characterisation of these fibres is necessary to accurately determine their specific contribution to the material behaviour. Further discussion regarding the inclusion or exclusion of fibres is provided in Sect. 5.1.

In addition to removing fibres from cow-dung, experiments were also conducted with cow-dung soil mixture with doubled microbial biomass, MSMA + SSMA (2.32%) (Test series D2, see Table 3). In contrast to expected positive influence, CD-CEBs with extra microbial aggregates had inferior performance.

4.3.2 Comparison of dry and wet cow-dung stabilised CEBs

All the previous scientific studies on cow-dung utilised dry cow-dung, with exception of the earliest study by Ngowi [6] which utilised wet cow-dung. To understand the difference of the impact of using fresh and dried cow-dung, CD-CEBs were prepared with dry cow-dung (Test series E). The results of the

immersion test shown in Fig. 8 gives clear evidence that dry cow-dung is not as effective as wet/ fresh cow-dung. CD-CEBs with dried cow-dung did not survive 1 h of immersion. The mass loss of CD-CEBs with dry cow-dung after 60 min was measured to be 23.7%, in contrast to 0.28% for CD-CEBs with wet cow-dung. Hence, use of wet cow-dung provides 80 times more water resistance than dried cow-dung.

Additional CD-CEBs prepared with dried microbial aggregate (oven dried at 60 °C for 24 h) provide clear evidence that drying microbial aggregates before mixing them with soil does not facilitate water resistance characteristics (Fig. 8). Their water resistance characteristic was slightly better than the CD-CEBs made with dried CD, possibly due to the absence of fibres.

4.3.3 Influence of soil type on water resistance of CD-CEBs

A limited test series was conducted on artificially created soils with varying soil components (Test series F). As shown in Fig. 9, the presence and type of clay minerals have a major influence on the water

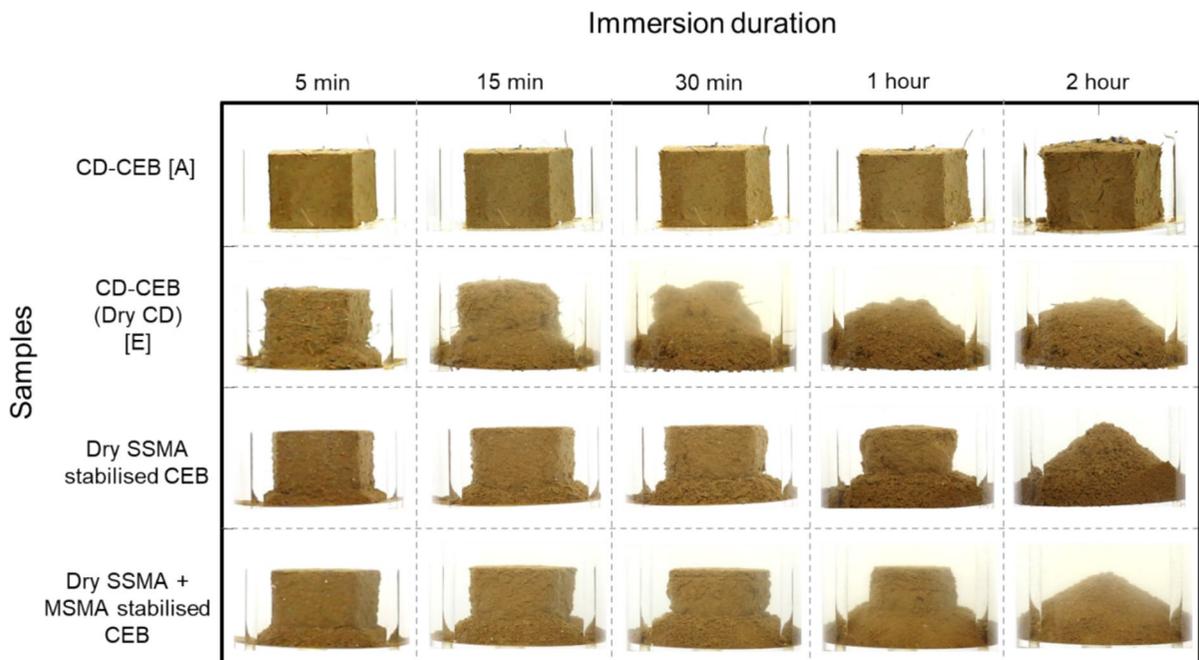


Fig. 8 Time-lapse showing disintegration of stabilised CEBs prepared with fresh/wet cow-dung, dry cow-dung and various combinations of dried microbial aggregates



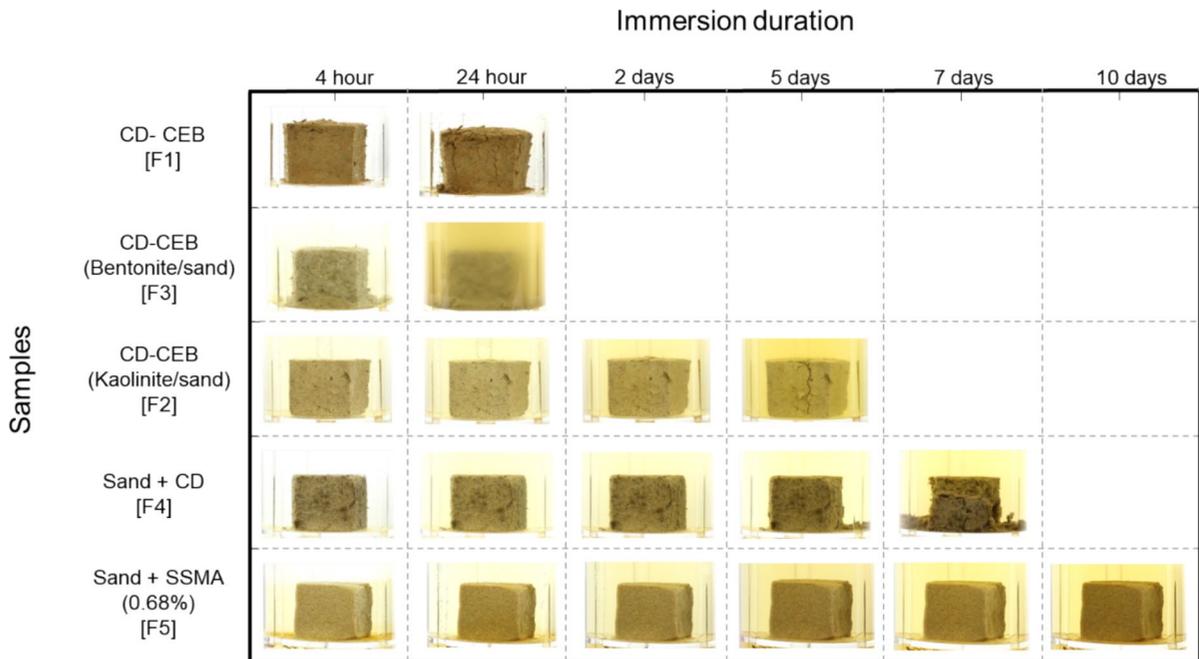


Fig. 9 Time-lapse showing disintegration of CEBs prepared with different types of soil minerals (Test series F)

resistance of CD-CEBs. The CD-CEBs prepared with bentonite/sand mixture (Test series F3) start disintegrating faster than the CD-CEB made with natural Dutch soil (Test series F1, Table 2).

The CD-CEBs prepared with kaolinite soil performed extremely well with the first cracks appearing in 5 days. With increasing immersion duration, the colour of the surrounding fluid changed to yellowish probably due to leaching of microbial aggregates which have shown the same colouration when diluted with water. However further analysis is needed to confirm this hypothesis. Based on the performance of kaolinite and bentonite clay-rich soil, it can be inferred that the lower cation exchange and low surface area, thus low-activity of clay (such as in kaolinite clay) is favourable to cow-dung stabilisation. Whereas, clays with higher activity such as bentonite and the clay in the natural Dutch soil are susceptible to disintegration upon immersion. Moreover, the absence of clay is even more favourable for water resistance. The cow-dung stabilised sand block resisted immersion for over 2 days without any disintegration (Fig. 9). The disintegration started on the 4th day and a significant mass disintegrated after 7 days. As known from the previous discussion,

fibres aid to disintegration. Therefore, a block was also prepared with 0.68% SSMA (corresponds to the amount in 2% cow-dung) and sand. These blocks could survive disintegration for 10 days with no erosion. Although stable in water, SSMA stabilised sand blocks (and cow-dung stabilised sand blocks) were fragile and had no measurable strength (further results confirming this are shown in Sect. 5.2).

4.4 Compressive strength of cow-dung stabilised compressed earth blocks (CD-CEBs)

The maximum compressive strength measured for unstabilised CEB (Test series A) was 4.2 MPa, similar to the maximum average compressive strength of CD-CEBs. Thus, it can be concluded that the addition of cow-dung does not have a positive impact on the compressive strength of earthen blocks prepared with the soil used. Although, making a comparison on compressive strength between CD-CEBs and unstabilised CEBs is challenging due to their different dry densities (1.88 g/cm^3 for CD-CEBs as compared to 1.98 g/cm^3 for unstabilised CEBs), caused due to addition of low-density fibre rich cow-dung.

The compressive strength trends for a few selected CD-CEBs are presented in Fig. 10 (more results compiled in Sect. 5). The ageing of cow-dung does not have a significant influence on the compressive strength of CD-CEBs, as the compressive strengths (found to be in a narrow range of 3.5–3.8 MPa) correlate strongly with the dry density variation. Influence of soil cow-dung mixture ageing duration (Fig. 10, Test series B2) is significant on the compressive strength. Irrespective of similar densities, a significant increase in compressive strength is observed in the mixture stored for 14 days. With increase in mixture ageing duration from 1 to 14 days, the compressive strength increased with 14% from 3.6 to 4.1 MPa. This increase in strength is found to be independent of compaction liquid content and mineralogical difference in soil.

The influence of compaction liquid content on compressive strength is significant and directly correlated to dry density. The compressive strength increased from 3.3 MPa to 3.8 MPa with an increase

in compaction liquid content from 12.1 to 13.1% (Fig. 10, Test series B3). The maximum strength was achieved around the optimum liquid content which reduces with a further rise in compaction liquid content to 14.2%. A further rise in the compaction liquid results in a slight decrease in dry density reaching a value of 1.88 g/cm^3 , similar to the value observed for the compaction liquid content of 12.1%. An increase in liquid content beyond compaction liquid content of 14.2%, results in an unexpected increase in compressive strength, irrespective of relatively lower dry density values. This was corroborated by overlying a region of compression strength (blue) and dry density (orange values) of various CD-CEBs. Due to the lack of explanation behind this unusual trend, it is recommended to study the influence of liquid content on characteristics of CD-CEBs further in detail.

A reduction in compression force during manufacturing of blocks reduces the dry density and compressive strength. The strength and dry density of CD-CEB compressed with the 1.25 MPa force

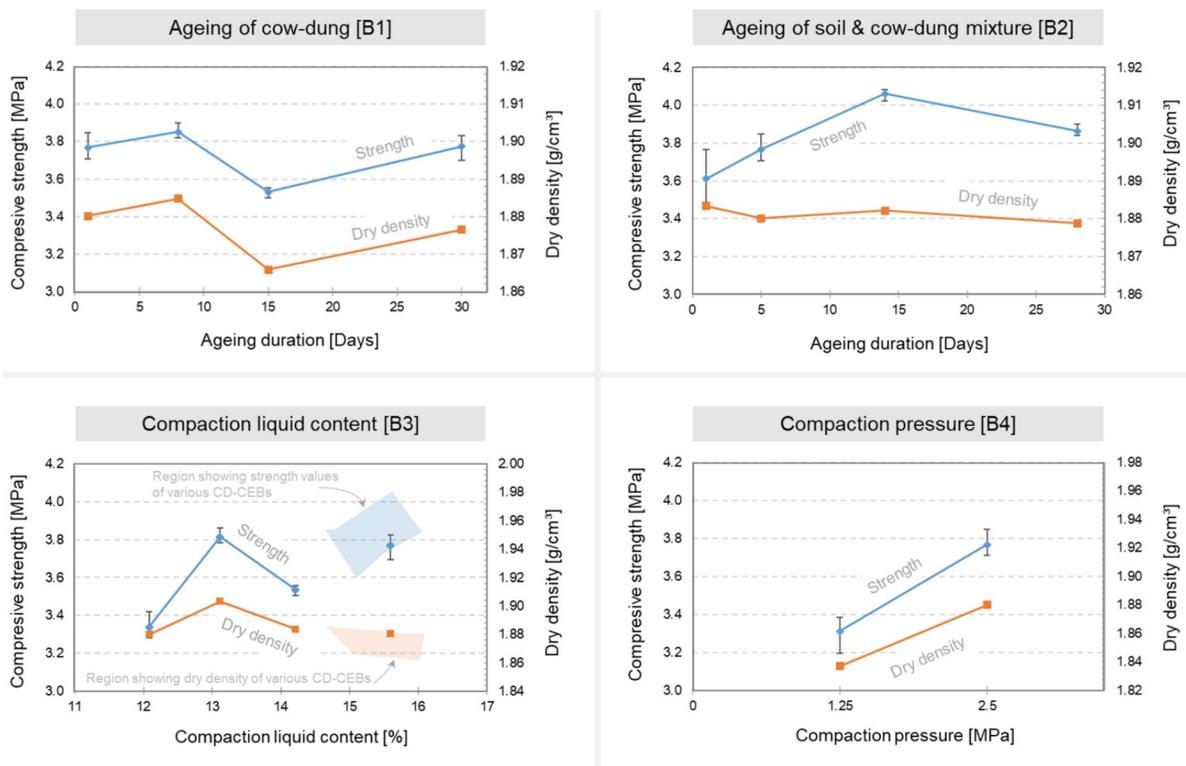


Fig. 10 Compressive strength of CD-CEBs. Trends are shown for influence of ageing of cow-dung (Test series B1), ageing of soil and cow-dung mixture (Test series B2), compaction liquid content (Test series B3), compaction pressure (Test series B4)



was 3.3 MPa and 1.84 g/cm³, respectively. Interestingly, the strength of 3.3 MPa was also observed in CD-CEBs (compaction liquid content of 12.1% and compaction force 2.5 MPa) of dry density 1.87 g/cm³. This further reinforces the previous observations that a higher compaction liquid content of CD-CEB results in higher strength than the CD-CEBs compacted near optimum or drier liquid content.

Unlike the influence of cow-dung on strength of CEBs made with natural Dutch soil (Table 2), the strength of CD-CEBs prepared with kaolinite rich soil improved drastically with the addition of cow-dung. The compressive strength was found to increase by 17 times (from 0.1 MPa for unstabilised CEBs made with kaolinite clays to 1.7 MPa with cow-dung stabilisation). A similar observation was reported by Rao et al. [14]. Hence, the interaction of cow-dung and its component varies significantly with the type of soil mineral.

5 Discussion

5.1 Strategies for enhancing CD-CEBs: insights from water resistance and strength analysis

To evaluate the relative impact of different variables for identification of strategies resulting in maximum performance gain, the water resistance and strength results obtained in experiments are compiled and the results of selected stabilised CEBs is presented in Fig. 11. The bottom plot presents key findings that leads to better water resistance.

Figure 11 shows the relationship between compressive strength and mass loss in the drip erosion test of several stabilised CEBs. The mass loss in most cow-dung stabilised blocks was measured in the range of 0.1–1% (60 min test duration). Moreover, most CEBs have sufficient compressive strength for construction (> 1 MPa), with the exception of stabilised sand blocks that were fragile (see blue markers in the plot). Figure 11 (bottom) provides a visual of the dominant variables affecting CD-CEBs performance. Increasing the compaction liquid content by 3%, results in over 40 times improvement in water resistance of CD-CEBs (see route 1, compare orange and red markers in Fig. 11 (bottom)).

Use of wet cow-dung over dry cow-dung results in over 80 times better water resistance and 17% higher

compressive strength (see route 2, compare grey and red markers). An investigation into dry and wet microbial aggregates revealed that when the microbial aggregates were dried and ground (through ball milling), the mean diameter measured was roughly 4–10 times more than the wet microbial aggregates (particles in suspension). When cow-dung dries, it is expected that the microbial aggregates coagulate and reduce the effective surface area significantly (details available in [36]). The reduced surface area and increased size of microbial aggregates could narrow their spatial distribution in the block and reduce their interaction with other particles resulting in lower efficiency.

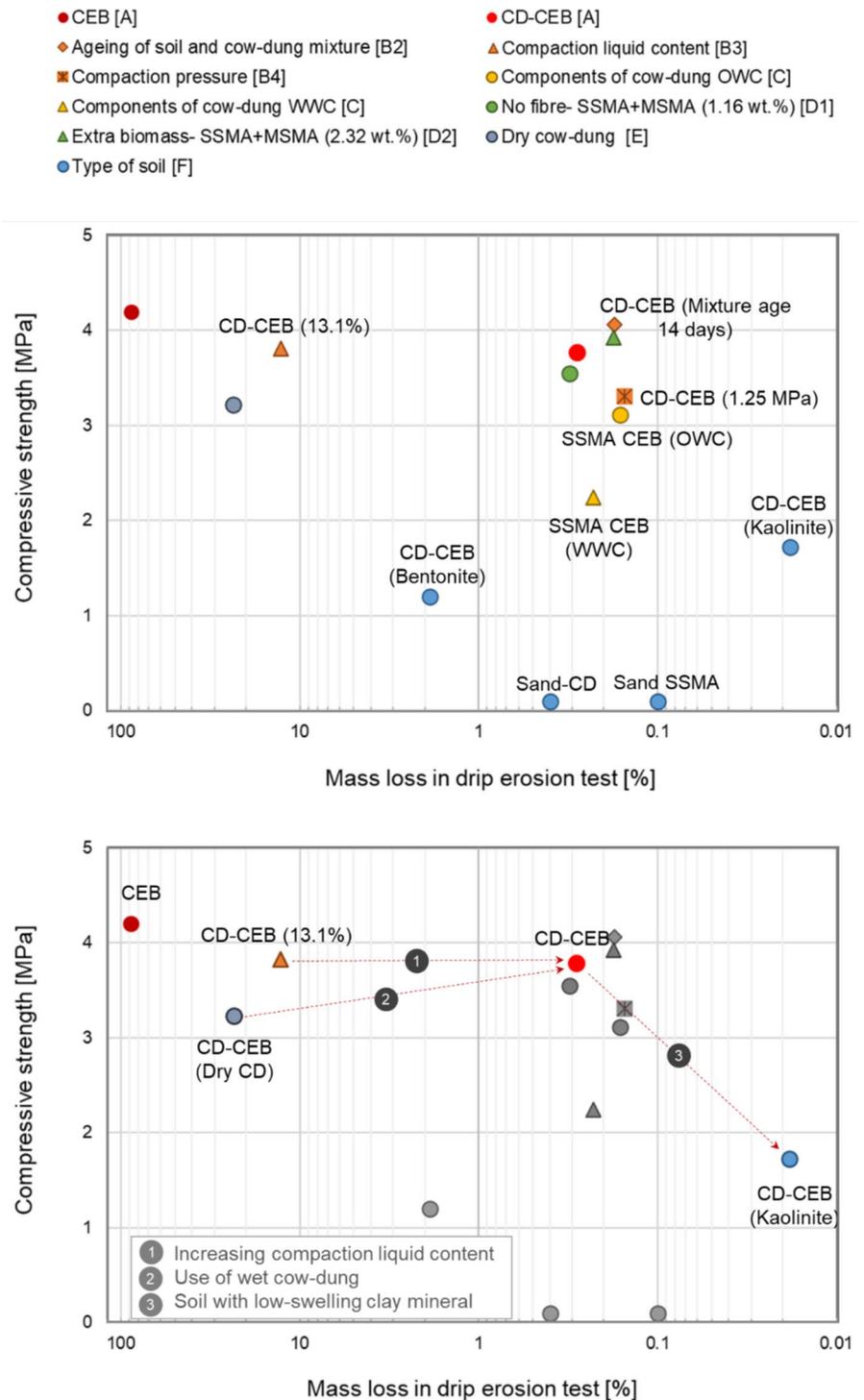
The water resistance of CD-CEBs was improved 30 times by using a low-swelling clay mineral such as kaolinite rich soil (see route 3, compare red and blue markers). Although, use of kaolinite rich soil decreases the strength by more than half. The lower strength of artificially created soil could be due to poor grading and lower cohesion than clays present in natural soil. Even though the immersion test of cow-dung /SSMA stabilised sand blocks (shown in Fig. 9) indicates they are more water stable than all other CD-CEBs, the result from drip erosion test show erosion due to their fragile nature. This indicates that while the absence of clay may favour water resistance, clays are required for the strength of earthen materials.

The results from the drip erosion test provide a quantitative assessment of the relative influence of several variables however, it makes the comparison between CEBs with closer erosion values challenging. Due to the longer duration of the immersion test, it provides more nuanced information on the relative performance of stabilised CEBs. Hence, in addition to drip erosion test results, immersion test results are compiled and presented in Fig. 12. In Fig. 12, the region left to the red line shows images of CEBs captured after 60 min of immersion, whereas the region on the right shows images captured after 24 h of immersion. Moreover, In CEBs with a similar disintegration profile after 24 h of immersion, the drip erosion test values were used in positioning the samples on the relative scale of water resistance performance.

The immersion test provides a clearer information on the influence of some variables such as ageing of soil and cow-dung mixture (Test series B2) and components of cow-dung (Test series C and D). Figure 12 (bottom) shows the positive impact of



Fig. 11 Relationship between compressive strength and mass loss in drip erosion test (60 min) for selected samples. For CEBs that were tested only up to 10 min, the 60 min value was estimated through linear extrapolation by multiplying the 10 min erosion value by 6



the ageing of soil and cow-dung mixture (14 days) on both strength and water resistance of CD-CEBs (see route 4). An extended period of ageing (over

3 days) not only removes the pungent smell of cow-dung from the mixture but it does not re-occur even after wetting the blocks.



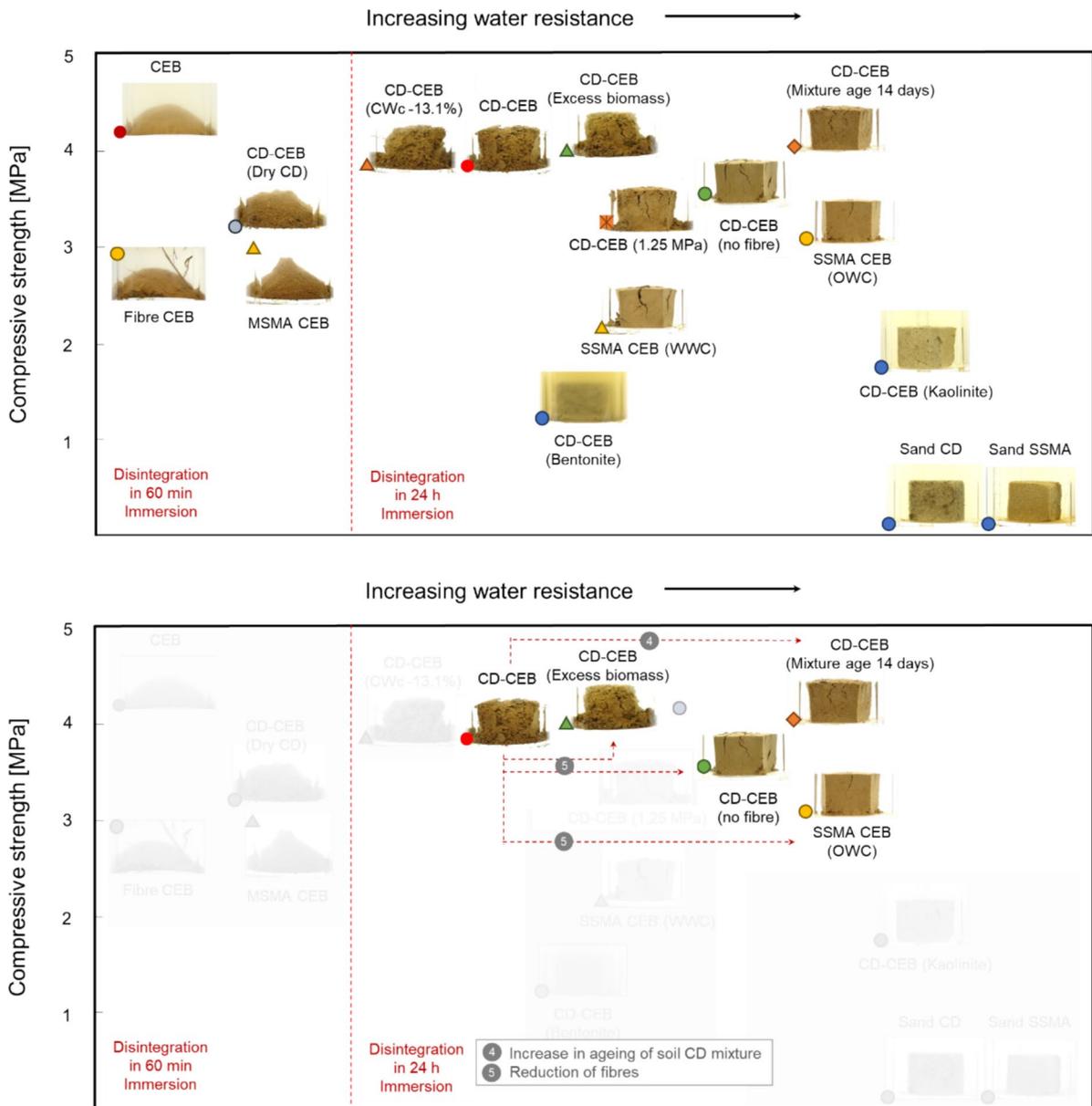


Fig. 12 The relationship between compressive strength and water resistance measured through immersion test. The region left to the red line show images of CEBs captured after 60 min of immersion whereas, the region on the right show images captured after 24 h of immersion. The horizontal axis provides

information on the relative performance of CEBs and is not to scale. In CEBs with a similar disintegration profile after 24 h of immersion, the drip test values were used in positioning the samples on the relative scale of water resistance performance. The markers (legend) used in the figure are defined in Fig. 11

The positive influence of reducing the fibres (as in CD-CEBs with no fibres and SSMA stabilised CEBs) is presented (route 5) in Fig. 12. While the addition of extra biomass improves the strength, the improvement

in water resistance is negligible. The improvement in water resistance is noticeable in CD-CEBs with no fibres and SSMA stabilised CEBs, although strength reduces by 6 and 17% respectively. Fibres are known

to prevent shrinkage and improve flexural strength [23]. Moreover, the extraction of fibres through sieves can be time-intensive and increase the overall cost of construction. Therefore, a careful assessment should be carried out based on application before implementing fibre extraction.

The results presented in Fig. 11 and 12 provide an insight into various processes or choices such as increase in compaction liquid content, use of wet dung, use of low-swelling mineral, longer soil cow-dung mixture ageing etc. that could lead to the optimisation of CD-CEBs for practical application. A further investigation into the underlying reasons behind improvement in performance due to increasing compaction content and optimised ageing of soil cow-dung mixture is recommended.

5.2 Understanding the water resistance characteristics of CD-CEBs

The addition of a cow-dung modifies the material composition of the stabilised soil mixture and therefore, affects the water resistance of cow-dung stabilised earthen material through transforming cohesion, capillary suction and/or water permeability. The addition of biological stabiliser often results in pore-filling leading to the reduction in the size of pores, therefore reducing the water permeability [39]. MIP tests conducted on CEBs stabilised with SSMA and unstabilised CEBs reveal that pore-filling is not responsible for better water resistance of SSMA stabilised CEBs and cow-dung stabilised CEBs (details available in [32]).

The results from Sect. 4 and 5 reveal that the water resistance of stabilised blocks is dependent on the

presence of SSMA, fibres and clay minerals. Therefore, to understand the water resistance characteristics of CD-CEBs it is essential to understand the role and interaction of all these components.

The blocks prepared with sand and SSMA provides a simple experimental model to understand the role of SSMA in binding the sand grains. To better visualise the interaction, specimens with a higher dosage of SSMA were prepared. The microscopic images shown in Fig. 13 provide evidence that SSMA acts as ‘glue’ and binds the sand particles together. Clay particles also play a similar role of bridging the sand particles, however their response to water ingress is significantly different to that of SSMA. In case of a block prepared with clay and sand grains, the water ingress decreases the capillary suction holding the hydrophilic clay and sand grains together, leading to disintegration. Whereas, SSMA are hydrophobic and the water ingress is expected not to substantially reduce the capillary suction holding SSMA and sand grains together. Thus, SSMA stabilised sand showed no disintegration whatsoever, indicating that the cohesive bond between SSMA, and SSMA and sand is stable upon immersion or wetting. This bond could be due to presence of extracellular polymeric substances (EPS), as shown in a study by Rao et al. [14], where EPS were suggested to be responsible for bonding between clay particles.

SSMA stabilised sand contains low quantity of SSMA (0.68%) which lead to extremely weak cohesive bonds as suggested by the fragile nature of these blocks. Thus, in scenarios such as the drip erosion test, the force of eroding water was sufficient to erode the top surface locally. Upon wetting, there is no volumetric swelling in sand or SSMA. It is expected that the effectiveness of cohesive bond reduces over

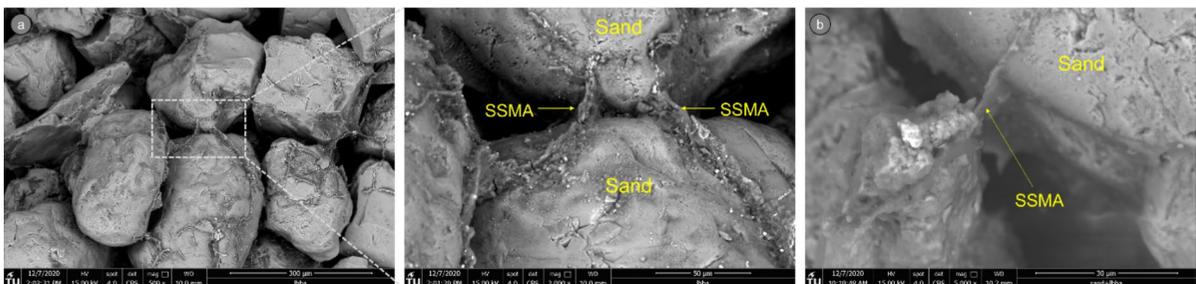


Fig. 13 ESEM images illustrating bonding of sand particles through small-sized microbial aggregate bridges: **a** Sand+SSMA (1.5%) and **b** Sand+SSMA



the duration of immersion, leading to the de-bonding of sand grain and SSMA (observed through leaching of SSMA in the surrounding fluid). The conceptual process of SSMA stabilisation of sand upon wetting is visualised in Fig. 14.

The addition of fibre increases the susceptibility of stabilised sand block upon immersion (Fig. 9). Fibres are expected to act as water transportation channels in the stabilised blocks and facilitate water ingress to the inner core of the sample. Upon wetting, the fibres not only swell but could re-align themselves to their original orientation. Thereby, swelling and re-alignment of fibres could create sufficient pressure to break the bonding between sand grains and SSMA. The swelling of fibres is expected to occur instantaneously, whereas the

realignment could be much slower and occurs after a sufficient duration of immersion. It is expected that the effectiveness of cohesive bond reduces over the duration of immersion, leading to the de-bonding of sand grain and SSMA (observed through leaching of SSMA in the surrounding fluid). The reduction in the effectiveness of cohesive bond in time (leaching of SSMA upon immersion) coupled with the realignment of fibres could be responsible for the disintegration of blocks. A simple illustration of the impact of fibre addition in SSMA stabilised sand is illustrated in Fig. 14.

The impact of fibre on water resistance is much more pronounced when clay particles are present in the soil (Fig. 14). The type, activity and swelling potential of clay minerals play a major role in the

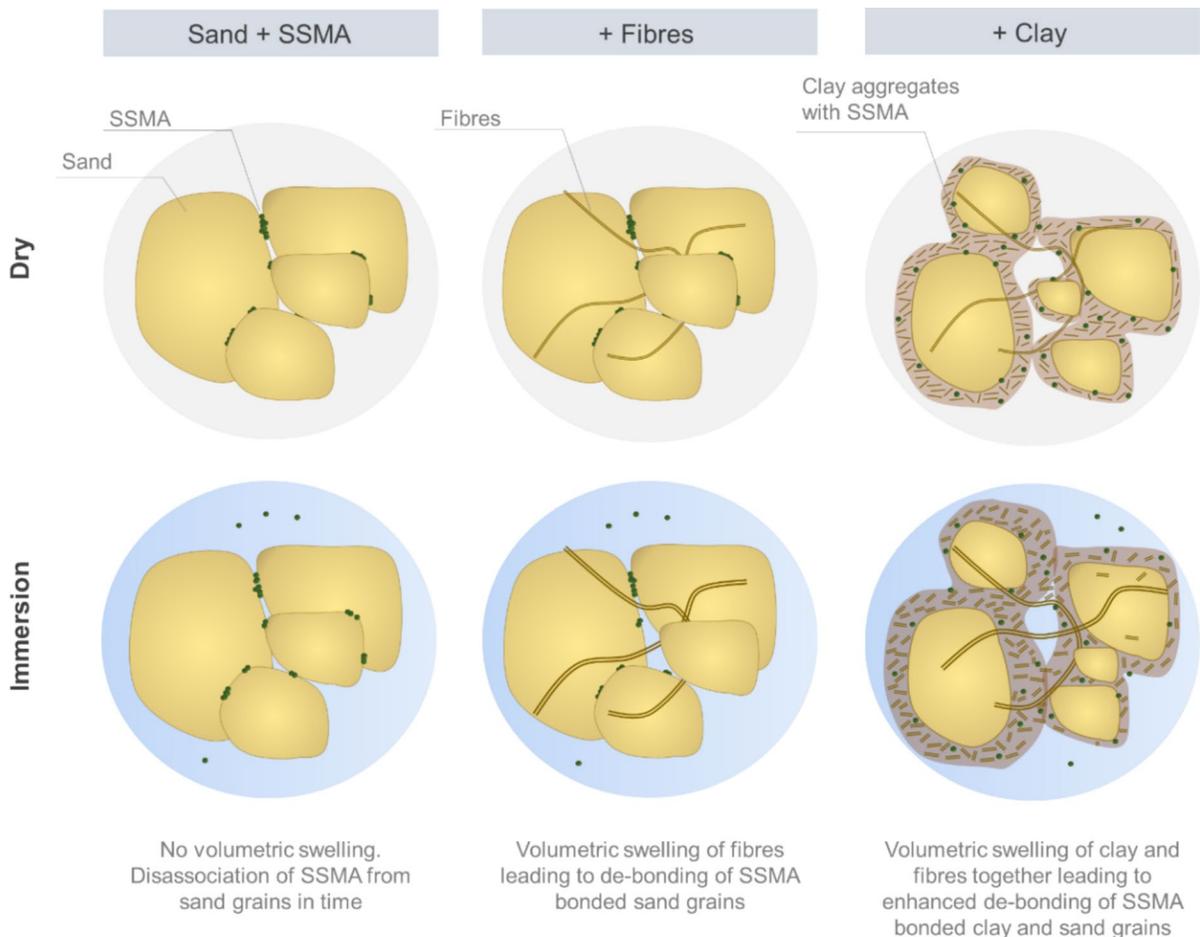


Fig. 14 Conceptual explanation of failure of cow-dung stabilised CEB upon water ingress. Impact of immersion on **a** Sand + SSMA, **b** Sand + SSMA + Fibres, **c** Sand + SSMA + Fibres + Clays

water resistance characteristics (as shown in Fig. 9). However, it is the combination of clays with fibres and SSMA, that determine the overall water resistance characteristics of CD-CEBs. A low swelling clay such as kaolinite has limited swelling that is insufficient to disrupt the bonding between SSMA and clay/ sand instantaneously. However, with an increase in immersion duration, the effectiveness of EPS is expected to reduce facilitating re-alignment of fibres. The softening of the bond between clay minerals coupled with the re-alignment of fibres disrupting the bond between aggregates results in the disintegration of the sample. In a high swelling clay mineral such as bentonite, the swelling has been shown to prevent water ingress and improve stability [32]. However, the presence of fibres provides water ingress routes to the core of the material, leading to faster disintegration. The presence of fibres in CD-CEBs (prepared with natural soil) also increased the rate of disintegration. Therefore, the swelling of clay minerals together with swelling and re-orientation of fibres leads to debonding of SSMA and soil minerals, causing disintegration upon wetting.

5.3 Valorisation of cow-dung for construction of improved CEBs

Cow-dung is an important resource that is used as a fertiliser in farmlands. When not treated properly, its usage as a fertiliser can cause environmental problems such as acidification and eutrophication [40, 41]. Valorisation of cow-dung in the production of compressed earth blocks could provide farmers with the opportunity to get rid of waste with no extra cost and prevent leaching of cow-dung components into the groundwater.

The production of CD-CEBs requires only two ingredients, the soil and the cow-dung. The quantity of cow-dung required in the production of CD-CEB in this study is recommended to be 2% solid cow-dung, which corresponds to around 16–20% wet cow-dung (depending on the amount of liquid in cow-dung). In order to determine the exact amount of cow-dung to be added to a particular soil, some testing and trials would be required. It is recommended to mix freshly collected cow-dung with soil to form a mixture that can be stored for a longer duration (as long as one year). The storage process not only removes the pungent smell and fungus growth (if any) but also

improves strength and water resistance performance. This study also reveals that the removal of fibres from the cow-dung is favourable. However, fibres are known to provide several other benefits. Therefore, a careful assessment should be undertaken before making the decision to remove/reduce fibres.

The feed of cow-dung has a major impact on the gut microbial communities and the formation of volatile fatty acids. The water resistance in the cow-dung is dependent on the volatile fatty acids which will be formed in all cows (irrespective of location) as they are produced during the metabolism of feed cows eat. Hence, improvement in water resistance characteristics by the addition of cow-dung is expected globally. However, the degree of improvement is expected to depend on the breed of cows, feed, concentration of fatty acids, microbial communities in gut and quantity of fibres. The quality of cow-dung collected in different time duration or seasons can also have an impact on the characteristics of CD-CEBs sourced from the same farm. Comparing the performance of CD-CEBs with cement/lime stabilised CEBs reveal that CD-CEBs have better water resistance characteristics than chemically stabilised CEBs (for 2% stabilisation), however, higher chemical stabilisation (>5%) results in water stable samples that do not disintegrate in water (details available in [32]).

To understand the opportunities and challenges in scaling up this research, 1000 kg of cow-dung was collected from the cow farm and mixed with 6000kg of soil to produce CD-CEBs which were used in the construction of a demonstration structure at The Green Village located in Delft, Netherlands as shown in Fig. 15. This demonstration structure consists of one wall section made with CD-CEBs and another with unstabilised CEBs. Both walls are exposed to natural climate conditions of Delft (temperate maritime climate) for over three years and have performed well overall. However, major differences are observed at the interface between the concrete column and the blocks, where significant erosion is seen in the unstabilised CEBs compared to the CD-CEBs (Fig. 15e–f). While the deterioration appears to stabilise after a certain period (see erosion profile at 8th month and 39th month). If left unrepaired, this minor damage could increase water ingress, potentially leading to long-term structural deficiencies. Such erosion can be minimised through improved construction



Fig. 15 Upscaling of CD-CEBs for construction of demonstration walls at the Green Village, TU Delft. **a** Production of CD-CEBs with a hydraulic press, **b** Masonry with CD-CEBs. The mortar used has the same composition as the CD-CEB but with more water, **c** the fully constructed front wall of CD-CEBs (without the metal roofing), **d** The finished demonstration structure with an unstabilised wall on left and cow-dung stabilised walls on the right. **e** Erosion profile at the interface between the concrete column and blocks in the CD-CEB wall on the 3rd day, 8th month and 39th month, and **f** Erosion profile at the interface between the concrete column and blocks in the unstabilised CEB wall. (Image b and c are credited to Justyna Botor)



practices. This research is also currently being applied in Uganda and Rwanda with over 20 000 blocks produced so far.

6 Conclusions

Use of cow-dung is anecdotally attributed to its water resistance characteristics, which is confirmed by this

study where the addition of cow-dung from Delfgauw, the Netherlands improves the water resistance of earthen blocks significantly with no impact on compressive strength. However, there were no comprehensive studies that provide insight into the water resistance characteristics of cow-dung stabilised earthen materials. This study explores the insights into water resistance through an extensive experimental investigation and found that small-sized microbial aggregates (SSMAs), which constitute approximately one-third of the solid mass of cow-dung, are entirely responsible for water-resistance of cow-dung used in this study and cow-dung stabilised compressed earth blocks (CD-CEBs). SSMAs are negatively charged clay-sized particles of low specific surfaces that are hydrophobic and stable upon wetting. Swelling of clays, in conjunction with swelling and re-alignment of fibres, can disrupt the bond between SSMAs and soil, leading to disintegration of cow-dung stabilised earthen blocks.

Contrary to the anecdotal belief in the role of fibres in water resistance, this study provides evidence that removing fibres from cow-dung can, in fact, improve the water-resistance of stabilised earthen blocks. It is interesting to note that the pH measurement on fresh and dried cow-dung, and multiple cow-dung-soil mixes was in the range of 6–9. This signifies that an alkaline medium and thereof, the formation of an insoluble compound, is not a pre-condition for the enhanced water-resistance behaviour of cow-dung stabilised earthen blocks, as suggested in previous studies.

The insights gained through the experimental study could facilitate the valorisation of cow-dung in practical earthen construction applications. These insights are compiled in form of recommendations such as:

- Use of fresh or wet cow-dung is advised over dry cow-dung. CD-CEBs prepared with wet cow-dung perform 80 times better than dried cow-dung used in this study.
- It is useful to adopt a higher compaction liquid content for casting the cow-dung stabilised earthen materials. Increase in compaction liquid content by 3% results in over 40 times improvement in water resistance. It is possible to make CD-CEBs with lower compression force as compaction force has minimal influence on water resistance.

- The low activity, swelling or cation exchange capacity of clay minerals is favourable for the water resistance (30 times improvement observed). Therefore, it is advised to select soil with low swelling clay minerals, such as kaolinite. It is necessary to evaluate if the selected soil provide sufficient strength for the construction.
- Once the fresh cow-dung is collected, it is recommended to mix it with soil soon and store this mix until casting blocks. The ageing of soil cow-dung mix has a positive influence on strength and water resistance characteristics. In this study, the optimal ageing duration was found to be 14 days. Moreover, by ageing the soil and cow-dung mix for over 3 days removes the pungent smell from the mix and does not re-appear even after wetting the blocks.
- Removal of fibres from cow-dung has shown a positive influence on the water resistance characteristics of CD-CEBs produced in this study however, it is advised only if it is economically feasible and appropriate for the construction project.

With a growing interest in ecological building materials, application of earthen materials is expected to grow. In this regard, cow-dung stabilised compressed earth blocks can offer a significant improvement over unstabilised blocks by using locally available resources. The recommendations proposed in this article can facilitate architects, practitioners, self-builders and natural-building enthusiasts to build earthen houses that are affordable, durable and desirable.

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Data availability The data supporting the findings of this study are available within the article. Extended data are accessible at <https://doi.org/10.4233/uuid:0149cbb5-e3fe-4bc5-8333-8f888638055e>. Raw data are available from the first or corresponding author, upon request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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