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Durability and hygroscopic behaviour of biopolymer stabilised earthen construction materials

S. Muguda [a,b,*], G. Lucas [a], P.N. Hughes [a], C.E. Augarde [a], C. Perlot [b], A.W. Bruno [c], D. Gallipoli [d]

[a] Department of Engineering, Durham University, Durham DH1 3LE, United Kingdom
[b] Université de Pau et des Pays de l'Adour, E2S UPPA, SIAME, Anglet, France
[c] School of Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom
[d] Dipartimento di Ingegneria Civile, Chimica e Ambientale, Università degli Studi di Genova, Genoa, Italy

HIGHLIGHTS

- Guar and xanthan gums are assessed as stabilisers for earthen construction materials.
- Both biopolymers have significant positive impact on mechanical properties of the earthen construction materials.
- At the end of their life, these materials can also be recycled efficiently with minimal environmental impact.
- Biopolymer stabilised earthen material has a satisfactory durability performance against water-induced deterioration.
- Unlike cement, biopolymers would not compromise on the hygroscopic properties of the material.

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ABSTRACT

Earthen construction materials are often chemically stabilised in order to improve their durability against water-induced deterioration. However, chemical stabilisers like cement can negatively affect the hygroscopic behaviour and recyclability potential of the materials they are used to stabilise. This study investigates the potential of using biopolymers (namely guar and xanthan gums) as stabilisers in earthen construction materials. These biopolymers have some advantages over cement in terms of embodied energy and carbon footprint, and are widely available around the world. Previous research has suggested that these biopolymers can provide suitable mechanical properties and here we show that in addition they can provide satisfactory durability performance and improved hygroscopic behaviour. These findings suggest that biopolymers could have significant potential to be used as stabilisers for earthen construction materials.

1. Introduction

As a structural component of a building, an earthen construction material (e.g. rammed earth or a compressed earth block) needs to possess requisite strength to support different structural loads. These materials also need to resist environmentally driven deterioration without disrupting their original functional requirement. In many situations, when the soil used for manufacturing earthen construction materials cannot provide adequate strength and durability a chemical stabiliser is added. Amongst different chemical stabilisers used, cement has been the most popular as it produces rapid strength gain and improves the resistance of the material against erosion and frost attack [1,2]. The recommended cement content to provide adequate strength and durability is in the range of 6–10% depending on the soil type, which is close to having an equivalent carbon footprint of fired bricks or weak concrete [3–5]. While providing the requisite strength and durability cement stabilisation however leads to compromises in the hygroscopic and recyclability properties of the material. Moisture buffering value (MBV) which describes the hygroscopic behaviour of a material is comparatively lower for cement stabilised materials than unstabilised materials [6,7]. This implies that a building constructed of cement stabilised earthen construction materials would require higher operational energy to maintain a good indoor air

* Corresponding author.
E-mail addresses: sravan.muguda-viswanath@durham.ac.uk (S. Muguda), george.lucas@virgin.net (G. Lucas), paul.hughes2@durham.ac.uk (P.N. Hughes), charles.augarde@durham.ac.uk (C.E. Augarde), celine.bascoules@univ-pau.fr (C. Perlot), agostino.bruno@ncl.ac.uk (A.W. Bruno), domenico.gallipoli@unige.it (D. Gallipoli).

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quality than a building constructed of unstabilised earthen materials. The processes required to recycle cement stabilised earthen construction materials are energy-intensive and therefore usually uneconomical [8]. Hence, at the end of their life, cement stabilised materials are typically downcycled or dumped in a landfill [9]. It is therefore desirable to explore suitable alternatives to cement which not only provide required strength and durability but also retain desirable hygroscopic and recyclability properties.

This study explores the possibility of using biopolymers as a potential alternative to cement as a stabiliser for earthen construction materials. Biopolymers are biologically synthesised polymers which have been previously used for improving different soil properties in many geotechnical applications [10–13], as well as finding many uses in, for instance, the food processing industry. However, there are limited studies which have used biopolymers as a potential alternative to cement for stabilising earthen construction materials [14,15]. To explore the potential of biopolymers as a stabiliser, a laboratory testing campaign was set out by the authors to understand the effect of biopolymers on mechanical and durability properties of earthen construction material and to assess the potential of these earthen materials to be building materials. As an initial step, two commercially available biopolymers, namely guar and xanthan gums were selected as potential stabilisers due to their availability and effectiveness in withstanding temperature and pH variations [16,17]. The effect of these biopolymers on the mechanical properties of stabilised earthen construction material is presented in [18] and is summarised briefly below. Biopolymers essentially provide stabilisation to the soil through the formation of "hydrogels" which bind soil particles through hydrogen bonding along with/without ionic bonding depending on the biopolymer used. The hydrogels are formed through the interaction of biopolymer and water and are initially in a rubbery state (~1 h), and which gradually transform to a glassy state as the soil dries. Complete transformation of hydrogels from rubbery to glassy state occurs within 3–5 weeks [19]. The transformation of hydrogels has significant impact on the mechanical behaviour of the stabilised material and the use of guar and xanthan gums were seen to have significant impact on the compressive strength of the stabilised material. Much of the compressive strength gain for biopolymer stabilised material was seen to occur within 7 days of curing, while there was marginal increase in strength between 7 and 28 days. The tensile strength of guar gum and xanthan gum stabilised material also increased in the first 7 days of curing. However, whilst the xanthan gum continued to improve between 7 and 28 days the guar gum samples reduced in strength over the same period. It was determined that about 1.5–2.0% of biopolymer content was sufficient to achieve a comparable air-dried compressive strength of 8.0% cement stabilised earthen material. Based on these findings, preliminary studies were undertaken to assess the potential of biopolymers as stabilisers in improving the durability of earthen material [20,21]. In the preliminary studies, Geelong drip tests were performed on 7-day cured biopolymer stabilised specimens and the eroded depths observed were well within the prescribed limit of the test. The satisfactory performance of biopolymers has prompted further durability studies which are presented in this manuscript. Further, hygroscopic properties of these novel building materials which have a direct impact on green credentials are also assessed in this study.

2. Materials and sample preparation

2.1. Materials

An engineered soil mixture comprising 20% kaolin, 70% sharp sand and 10% gravel by mass (denoted as Soil 2-7-1) was used as the base soil in this study. The soil mixture complies with the requirements for earthen construction materials as recommended in earlier publications [22–26], is a combination widely investigated and is consistent with previous research conducted by the authors of this study [18,20,21]. The physical properties and compaction characteristics of the unamended soil mixture are presented in Table 1. Figs. 1 and 2 present the soil gradation and plasticity properties of the soil mixture along with the recommended limits.

Both biopolymers (guar gum and xanthan gum) in powdered form were procured from M/s Intralabs, United Kingdom. Guar gum is a neutrally charged polysaccharide which is extracted from the endosperm of cluster beans belonging to Leguminosae plant family [16,27]. Xanthan gum is an anionic polysaccharide which is synthesised from plant-based pathogenic bacterium Xanthomonas campestris [17,28]. Based on the recommendations from the previous study, the biopolymer stabiliser content in this study was 2.0% of the dry soil mass [18]. In a few tests, the performance of the biopolymer stabilised samples was compared with 8.0% cement stabilised samples. Cement used in this study was CEM II type which conformed to the specifications set out in BS EN 197-1 [29].

2.2. Earthen mixtures and sample preparation

For the different experiments carried out in this study, the size and geometry of the samples used varied according to the requirements of the test procedure whilst the density and moisture content of the samples were consistent. The required quantities of the ingredients (sand, gravel and kaolin) were weighed and initially mixed in the dry condition. For the stabilised samples, the chosen stabiliser was pre-mixed with the dry ingredients of the soil mixture. After dry mixing, water equivalent to the optimum water content for compaction as determined by BS 1377 [30] was added. The samples stabilised with biopolymer required a small amount of additional water to make the soil mix workable. For guar gum samples additional water of 2.0% of dry soil mass was needed, while for xanthan gum samples it was 1.0%. After mixing, the required bulk mix was weighed and placed into sample moulds and statically compressed to achieve the maximum dry density of the unamended soil mix (i.e. 19.62 kN/m^3) as determined by BS 1377 [30]. The compacted test specimen was then extracted from the sample mould and left to air-dry on a laboratory bench to gain strength. Table 2 presents the dimensions of samples and details of the laboratory ambient conditions for the investigations in this study.

3. Durability tests

As per BS ISO 15686 [31], durability is defined as, "capability of a building or its parts to perform its required function over a specified period of time under the influence of the agents anticipated in service". For an earthen material, the durability performance is primarily assessed through its ability to resist deterioration against water intrusion [32,33]. Deterioration of the material due to water can occur in different ways such as water absorption from immediate surroundings, sudden submergence or rainfall-induced erosion. The standard durability tests as recommended by various international standards seek to emulate the above conditions [32,34,35]. Many of the standard durability tests are however primarily aimed to assess cement stabilised earthen materials, and use of these tests to assess unamended materials or those stabilised using alternative stabilisers may be inappropriate [35]. Hence, in this study, the performance of biopolymer stabilised specimens was either compared with unamended specimens alone or along with cement stabilised specimens based on the test methodology of a particular durability test.

Table 1
Physical properties of the unstabilised soil mixture used in this study.

Soil	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Liquid Limit (%)	Plastic Limit (%)	Linear Shrinkage (%)	OWC (%)	$\gamma_{d,\ max}$ (kN/m^3)
2-7-1	16	04	70	10	36.2	18.4	5.0	9.8	19.62

OWC: Optimum water content.
$\gamma_{d,\ max}$: Maximum dry density.

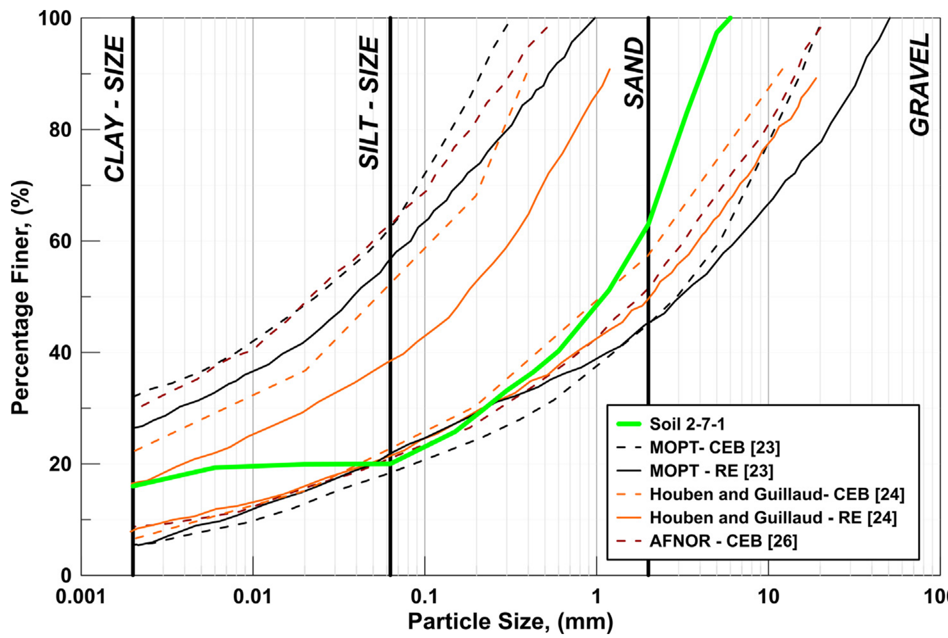

Fig. 1. Soil gradation of the soil mixture used in this study.

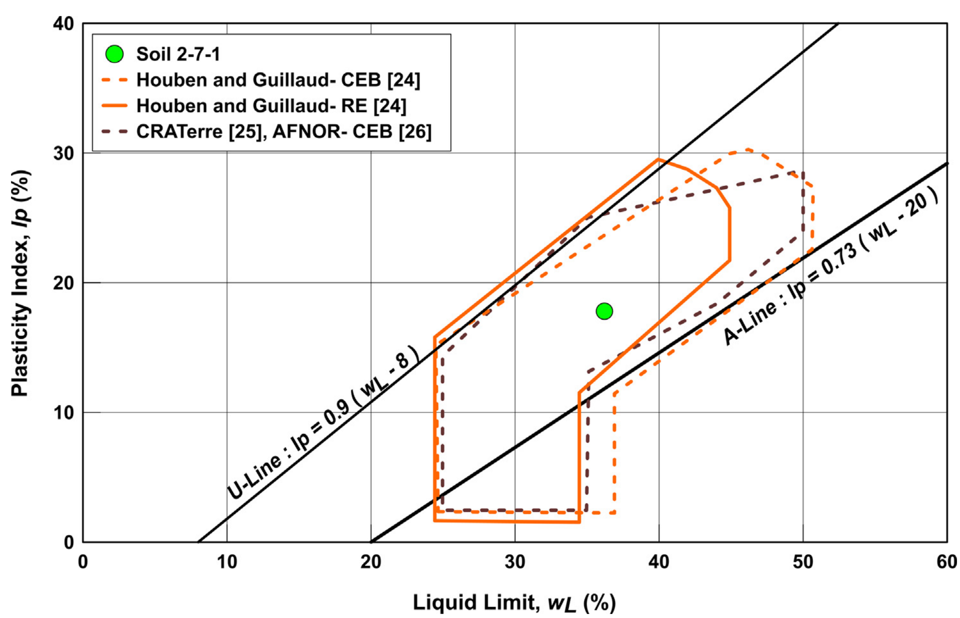

Fig. 2. Plasticity properties of the soil mixture used in this study.

3.1. Contact tests

3.1.1. Test methodology

The primary objective of a contact test is to assess the response of a material unit to moisture absorption in a condition which simulates the application of a mortar joint, hence this test is specifically relevant to compressed earth blocks, rather than rammed earth. Contact tests were performed on unamended, guar gum and xanthan gum stabilised bricks (dimension: 200 mm × 100 mm × 75 mm) 28 days after their preparation. At 28 days, hydrogels in the biopolymer stabilised bricks would have completely transformed to a glassy state and bricks in this condition would be representative of actual field conditions. For each combination, three identical bricks were tested. Prior to the

Table 2
Different sample configurations considered in this study.

Sample	Durability tests	Hygroscopic tests	Laboratory conditions
Cylinder (38 mm diameter and 76 mm height)	√	–	21 °C and 50%RH
Tile (150 mm × 150 mm × 20 mm)	√	–	21 °C and 50%RH
Cylinder (50 mm diameter and 100 mm height)	√	√	23 °C and 50%RH
Brick (200 mm × 100 mm × 75 mm)	√	√	23 °C and 50%RH

start of the test, the brick specimens were left to equalise in a climatic chamber under 50% RH and 23 °C for 48 h. The test procedure used in this study was in accordance with DIN 18945 [36] and consisted of applying a wet cellulose cloth on the intermediate face of the brick, to simulate a mortar joint or coating (Fig. 3). The amount of water in the wet cloth is set equivalent to 0.5 g/cm^2, which is the average amount of water contained in a 15 mm thick mortar layer [9]. The brick along with the wet cloth were then placed in a container and supported by a metallic block. Water was added to the bottom of the container to ensure a humid environment. The container was then sealed for 24 h. After 24 h, the brick was removed from the container and exposed to atmospheric conditions (50 ± 5% RH and 23 ± 2 ^{0}C) for 48 h. The brick was then visually examined for any cracks or swelling which would lead to permanent deformations due to water absorption.

3.1.2. Test results

Fig. 4 shows the condition of bricks before and after the completion of contact tests for unamended, guar gum and xanthan gum stabilised bricks. It can be observed that all bricks showed no signs of visible cracks after the completion of the tests. The soil mix (2–7-1), which has kaolinite as the principal clay mineral, has a linear shrinkage value of 5.0%, indicating the soil is less prone to cracking [37]. With this property, the unstabilised brick may be less susceptible to cracks under these experimental conditions. As these tests were conducted after 28 days, the hydrogels which are in a glassy state may resist shrinkage thus inhibiting crack formation on the surface of these biopolymer stabilised bricks.

3.2. Suction tests

3.2.1. Test methodology

The suction test investigates the durability of earthen blocks when exposed to an excess supply of water. This test emulates the capillarity water rise from the foundation to the walls of the earthen building. Similar to the contact test, suction tests were performed for unamended, guar gum and xanthan gum stabilised bricks. For each combination, three identical bricks were tested. A support made of a conventional fired brick with an absorbent cloth on top was placed inside a container. The container was then filled with water up to 1–5 mm below the upper edge of the fired brick (Fig. 5). After this, the test brick was placed over the absorbent cloth, which marks the start of the suction test. Water was maintained at this level, as it is absorbed by the earthen bricks. Samples were then visually assessed at intervals of 30 min, 3 h and 24 h from the beginning of the test in order to detect cracks and permanent deformations owing to swelling.

3.2.2. Test results

Fig. 6 shows the condition of bricks before and after the completion of suction tests (24 h after the start of the test) for unamended, guar gum and xanthan gum stabilised bricks. After the completion of the tests, all bricks showed no signs of cracking or swelling. As discussed previously in contact tests, the satisfactory performances in suction tests for unamended and biopolymer stabilised samples are mainly due to shrinkage properties of the soil mix and the nature of hydrogel formation respectively.

3.3. Dip tests

3.3.1. Test methodology

The dip test as described in DIN 18945 [36] assesses the resistance of earthen materials to deterioration whilst suspended in water rather than absorption from immediate surroundings [9]. This test simulates sudden flooding or immersion of earthen material in water and is clearly a very stringent test for an unstabilised material. As with the other tests, dip tests were performed on unamended, guar gum and xanthan gum stabilised bricks and Fig. 7 shows the test setup for these tests. Before the start of the test, the mass of the test bricks was recorded. The brick was mounted in a clamp and lowered 10 cm into the water for 10 min. After this specified time, the brick was removed from the water bath and allowed to dry at 40 °C for 24 h. It was then placed under atmospheric conditions (50 ± 5% RH and 23 ± 2 ^{0}C) to cool and equalise with conditions before its final mass was measured. The loss of mass was then calculated through the differences between initial and final masses as measured by a laboratory balance. The results presented herein are the average values of three replicate samples.

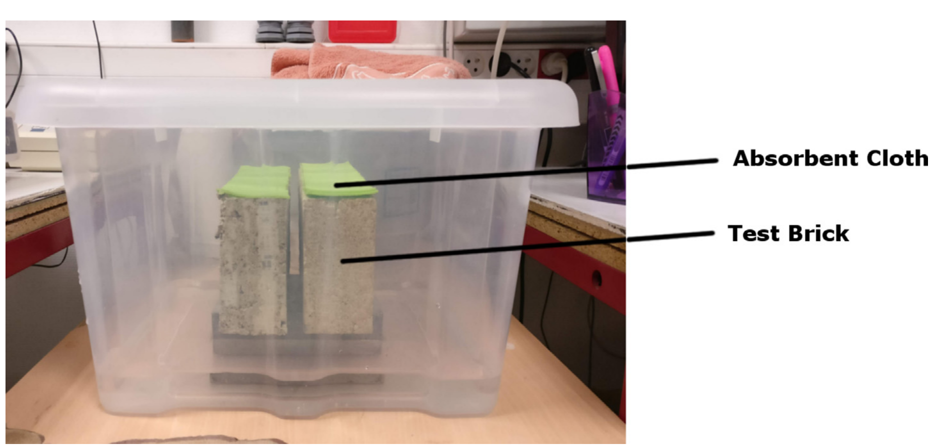

Fig. 3. Test setup for contact tests.

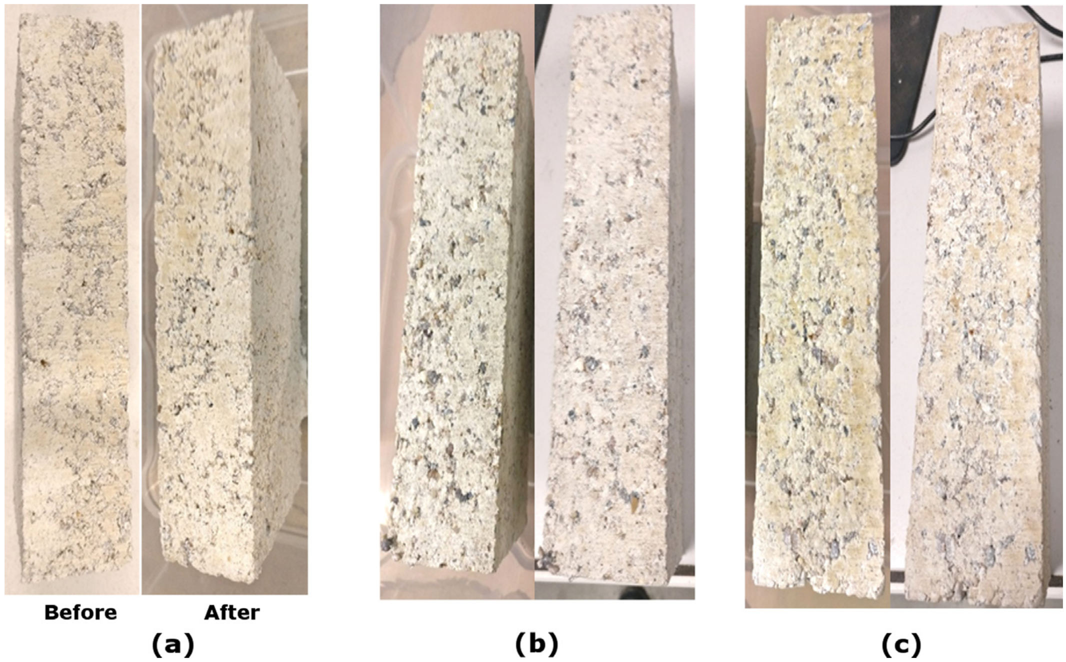

Fig. 4. Conditions of bricks before and after contact tests for, (a) unamended bricks, (b) guar gum stabilised bricks, and (c) xanthan gum stabilised bricks.

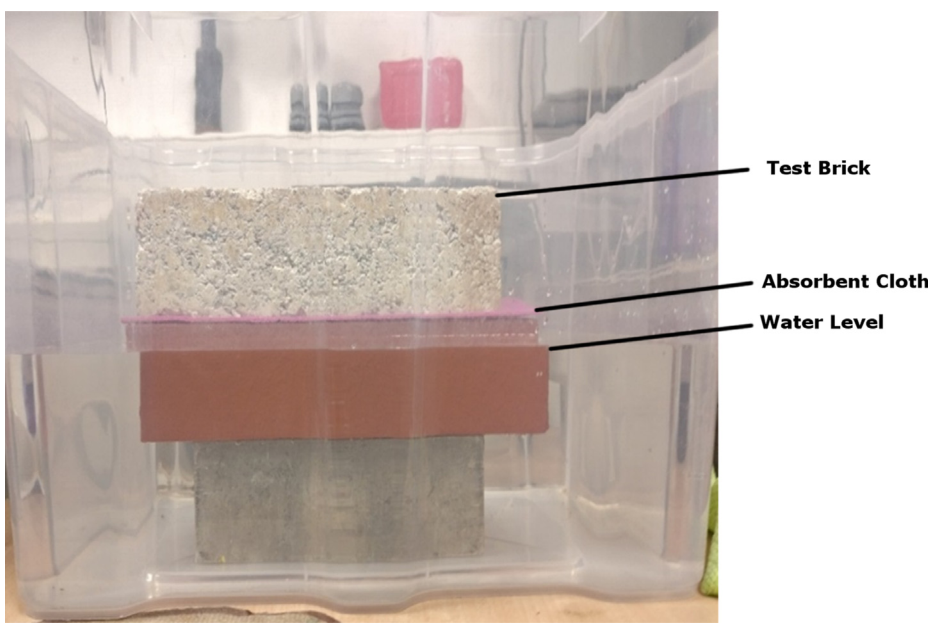

Fig. 5. Test setup for suction tests.

3.3.2. Test results

Fig. 8 shows the mass loss for all the bricks tested. It can be observed that, as might be expected, the loss of mass of unamended bricks is significantly higher (greater than 15% in some cases) than for biopolymer stabilised bricks. However, in the cases of both guar and xanthan gum stabilised bricks, the observed loss of mass was less than 5% and at these low mass losses, the biopolymer stabilised bricks can be deemed suitable for use in external walls as per DIN 18945 [36]. It was noticed that for guar gum stabilised bricks even after drying the sample at 40 °C for 24 h, the immersed portion of brick was slightly moist as compared to the dry portion. Fig. 9 shows the conditions of bricks immediately after removing from water for all bricks.

3.4. Geelong drip tests

3.4.1. Test methodology

The main objective of the Geelong drip test is to assess the durability performance of earthen materials against rainfall-induced erosion. The Geelong test was originally developed in Deakin University, Australia to determine the suitability of soil for making adobe bricks [38]. Based on the performance of 20 earthen buildings Frencham [39] later developed a concept of categorising the earthen materials based on erodibility index which relates the depth of erosion to real life performance. The recommendations given by Yttrup et al. [38] and Frencham [39] have since led to the present day New Zealand standard

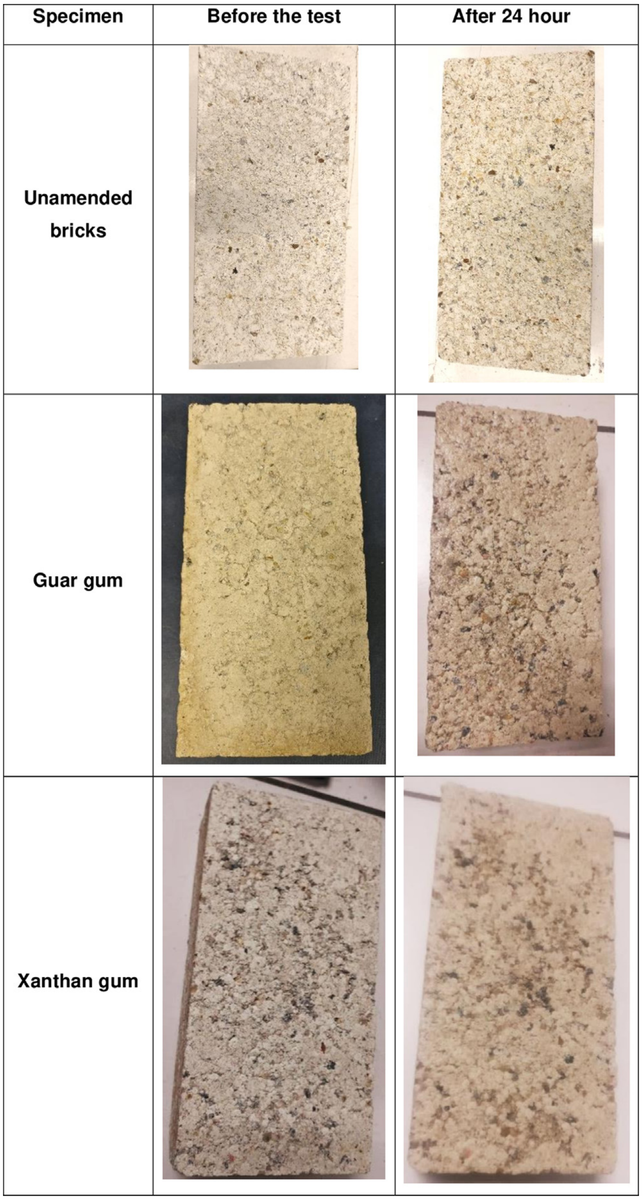

Fig. 6. Conditions of bricks before and after suction tests.

NZDS 4298 [37] test procedures and associated material categorization (reproduced here in Table 3) and it is the procedure used here. In this test the performance of the biopolymer stabilised earthen materials was compared with unamended and cement stabilised materials. For this experiment, samples in the form of small cylinders (38 mm diameter and 76 mm length) and tiles (150 mm × 150 mm × 20 mm) were tested. The Geelong erosion tests were then performed on samples cured for 7 and 28 days. In total, four combinations of samples were chosen in this study: unamended, guar, xanthan and cement stabilised samples. A total of 80 samples i.e. 40 cylinders and 40 tile specimens were considered in this investigation. The results presented herein are the average values of five replicate samples. For the tile samples, the surface was kept at an inclination of 2H:1V, while for cylindrical specimens the surface of erosion was held perpendicular (see Fig. 10). As well as noting the final erosion at 60 min as recommended by the standard, the eroded depths were also noted at intermediate 15-minute intervals.

3.4.2. Test results

Fig. 11a and 11b present the final eroded depths at the end of the test for both tile and cylindrical samples for all the combinations considered. In each plot, for each combination, the erosional depths measured at 7 and 28 days are plotted adjacent to each other. It can be observed from the results that the unamended samples have higher depths of erosion for both tile and cylindrical samples, while cement stabilised samples have negligible erosion. Based on the recommendations in [38], the erodibility indices for unamended and cement stabilised specimens are 3 and 2 respectively, indicating that unamended specimens are prone to more erosion. For both biopolymer stabilised samples, the final erosional depths are well within 5 mm, indicating the erodibility index for these samples to be 2. Between biopolymers, xanthan gum stabilised samples demonstrated greater resistance against erosion.

To compare the individual performances of the biopolymers, the rate of erosion determined during the Geelong drip tests was plotted (see Fig. 12). The rate of erosion for xanthan gum stabilised specimens can be seen to be less than that of guar gum stabilised specimens. A linear extrapolation was also carried out to arrive at the time required to achieve an erosion depth of 5 mm. In real world conditions, a linear relationship of erosion with time is unlikely to occur as the factors which influence erosion such as rainfall intensity, angle of impact and duration of rainfall are highly variable. However, past studies have incorporated linear extrapolation of erosion to obtain fair indication on the erosional resistance of the material [40] and such analysis is useful for comparison. It can be observed from Fig. 12a and b, the rates of erosion for 28 day cured guar gum stabilised specimens are marginally higher than those cured for 7 days, indicating with ageing, the specimens tend to erode faster. As noted in [18], guar gum stabilised samples tend to lose tensile strength when the nature of hydrogels changes to a "glassy" state in which the network of hydrogels which connects soil particles with weaker hydrogen bonds can be easily broken under low tensile stresses. Under repeated impact of water in erosion tests, it can therefore be expected that 28-day specimens with lower tensile strength have higher erosion rates than 7-day specimens. In the case of xanthan gum (Fig. 12c and d), the additional ionic bonds which provide higher tensile strength after 28 days may provide necessary resistance against erosion even when the hydrogels are in the glassy state. This could explain why the observed rates of erosion are similar for 7-day and 28-day xanthan gum stabilised specimens.

3.5. Discussion of durability test results

The primary objective of the contact and suction tests was to assess the resistance of these earthen construction materials to water intrusion caused by capillary action. The unamended soil mixture contains for its clay fraction, refined kaolin which has kaolinite as the principal clay mineral, which amongst all the clay minerals has the least affinity towards water and is less susceptible to volume change [41]. As supported by the linear shrinkage value presented in Table 1, it would be expected that the unamended bricks would therefore anyway be less prone to crack formation due to capillary action and this is confirmed by the results of contact and suction tests. The effect of capillary action of water on volume change of the test specimens seems to be less pronounced on amended bricks compared to the unamended bricks. This may be linked to the age of the bricks on which these tests were conducted. Both the contact and suction tests were performed on bricks left to cure for 28 days. At this stage, it can be expected that the hydrogels formed within the bricks due to the presence of biopolymers will primarily be in a glassy state [18,19] and thus provide necessary resistance against moisture ingress caused by capillary action.

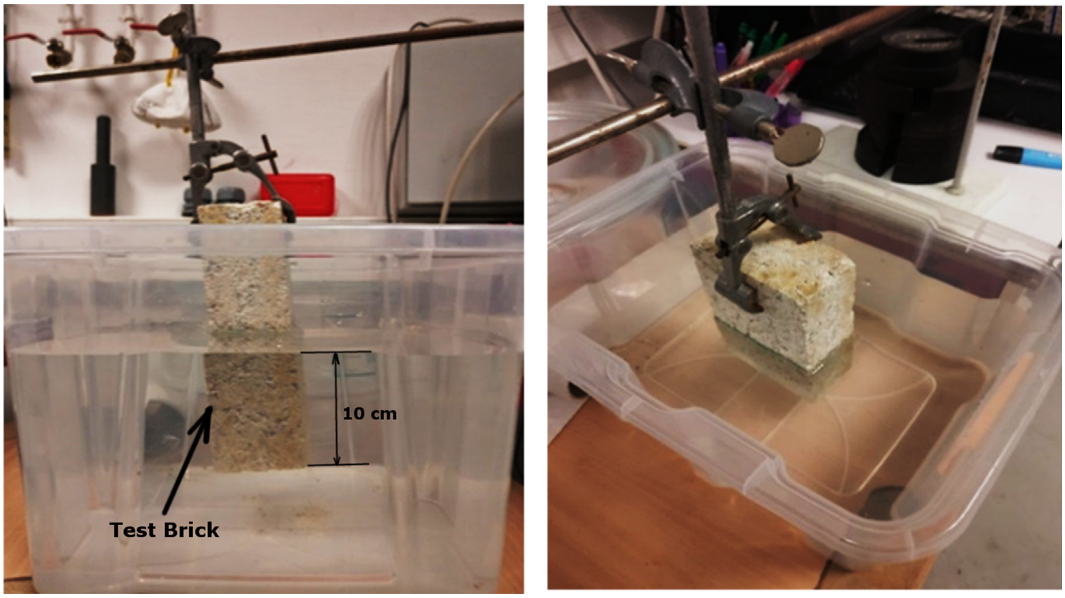

Fig. 7. Test setup for dip tests.

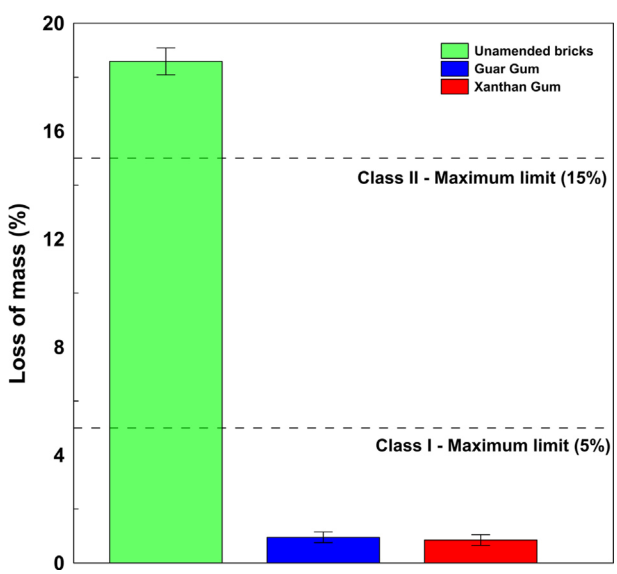

Fig. 8. Loss of mass for all the bricks after dip tests.

Test results obtained from dip tests clearly show the inability of unamended bricks to withstand immersion. During the dip test, as the mounted brick is half immersed into water, the submerged portion of the brick saturates rapidly which significantly reduces the soil suction which binds the soil particles when in an unsaturated condition. Additionally, as the brick is lowered into water, there is some initial uplift created due to buoyancy, subsequently, as the water percolates into the brick, the uplift is reduced and the submerged portion of the brick gets heavier. The submerged portion of the brick then starts to settle down in the water away from the fixed end of the brick which create tensile stresses within the brick. As noted in a previous study by Muguda et al. [18], the tensile strength of the unamended soil mix in an unsaturated condition is lower than with a biopolymer stabilised soil mix. It can therefore be expected during immersion the mobilised tensile strength of the unamended soil mix would be much reduced. In this condition, the unamended brick can be expected to deteriorate rapidly. In the case of biopolymer stabilised samples, when subjected to immersion, the hydrophilic hydroxyl groups at the outer chains of the biopolymer absorb and hold water [42]. As water is absorbed within the chains of biopolymer and fills up the voids, the hydrogels within the soil matrix tend to swell slightly before starting dilution which is a process were the outer chains of biopolymer dissolve after holding water. The amount of water absorbed and held within the chains of biopolymer and the time taken for dilution depends on the intrinsic chemical properties of the biopolymer [42,43]. It can be seen from the test results that there is negligible loss of mass for both guar and xanthan gum stabilised bricks, while for the guar gum stabilised bricks, even after drying the sample at 40 °C for 24 h, the immersed portion of the brick was slightly moist. From this observation, it may be concluded that within the time period of the test, the biopolymer chains may have only absorbed water and hydrogels may not have reached the stage of dilution to cause any deterioration.

Based on the contact, suction and dip test results, these materials can be classified into different categories as per the recommendations given by DIN 18945 [36] (Table 4). Based on these recommendations, the tested specimens in this study are classified in Table 5. It can be noted that, apart from the dip tests, unamended bricks perform well in contact and suction tests, however, with the addition of biopolymers, acceptable performance is achieved also in dip tests which enhances the classification to Ia. With this improvement, biopolymer stabilised earthen blocks could potentially be competitive for external walls exposed to natural weathering.

The beneficial effect of biopolymer stabilisation is also more evident in the Geelong drip tests. The depths of erosion observed in these tests were as low as 2.0 mm for biopolymer stabilised earthen materials, while for unamended samples it was in the range of 8.0–10.0 mm. Based on the recommendations given in [39], biopolymer stabilised earthen material having depth of erosion less than 5.0 mm can be classified as “slightly erodible”. In terms of the approach in the New Zealand standard NZS 4298 [37], biopolymer stabilised bricks which have a depth of erosion less than 5.0 mm would then be subjected to a more precise durability assessment undertaken using a more adverse durability test such as a spray test. From these observations, however, it can be concluded that the addition of biopolymers certainly improves

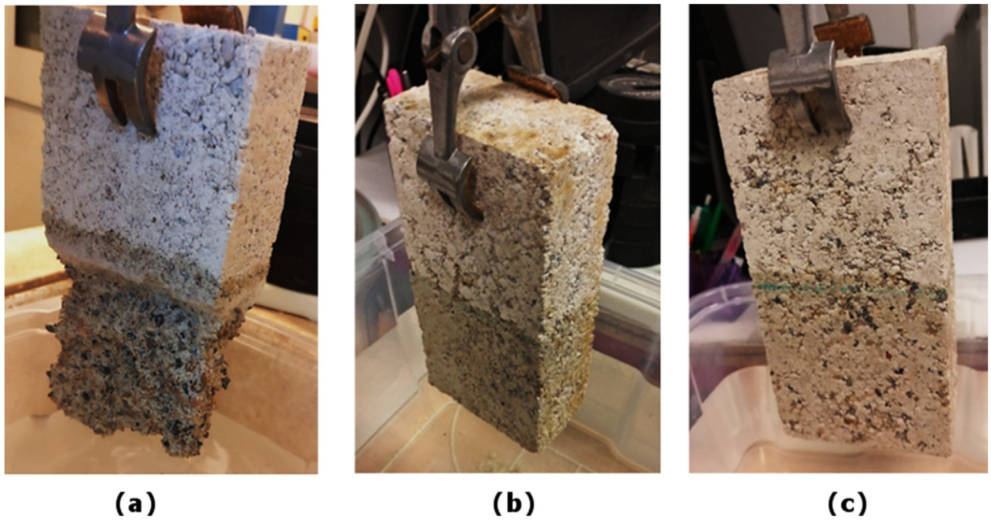

Fig. 9. Conditions of bricks after dip tests: (a) unamended brick, (b) guar gum stabilised brick and (c) xanthan gum stabilised brick.

Table 3
Classification of earthen materials after Frencham [39] and NZDS 4298[37].

Depth of erosion, D (mm)	Frencham [39] recommendations	Erodibility index as per NZDS 4298 [37]
0	Non Erodable	1
0 < D < 5	Slightly Erode	2
5 < D < 10	Erodable	3
10 < D < 15	Very Erodable	4
15 < D	–	5 (Fail)

the erosional resistance of this earthen material while there is clearly scope for future studies to assess durability performances through more vigorous tests.

4. Hygroscopic behaviour of earthen construction materials

4.1. Test methodology

To assess the hygroscopic behaviour of biopolymer stabilised earthen construction materials, the moisture buffering values (MBVs) of these materials were compared with unamended and cement stabilised materials. The moisture buffering value is a useful single parameter which can be used to understand the hygroscopicity (i.e. humidity buffering potential) of building materials [44].Though there are many recognised procedures as prescribed by Fraunhofer IBP, Lund University, DIN standards, Japanese industrial standards and ISO standards [45–49] amongst others to determine MBVs, the most common method used for earthen materials is the NORDTEST method [6] where the minimum exposed surface area of the specimen is set to be 0.010 m^2, and in order to satisfy this requirement, cylindrical specimens of 50 mm diameter and 100 mm length were used in this study. During tests, the specimens were placed in disposable aluminium cups exposing the top and lateral surfaces while sealing the bottom surface (Fig. 13a). Under this condition, the exposed surface area for a cylinder would be about 0.018 m^2. Three identical specimens were prepared for each combination considered, i.e. unamended, cement and biopolymer stabilised samples. A total of 12 cylinders were prepared in this investigation. In addition to investigate the influence of sample scale on the hygroscopic properties of the material, a comparison of hygroscopic behaviour was made between cylin-

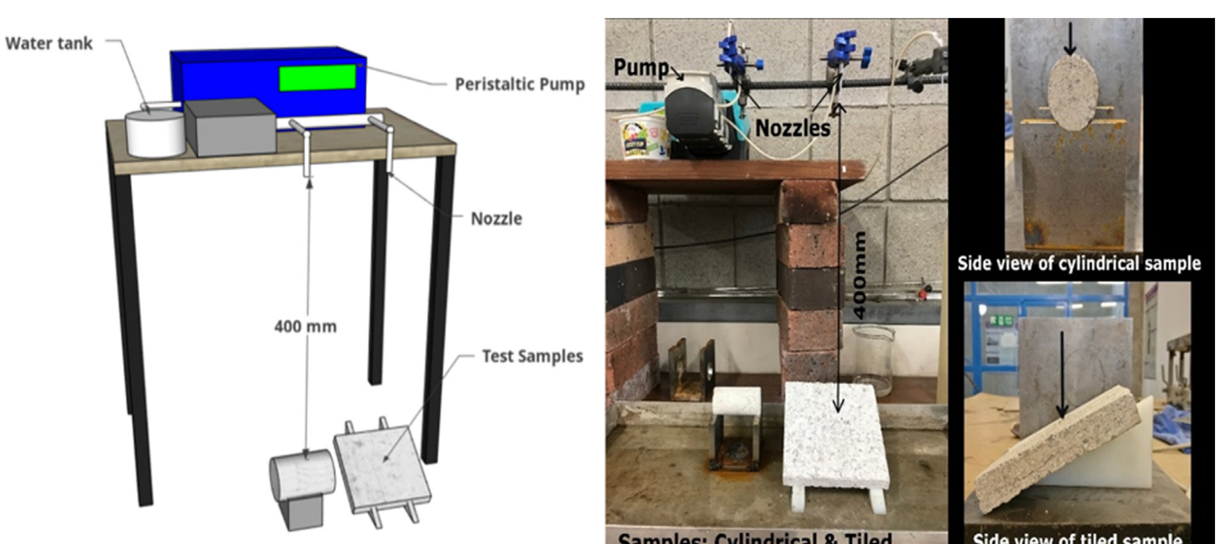

Fig. 10. Test setup for Geelong erosion test.

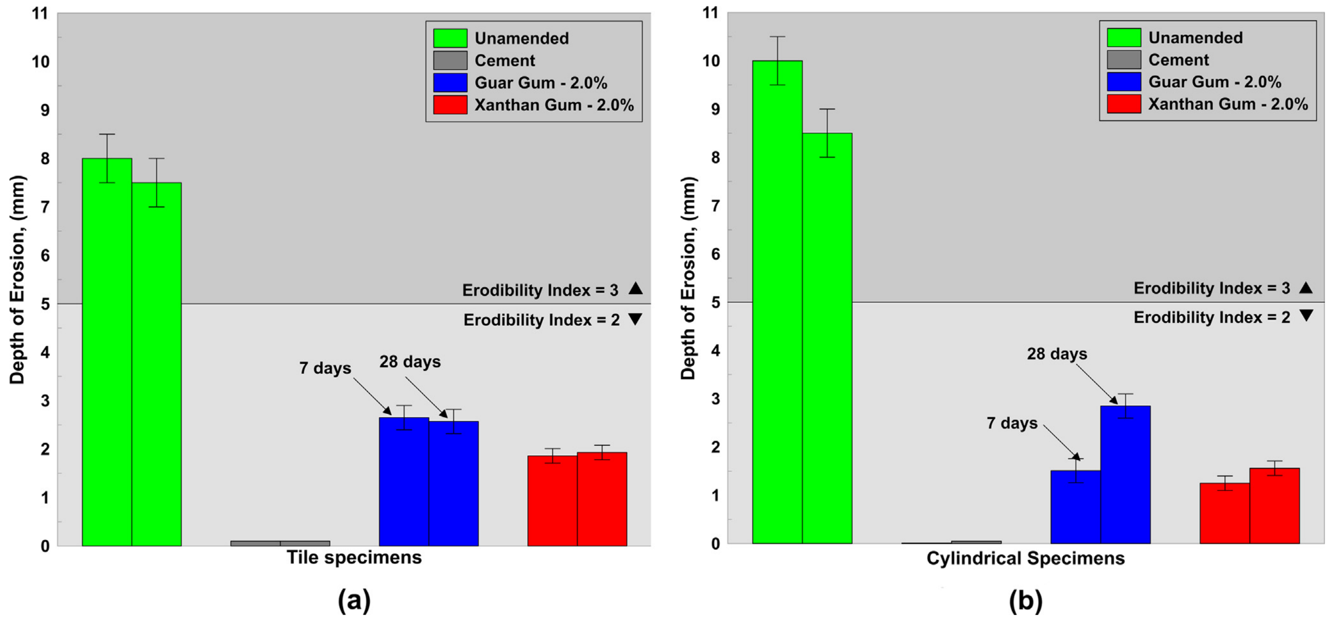

Fig. 11. Average depth of erosion, (a) tile specimens and (b) cylindrical specimens.

drical samples and three brick sized samples for each biopolymer combinations. For the bricks, all but one largest face (200 mm × 100 mm) was sealed using aluminium tape to obtain an exposed surface area of 0.020 m^2 (Fig. 13b). After preparation, all samples were left to be air-dried for 28 days under laboratory ambient conditions (50 ± 5% RH and 23 ± 2 °C). Cement stabilised earthen materials were wet cured in order to maximise the efficiency of stabilisation by wrapping the samples in a wet cloth during curing. The temperature during the test was maintained constant at 23 °C although it is important to note here that the effect of temperature on moisture buffering tests is negligible for temperatures between 20 °C and 70 °C [50,51]. Moisture buffering tests were performed inside a climatic chamber CLIMATS Type EX2221-HA.

Prior to the start of a test, the initial dimensions of all samples were recorded and samples were then left to equalise under a temperature of 23 °C and relative humidity of 33% until the observed mass variation of a sample was less than 0.1%. All samples reached equilibrium within 18 days. After equalisation, sample dimensions were noted for any variation from the initial dimensions. The samples were then exposed to cycles of a high humidity (75% RH for 8 h) followed low humidity level (33% RH for 16 h) as per the NORDTEST requirements. Sample masses were recorded at regular intervals by means of a laboratory balance with a resolution of 0.01 g. After all samples reached two stable cycles, they were removed from the climatic chamber and their final dimensions were recorded. For the final stable cycle, the MBV for a given material was determined using Equation (1).

$$MBV = \frac{\Delta m}{S \times \Delta\%RH} \tag{1}$$

where Δm is change in mass of the sample due to change in relative humidity, S is the total exposure surface area and Δ%RH is difference between the humidity levels.

4.2. Hygroscopic behaviour results and discussion

Fig. 14a and 14b show the moisture absorption curves at the last stable cycle for both guar gum and xanthan gum stabilised samples respectively. Moisture absorption curves for unamended and cement stabilised samples are also plotted. It can be noted from these figures, at the given ambient conditions, biopolymer stabilised earthen materials retain more water within the soil matrix than both unamended and cement stabilised earthen materials. Moisture absorption of unamended samples is primarily dependent on the clay mineral present in the soil mix, i.e. kaolinite. Having least affinity towards water, it can be expected that the amount of moisture absorbed by unamended samples would be correspondingly low [52,53], and this is beneficial from the point of view of shrinkage of course. In the case of cement stabilised samples, the addition of cement leads to the formation of cementitious products which may cover the clay surface and reduce the moisture absorption capabilities [7]. However in the case of biopolymer stabilised samples, in addition to the clay activity, the ability of hydrogels to absorb or diffuse moisture under varying ambient conditions may affect moisture absorption [54]. Having natural affinity towards water, it can be expected that the biopolymer stabilised earthen materials would attract water vapour at higher humidities. Further, addition of biopolymers may also affect the pore structure of the material which would facilitate in exchanges of water vapour and thus improving its buffering potential [55]. Between the biopolymers, xanthan gum stabilised samples have slightly higher moisture absorption than guar stabilised samples.

It can be observed from Fig. 15, that the final moisture buffering values of biopolymer stabilised samples are higher than unamended and cement stabilised samples. Lower moisture absorption capabilities can be expected with the latter is in concurrence with the previous literature [7,56]. However, unlike cement stabilisation, biopolymer stabilisation improves the hygroscopic properties of the earthen material as judged by the increase in moisture buffering value. As noted previously, the interactions of hydrogels with moisture due to changes in ambient conditions enables it to retain more water leading to these results. This is an important finding further supporting the practical use of biopolymer stabilisation considering that while the addition of cement improves mechanical and durability properties, it actually compromises the hygroscopic properties of the earthen construction material.

Fig. 16 presents the moisture buffering values of all the tested samples in the current study alongside values determined using

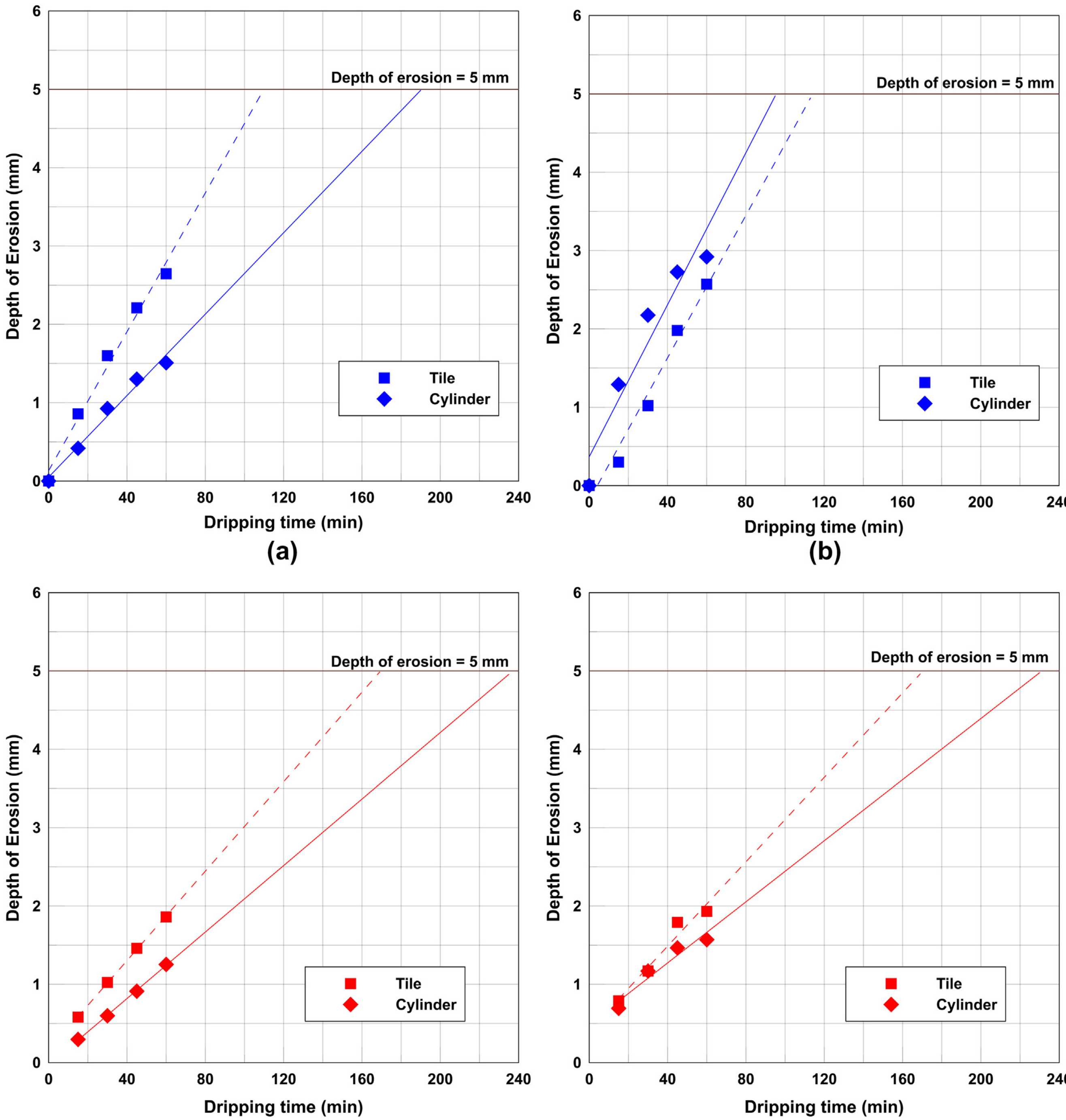

Fig. 12. Rate of erosion for (a) guar gum, 7 days, (b) guar gum, 28 days, (c) xanthan gum, 7 days, (d) xanthan gum, 28 days.

Table 4
Classification of compressed earth blocks after DIN 18945 [36].

Class	Application	Contact tests	Suction tests (h)	Dip tests Mass loss (%)
Ia	External wall exposed to natural weathering	No cracks and no permanent swelling deformation	≥ 24 h	5%
Ib	Coated external wall		≥ 3 h	5%
II	Internal wall		≥ 0.5 h	15%
III	Dry applications	No requirement	No requirement	No requirement

Table 5
Classification of earthen construction materials after DIN 18945 [36].

Series	Contact tests	Suction tests	Dip tests
Unamended	Ia	Ia	III
Guar gum	Ia	Ia	Ia
Xanthan gum	Ia	Ia	Ia

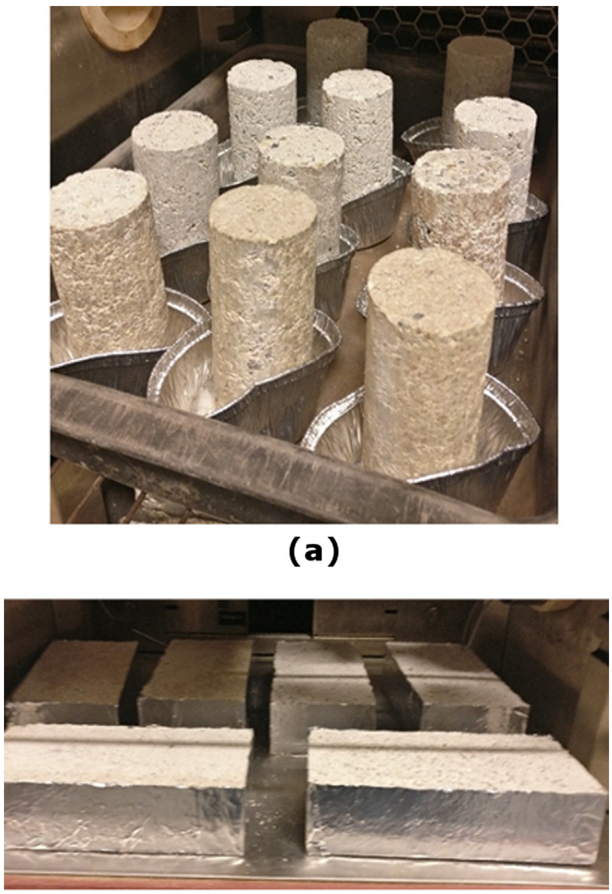

Fig. 13. Moisture buffering tests (a) cylindrical samples (b) brick samples.

the NORDTEST approach for other materials taken from the literature. Values are shown for fired brick and concrete as determined by Rode et al. [44] and for earthen construction materials as determined by Allinson and Hall [57], McGregor et al. [52,56], Oudhof et al. [58] and Arrigoni et al. [7] along with the MBV classification as proposed by Rode et al. [44]. The moisture buffering values for the specimens tested in this study varied from 0.55 to 1.05 g/m^2%RH, and with these values most of the samples tested can be classified in the "moderate" category, only the xanthan gum stabilised brick falls into "good" category (Fig. 16). It can be seen that the hygroscopic properties of biopolymer stabilised earthen construction materials are better than some conventional building materials such as fired brick and concrete. Also, in agreement with the findings of McGregor et al. [56] and Arrigoni et al. [7], the moisture buffering values of cement stabilised samples from this study were found to be lower than for the unamended samples. Also, it can be noted that the moisture buffering values of the unamended and cement stabilised samples from this study seem to be lower than the reported values in the literature. This may be attributed to other factors which control hygroscopic properties of earthen materials, i.e. soil gradation and the principal clay mineral content in the soil mix. It is well known under similar hygrothermal conditions, soils comprised of finer particles retain more water than those based on coarse particles [59,60]. In addition, soils with active clay minerals such as montmorillonite retain more water than soils with other clay minerals such as illite and kaolinite [52,53]. Hence, a higher percentage of fine particles and the principal clay mineral in the soil mix contributes to higher moisture buffering values. The reported higher moisture buffering values of compressed earth blocks by McGregor et al. [52] could therefore be attributed to a differences in the clay mineralogy and its content to the material used in the current study.

Arrigoni et al. [7] studied the effect of chemical stabilisers on the hygroscopic properties of stabilised rammed earth materials prepared using an engineered soil mixture and moisture buffering values were also obtained for a natural soil. It can be noted from the results included in Fig. 16 from [7] that the hygroscopic properties of the earthen construction material prepared with natural soil (denoted as RE_Pise) is quite high in comparison with those prepared with the engineered soil mix (ELS). The addition of cement was observed to further reduce the moisture buffering value of the stabilised engineered soil mix. From this study it is evident that the type of soil used for manufacturing earthen construction materials has a strong influence on hygroscopic behaviour, which is as expected. In the present study, the earthen construction materials were also prepared using an engineered soil mix consisting of a clay fraction of refined kaolin. Refined kaolin was preferred over natural kaolinitic soils as they enabled close control of clay mineralogy in order to better understand the behaviour of biopolymer stabilisation; a similar approach has been considered in past studies of earthen construction materials [61,62]. By using refined kaolin, however, the engineering behaviour of the prepared soil may be atypical to that of natural soil due to its defined particle size gradation and plasticity properties [63]. Having only kaolinite as the dominant clay mineral, which has low affinity towards water when compared to other clay minerals [53,64], it can be expected that moisture buffering values of the material prepared here may be lower than those of materials prepared with natural soils. Clearly, further work is necessary to assess the behaviours of biopolymer stabilisation on earthen materials with different dominant clay minerals, but the reported results herein are encouraging.

5. The suitability of biopolymer stabilised earthen materials for construction

To assess the potential of biopolymers as effective stabilisers in earthen construction materials, it is necessary to consider the effect of their use on a range of properties and behaviours, i.e. mechanical, recycling, durability and hygroscopicity. The first two have been dealt with previously and the latter two are covered by the study in this paper.

Mechanical properties: As has been demonstrated in previous studies [18,19,65] biopolymers essentially bind soil particles through the formation of hydrogels. The intrinsic chemical properties of the biopolymer control the physical nature of the hydrogels formed which has an impact on the mechanical properties (i.e. strength and stiffness) of the stabilised material. Guar gum, as a neutral polysaccharide essentially interacts with soil particles through hydrogen bonds. The network of hydrogels formed through hydrogen bonds mainly improves only the compressive strength of the material. As an anionic polysaccharide, xanthan gum binds soil particles with additional ionic bonds on top of hydrogen bonds. The additional ionic bonds bond with clay particles within the soil matrix resulting in better aggregation [65]. This interaction results in improved compressive and tensile strengths of the stabilised

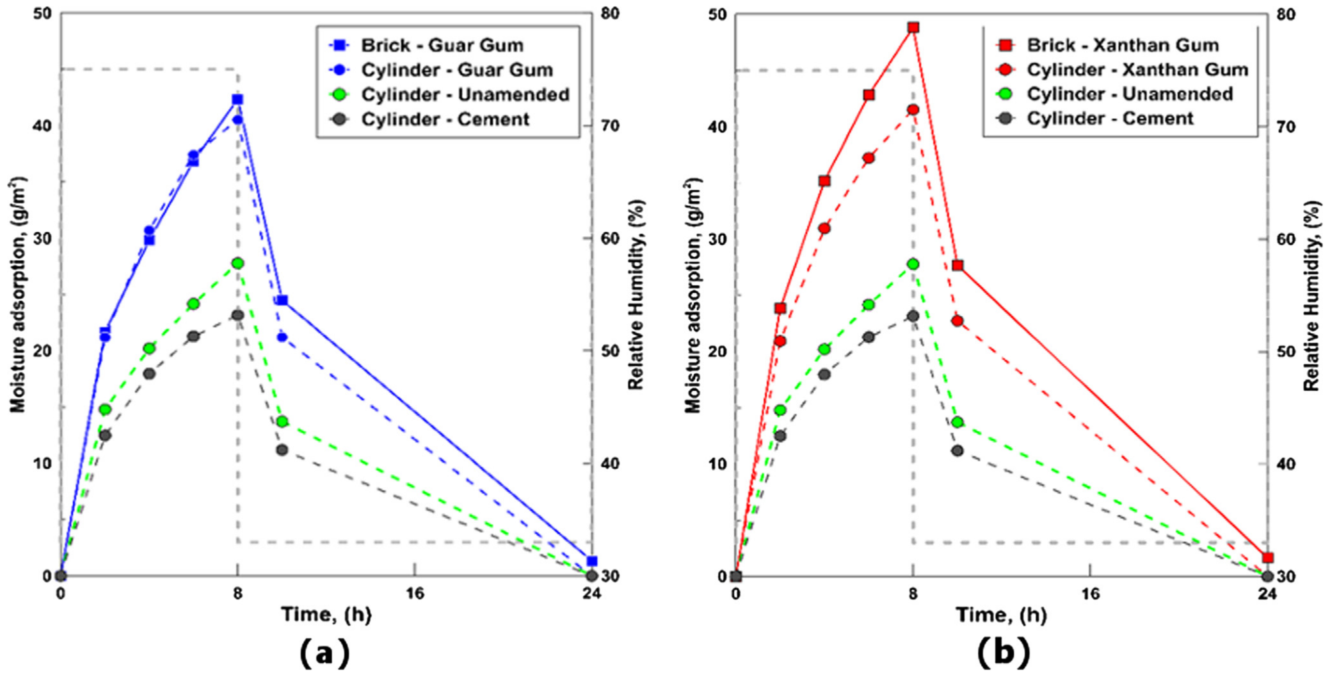

Fig. 14. Comparison of moisture absorption for the last stable cycle, (a) guar gum and (b) xanthan gum.

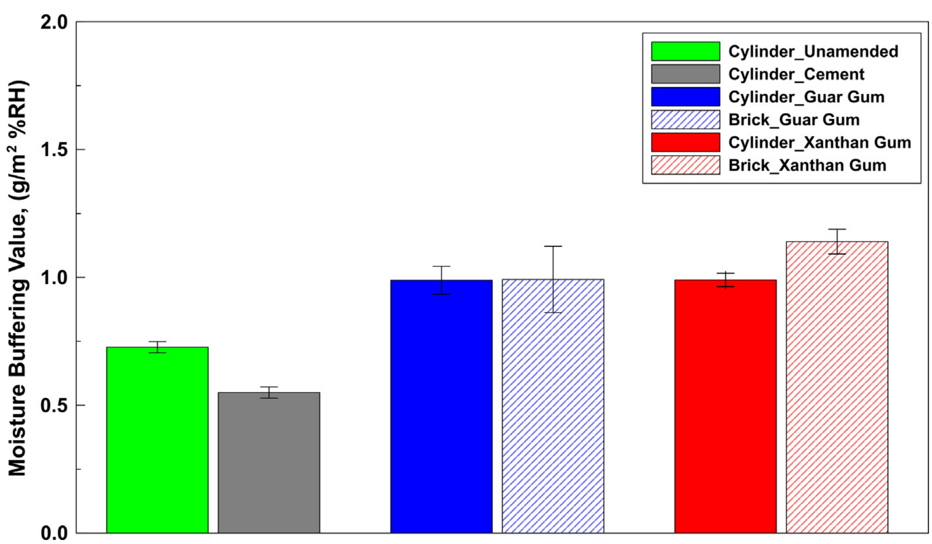

Fig. 15. Moisture buffering values for all samples.

material [18]. For biopolymer stabilised earthen materials, much of the strength gain occurs within 7 days of sample formation. Only small concentrations of biopolymer (typically about 1.5–2.0% of dry soil mass) are required to achieve comparable strengths of 8.0% cement stabilised earthen construction material.

Recycling properties: Life Cycle Assessment of earthen construction materials is in its infancy although there have been some encouraging recent studies, e.g. [66]. However, it is obvious that at the end of its lifetime, an earthen construction material should be able to be entirely recycled. Cement stabilised materials pose problems in recycling and are usually downcycled rather being entirely recycled. This situation poses environment and economic problems for its safe disposal on demolition [8]. The recycling potential of biopolymer stabilised earthen materials has been previously studied by the authors [67] where it was noted that a relatively low-level soil washing technique was sufficient to recycle and retrieve back much of the original soil gradation and plasticity properties for guar gum stabilised samples. For xanthan gum stabilised samples, the soil washing was less successful, resulting in a material with higher coarse particle fraction, higher plasticity and higher shrinkage potential than the original unamended soil mixture. However, it was concluded that the recycled soil mixture could be considered for single reuse. In both cases, the chemical properties of the water collected after washing suggested that it would not pose any environmental threat when disposed of so that in comparison to cement, biopolymers would seem to have better potential for recycling.

Durability properties: The results from various durability tests presented in this paper testify the potential of these two biopolymers to improve the durability performance of the stabilised material. Though the results from contact and suction tests did not show significant differences in behaviour between unamended

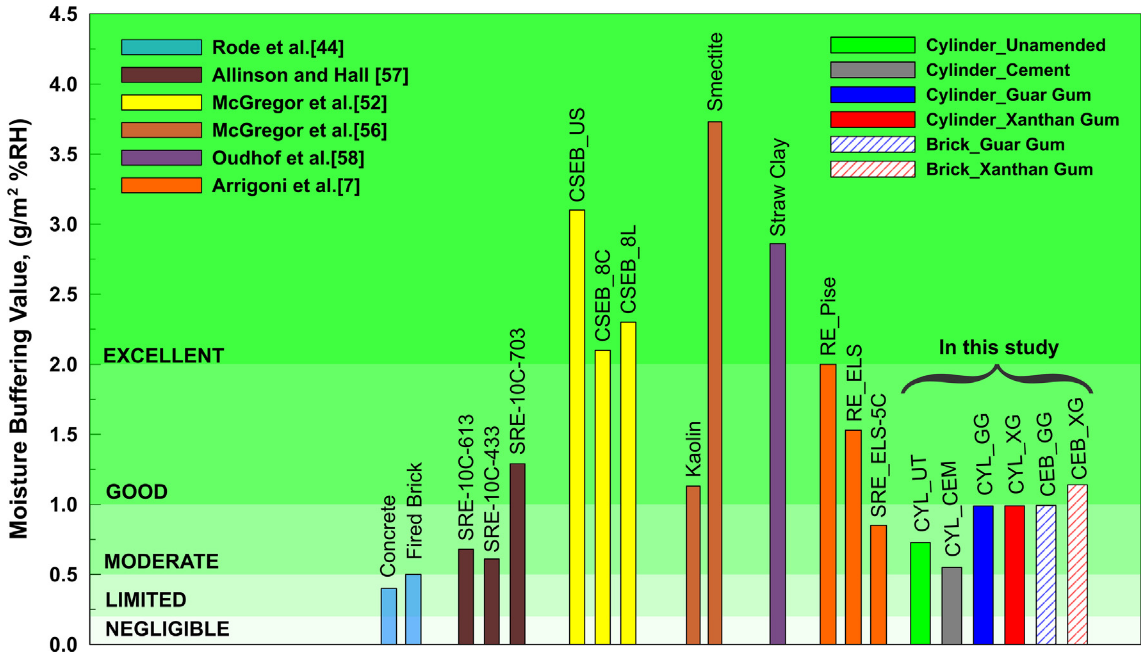

Fig. 16. Comparison of moisture buffering values of present study with literature data.

samples and biopolymer stabilised samples, the benefit of biopolymer additions was more evident in aggressive durability tests such as the dip and Geelong drip tests. In these tests, unamended specimens failed to satisfy the test requirements, while biopolymer stabilised specimens performed well. In dip tests, unamended bricks had higher loss of mass on immersion, while biopolymer stabilised earthen bricks were able to resist deterioration on immersion. This ensured the classification of biopolymer stabilised earthen brick to be Class Ia according to DIN 18945 [36] which are suitable for external wall exposed to natural weathering. In Geelong drip tests, biopolymer stabilised material showed better resistance than unamended samples, while it could not match the performance of cement stabilised samples. The relative differences in durability performance between cement and biopolymers, should not however, hinder the recommendation of these biopolymers as a potential stabiliser considering their satisfactory durability performance as per the test requirement.

Hygroscopic properties: The higher MBVs of biopolymer stabilised materials than unamended and cement stabilised materials as witnessed from the moisture buffering tests discussed in this paper suggests an improvement in hygroscopic properties of the material. Biopolymers, which basically provide stabilisation through formation of hydrogels [18,19], retain moisture within the material which improves its hygroscopic properties. This is certainly an important finding considering how the hygroscopic property of the material is directly linked with the operational energy required to maintain good indoor air quality within an earthen building [6]. Once again, as an alternative to cement, biopolymers appear to be prospective alternative stabilisers which not only provide necessary mechanical and durability properties, but also improve the hygroscopic behaviour of earthen construction materials.

6. Conclusions

Earthen construction materials are usually perceived to be a sustainable form of building material due to their inherent characteristics of having low embodied energy, low operational energy, fire-resistant and recycling capabilities. Modern earthen construction materials rely on chemical stabilisers like cement to improve its strength and durability, which however diminishes the positive environmental aspects markedly and negatively affects hygroscopic and recycling properties. As an alternative to cement, biopolymers which have been previously used in many geotechnical applications may prove to be potential stabilisers for earthen construction material.

Both biopolymers studied here, guar and xanthan gums, have a significant positive impact on mechanical properties. At the end of their useful life earthen materials can also be recycled efficiently with minimal environmental impact. As this study has shown, in addition to desirable mechanical and recycling properties, biopolymer stabilised earthen material has satisfactory durability performance against water-induced deterioration and, unlike cement, biopolymers would not compromise on the hygroscopic properties of the material. Of the two biopolymers, xanthan gum has demonstrated superior mechanical, durability and hygroscopic performances, while the guar gum stabilised samples exhibited greater recycling potential. While it is clear that further experimental research is necessary to confirm the long-term behaviour of these materials, the two biopolymers used in this study appear as exciting potential replacements for less environmentally friendly stabilisers for earthen construction materials.

CRediT authorship contribution statement

S. Muguda: Conceptualization, Methodology, Investigation, Visualization, Writing - original draft. **G. Lucas:** Investigation. **P. N. Hughes:** Conceptualization, Supervision, Writing - review & editing. **C. EAugarde:** Conceptualization, Supervision, Writing - review & editing. **C. Perlot:** Conceptualization, Supervision, Writing - review & editing. **A.W. Bruno:** Conceptualization, Writing - review & editing. **D. Gallipoli:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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