Case Studies in Construction Materials 16 (2022) e01023

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Strength and erosion resistance of mudbrick as an alternative local material for Australia's Northern Territory remote housing

Varuna Sumanasena [a], Ali Rajabipour [a,*], Milad Bazli [a,b], Cat Kutay [a], Dongxiu Guo [a]

[a] College of Engineering, IT & Environment, Charles Darwin University, Darwin, Australia
[b] School of Mechanical and Mining Engineering, The University of Queensland, Queensland, Australia

ARTICLE INFO

Keywords:
Mudbrick
Australia's Northern Territory
Remote housing

ABSTRACT

Housing in Australia's Northern Territory (NT) remote areas has remained a challenge despite many years of attempts by policy makers and engineers. Community engagement has been found a major factor in success of remote projects and one way to attract local engagement and reduce construction cost in remote areas is using locally available materials in construction. In this paper technical feasibility of using mudbrick made from local soil is studied through standard compressive and erosion resistance tests. Results show that both compressive strength and erosion resistance of the mudbricks made in the study meet the requirements recommended by HB 195 – Australia earth building handbook. Findings suggest that mudbrick could be considered as an alternative construction material to the current common practice of using block work in NT remote areas. Inclusion of a low amount of high lime content Portland cement was found significantly effective in improving mudbrick erosion resistance properties.

1. Introduction

Building houses in remote communities in Australia's Northern Territory (NT) has been suffering from high cost, poor quality of work, low quality of ongoing maintenance and relatively short lifespan [1–4]. Community engagement in remote projects is considered a key aspect in design and construction in remote [5–7] which could be improved by use of local materials. Community engagement in remote projects creates sustainable jobs for local people [8–10], improves adults literacy and numeracy [10] and encourages physical activities in communities [11–13].

One way to promote community engagement in NT remote areas is use of local materials in construction which also makes the opportunity to enjoy Indigenous people knowledge of materials in a two way learning process [14,15] and reduce environmental impacts [16]. Indigenous people of Australia traditionally use fibrous materials [17] such as spinifex [18] and termite mound [19] for making tools or in buildings. Further, since shipment of materials and deployment of skilled workers to remote areas largely account for high cost of construction in remote areas, use of local materials made by local people could significantly reduce construction cost in remote areas.

Mudbrick housing has been a feature in the construction industry of most developing countries due to its cost-effectiveness. Recently, the "Eco-friendly" reputation of mudbricks has led to highlight and use in the housing construction industry in developed countries like Germany [20], Australia and New Zealand [21,22] and to be advocated by the government [23] and technical societies

* Corresponding author.
E-mail addresses: varuna.sumanasena@students.cdu.edu.au (V. Sumanasena), ali.rajabipour@cdu.edu.au (A. Rajabipour), milad.bazli@cdu.edu.au (M. Bazli), cat.kutay@cdu.edu.au (C. Kutay), DONGXIU.guo2@students.cdu.edu.au (D. Guo).

https://doi.org/10.1016/j.cscm.2022.e01023
Received 3 February 2022; Received in revised form 13 March 2022; Accepted 18 March 2022
Available online 21 March 2022

[24,25]. Sun-dried mudbricks and burnt mudbricks are among the oldest earthen housing construction methods [21] with potential to provide cost-effective houses for NT remote areas, improve local engagement in the projects and promote local economy. An example is "Bawinanga" aboriginal corporation, a company with distinctive mudbrick production facilities to produce mudbricks for the construction of local houses and provide local jobs in the community of Maningrida, West Arnhem Region in Norther Territory [26].

Durability of earth structures has been a major concern and a large body of research on mudbrick has been formed around environmental effects on mudbricks. While public concern on durability of earth structures seemed valid in some studies [27], observations on real structures exposed to rain and other environmental effects for more than 20 years suggest functionality of earth structures a reliable building material [28–30]. In arid regions mud slurry flows under gravity. Sediment coatings and infillings, abrasion due to wind flow, puddling, and bioturbation are deemed as the main damage mechanisms in earth walls [31]. In regions with high frequency and intensity of rain fall which are of the interest of current study, erosion is deemed to be the main cause of damage in earth structures. Two mechanisms have been proposed for erosion of earth structures under rainfall, damage due to the kinematic energy of raindrops impact and turbulent flow along micro water streams on the surfaces [32]. As such, two general approach have been developed to reduce effects of erosion, surface protection [33–35] and strengthening the material. Latter could be done by addition of stabilisers such as hydraulic lime, cement, fly ash, etc. and/or by inclusion of (mostly natural) fibres in the mix [36–41].

Common approaches for direct testing of earth bricks erosion resistance include drip tests including Geelong method [42] and Swinburne Accelerated Erosion Test (SAET), Accelerated Erosion Test [43] and brush wire test [44,45]. Drip tests are not deemed to be reliable in areas with rain fall greater than 500 mm per annum [27] which could be due to effect of turbulent erosion [32] in such areas. Since annual rainfall in many NT communities exceeds 1500 mm with sever intensity, herein spray method according to the recommended set up in [46] was employed for erosion tests. Soil selection, preparation and details of tests conducted in the study are discussed in the next sections.

In here technical feasibility of using mudbrick made from local NT soil is studied with focusing on two aspects of compressive strength and erosion resistance. Erosion resistance is a critical material property in NT remote areas due to heavy rain and wind in these areas [47,48]. Adding Portland cement as a stabiliser to the mudbrick mix design can improve bricks resistance to the rainfall erosion. The aim of current study was to analyse the susceptibility of mudbricks made from local materials to rainfall erosion in Australia's Northern Territory (NT) remote areas. Mix designs and production were tried to be simple to make the process applicable in remote areas and also facilitate community engagement and knowledge exchange. In this regard, three different mix designs that include Portland cement were considered with an emphasis on simplicity of mix and production for remote application.

2. Experimental programme

2.1. Soil properties and soil preparation

Soil was collected from an excavation face at the new building site of Charles Darwin university in Darwin city. As per recommended by [49] subsoil was not used and rather the material was collected from the excavated face in depth of 1500–2000 mm. Kandosols and laterite soils are recommended for brick production in [38,46,50,51]. Laterite soil has been found to have relatively lower silica-sesquioxide ratio which results in more pulverise and being reactive towards cement hydration [52]. Therefore, laterite soiled used in this study is deemed to have a propensity to react effectively with cement and thus have more hydration products along with more C-S-H (Calcium Silicate Hydrate) bonds which could result in enhancement of the erosion resistance of the tested bricks.

By inspection, the soil layer, right below the subsoil at the depth of 300 mm from the surface, could be categorised as laterite. This soil is a common type of soil in Australia Norther Territory [53]. The extracted soil had the texture of red and dark yellowish and by

Fig. 1. Appearance of the soil used in this study taken from CDU new campus building site on Cavenagh st, Darwin.

inspection 30% material seemed to be Kandosols and rest laterite. Laterites soil is also a common type of soil in Northern territory, with a colour texture of red to brown [54,55]. Fig. 1 shows the appearance of the extracted soil.

Sieve analysis test [56,57] and hydrometer test [56] are suggested to evaluate suitability of soil for mudbrick production. Sediment Jar Test, Sieve analysis test, and Proctor compaction test were used to determine the suitability of extracted soil for mudbrick production according to [46]. It is worth mentioning that sediment Jar test was used as an initial test to evaluate the suitability of the extracted soil samples as per suggested by [57,58]. Sieve analysis test as per [59] was used to identify the clay and silt percentages of extracted soil samples to determine the suitable cement type for the mix. Finally, proctor compaction test issued to identify the optimum moisture content in each soil mix design as per recommended by [56]. Australian earth building handbook HB - 195 was used as the reference document to analyse the results and adjust mix design.

2.2. Composition and property enhancement

Sediment jar test and sieve analysis suggested a clay and silt content of about 47% in the extracted soil. While clay and silt content in the soil was slightly greater than the recommended amount of 45% by [46] it was less than the maximum amount of 50% recommended by [60] for making mudbricks. Sieve analysis was carried out according to ASTM C136/C136M [59]. Three sieve analysis test trials were conducted on extracted soil samples. The detailed results are summarised in Table 1.

Lime is deemed to reduce potential negative effects of clay through developing pozzolanic reaction with clay and silt and inclusion of lime has been recommended for soil with high silt and clay content [56,60–62] but is limited to a range of 6 – 10% of cement [63]. To keep the brick production simple and applicable in remote areas no hydraulic lime was added to the mix and instead General Purpose Cement (GP) cement with 7.5% limestone which is commercially available in Australian market was used. Composition of the cement used for stabilising is shown in Table 2. Three mix designs with 0%, 5% and 10% of cement to the weight of soil considered for producing mudbricks.

2.3. Optimum water content-proctor compaction test

A linear relation between Maximum Dry Density (MDD) and compressive strength of bricks was found for different mix designs compacted at their MDD [64]. To estimate MDD, proctor compaction test has been suggested to determine the optimum moisture content for mudbrick mix designs [56]. The proctor compaction test has standardised as two separate tests namely standard and modified proctor compaction test. In this regard standard proctor compaction test has been found more suitable than modified proctor compaction test since manual processes are commonly involved in mudbrick production and thus standard procedure was deemed more representative of the normal practice [65]. As such, standard proctor compaction test was conducted for three mix designs with 0%, 5% and 10% of cement to the solid weigh. Three trails were carried out for each mix design from which average results are shown in Fig. 2.

Results of the proctor compaction tests are tabulated in Table 3 and show that both MDD (Maximum dry density) and optimum moisture content have elevated with the incremental increase of cement percentage in the mix which is aligned with findings in [66].

Water content in each mix design was calculated according to the optimum moisture content shown in Table 3 and a 5% extra for evaporation.

To improve the durability of the moulds they could be built from waterproof commercial timber and application of oil is recommended to reduce adhesion of soil to the moulds [67]. In this study and according to HB 195 - Australia earth building handbook [46], bricks of size 76 mm × 230 mm × 110 mm were produced using slope moulding technique. Three sample from each mix and totally 18 samples were tested. Bricks kept in moulds for 48 h for setting followed by curing for three weeks after which samples were checked for any significant crack before compressive and erosion tests. Fig. 3 shows some samples after taking out from mould.

3. Results

Standard compressive strength test according to ASTM C1314-18 [68] and accelerated erosion test according to [46] were conducted in this study. Following details of the tests and results are presented followed by a discussion on the findings of this study.

3.1. Compression test

The Compression test performed as per ASTM C1314-18 [68] to determine the maximum compressive strength of brick samples. Three samples were tested in each design mix. The purpose of this test was to assess whether the bricks meet the recommended compressive strength values recommended by the Australian earth building handbook [46]. Before placing the bricks in the

Table 1
Composition of the extracted soil samples.

Description	Percentages	Sieve passing sizes
Coarse aggregate	30% (30.0% – Avg)	> 4.75 mm
Sand	23% (23.3% – Avg)	4.75–0.075 mm
Clay & Silt	47% (46.7% – Avg)	> 0.075 mm

Table 2
Composition of the selected Cement for stabilisation.

Ingredients of Cement	Percentages (%)
Limestone	7.5
Gypsum	0.5
Portland cement clinker	92

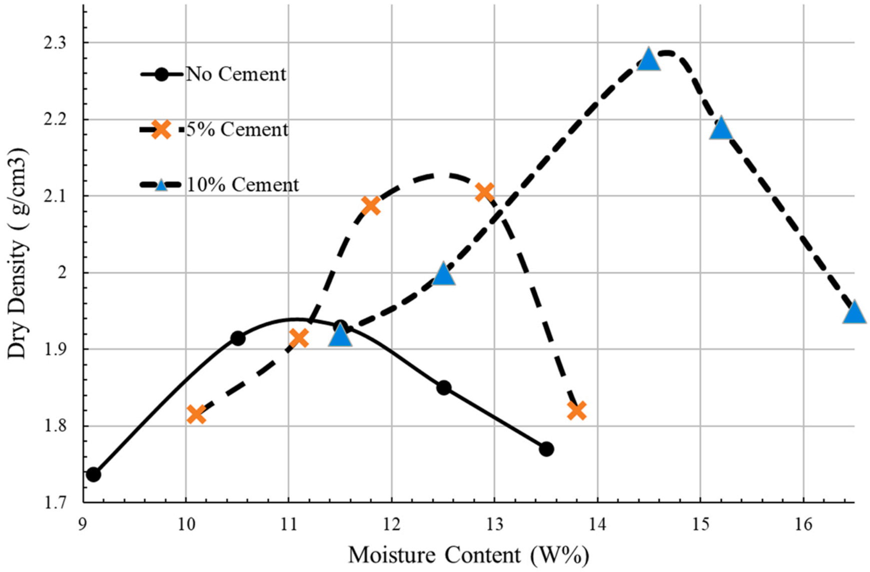

Fig. 2. Proctor compaction results for three brick soil mixes.

Table 3
Summary of standard proctor compaction test results.

Mix description	MDD (g/cm^3)	Optimum moisture content (Average)
No Cement	1.94	11.1
5% Cement	2.11	12.5
10% Cement	2.31	14.7

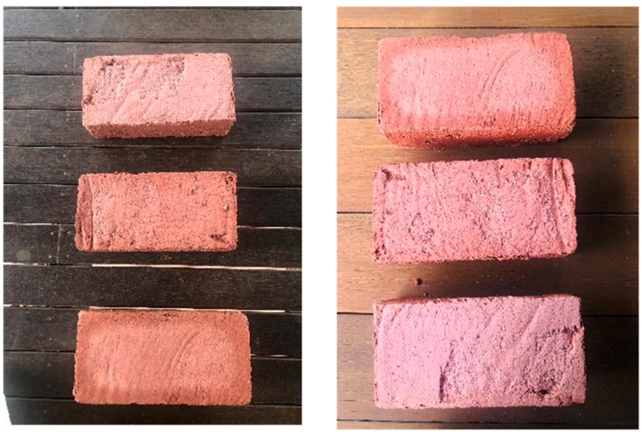

Fig. 3. Mudbricks after removing the moulds.

compression testing machine, surfaces of bricks were cleaned and levelled to impose the load evenly onto the surface. Dimensions of the bricks measured to the nearest 1 mm. A constant rate of compression load applied from the top plate to the surface of the brick until it fails as per in ASTM C1314-18. Fig. 4 shows samples during and after loading.

The maximum load applied at failure was recorded, and the compressive strength was measured. Fig. 5 shows the average compressive strength of the specimens for three tested mix designs. All design mixes satisfied the minimum compressive strength requirement of 2 MPa recommended by the Australian earth building handbook [46] as per shown in Fig. 5.

3.2. Spray test

Accelerated spray/erosion test was conducted as per for HB 195 - Australia earth building handbook [46] to determine the erosion rate of each brick specimen. The water pressure was set to 50 kPa and the suitability of Mudbricks were assessed based on the maximum erosion depth of 1 mm/1 min criterion as per in HB 195 –Australian earth building handbook. Fig. 6 illustrates the test set up used for the erosion test. All bricks were exposed to a water pressure of 50 kPa throughout an hour of testing period. Depth of pit (see Fig. 6) made due to water spray was measured as well as rate of erosion respectively in mm and mm/h.

Results of the erosion test are shown in Table 4 and Fig. 7 and suggest that all three design-mix tested in this study met the minimum requirement of average 0.25 mm pit depth per minute of spray recommended by HB 195 for cyclonic regions. This is worth to mention that this value is 1 mm /min for non-cyclonic regions.

Fig. 7 also shows that resistance of the bricks to erosion improved by the inclusion of the cement into the mix. Table 5 summaries the accelerated erosion test results for the three mix designs. All brick mix designs recorded an erosion rate less than 1 mm/min which is the maximum rate recommended by HB – 195.

4. Discussion

Possibility of using mudbricks made from local soil in remote areas of Australia's Northern Territory (NT) for construction purposes was explored in this study. Laterite soil is available in abundance in NT remote areas and therefore was selected as the based material for making mudbricks in this study. Compressive and erosion tests were conducted on three mix designs and results clearly show that the erosion resistance and compressive strength of the brick samples improve by inclusion of cement to the mix. The 10% cement brick samples have shown the lowest average erosion rate of 0.11 mm/min while no cement and 5% cement brick samples have shown average erosion rates of 0.19 mm/min and 0.16 mm/min, respectively. This could lead to creation of cement gel/hydrated cement which helps in filling the pores of mudbricks and thus enhances the bond between the inter-clusters and increase the strength of bricks. This is aligned with obtained test results which shows 10% cement brick samples had superior performance in accelerated erosion test in comparison to other mix designs. Furthermore, applying more cement in the mix makes more lime available to react with clay while lime has been found to reduce adverse effects of clay in soil [62]. Therefore, a higher cement content is expected to improve the compressive strength results. Obviously, inclusion of higher cement content results in increasing amount of hydrate products which

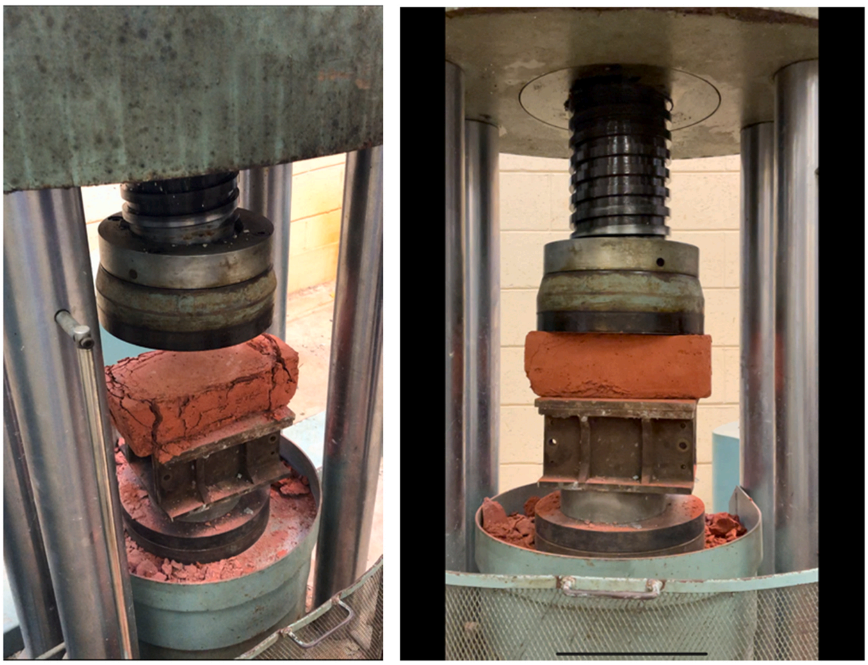

Fig. 4. Mudbricks during and after loading.

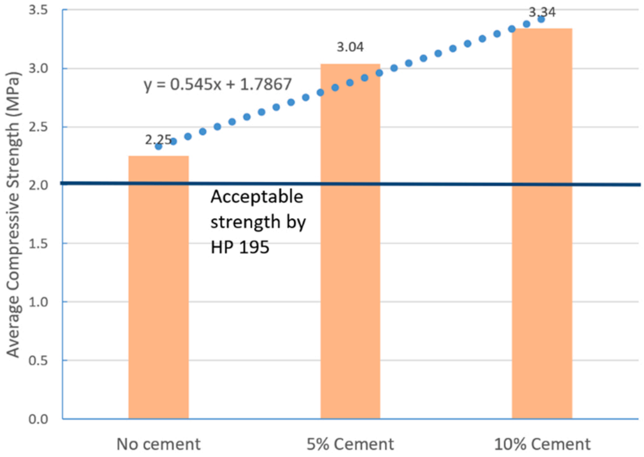

Fig. 5. Average values of compressive strength.

Fig. 6. Left: test setup for accelerated erosion test set up. Right: measuring the pitted depth by using Vernier Calliper.

Table 4
Erosion test results.

Brick type	Erosion depth (mm)	Mean	SD	CV (%)
No cement	11.8			
No cement	11.6			
No cement	12.6	12.0	0.43	3.6
5% Cement	9.9			
5% Cement	9.3			
5% Cement	9.4	9.5	0.26	2.7
10% Cement	6.3			
10% Cement	6.6			
10% Cement	6.4	6.4	0.13	2.0

enhances erosion resistance and compressive strength of the bricks.

Aligned with the results obtained by [69,70], results in here showed that inclusion of cement contributes to more consistency in the results in accelerated erosion test. As shown in Table 5, 10% cement bricks have shown the lowest standard deviation values while no cement samples have shown the highest standard deviation values. It is evidenced that inclusion of a consistent manufactured material like cement to a relatively less consistent and natural material like soil is likely to reduce the variation in material properties and performance [71]. Inclusion of 5% cement was not found significantly effective in improving erosion resistance which suggests that there could be a lower limit for cement to be effective in mudbrick mix. It is also plausible to consider an upper limit for inclusion of cement due to chance of shrinkage cracks and also economic, shipment and storage challenges in remote areas [3,72]. While almost all the buildings in remote areas are one story, the maximum compressive strength on a load bearing wall is unlikely to exceed 0.4 MPa

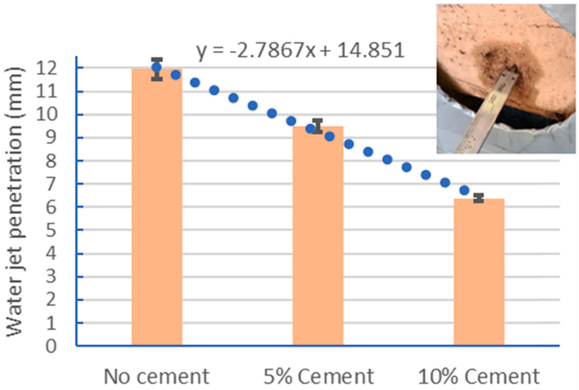

Fig. 7. Average and standard deviation of pit depth in erosion test.

which is way below the minimum compressive strength of samples reported in here and therefore adding more cement to the brick mix will not be structurally needed while it might improve durability of the building. It is also worth to mention that HB – 195 Australian earth building handbook recommended a limit of 12% on the cement content in mudbricks.

Applicability of the findings to NT remote areas was highly intended in this study thus a very simple mix of natural soil with widely available General Purpose Portland cement was studied. Satisfactory properties of the mudbrick made in this study and the fact that laterite soil mix used in here is the common soil type in almost all 72 NT remote communities, suggest that mudbrick has the potential to be widely used in NT remote construction. Similarity of soil type in different communities and simplicity of mudbrick production also make the opportunity for seamless knowledge exchange between communities and external people which promote two-way learning, community engagement and sense of ownership to the built environment.

Table 6 and Fig. 8 show compressive strength of earth block samples in a few studies including the current study. The intention to present such a comparison is firstly showing the range of compressive strength of earth blocks made from different soils and secondly highlighting that soil used in this study (and is abundant in NT remote areas) has the right properties for earth brick production in NT remote areas. Results in Table 6 suggest that earth block made from soil with very low silt and clay (see mix F) shall not offer fair compressive strength while a well selected soil like J offers high compressive strength even without stabiliser or fibre. Soil mix J used in [73] was sourced from a commercial earth block manufacturer of earth blocks and thus is expected to be well examined and selected by industry. Soil used in the current study offers relevantly acceptable compressive strength as shown in Fig. 8 which suggests the potential of earth block as a construction material in NT remote areas given abundance of this type of earth in these areas and satisfactory erosion resistance of the tested blocks.

5. Conclusion

Sustainability and use of local materials is well integrated in Australia's Indigenous design. Mudbrick made from local material is deeded a sustainable solution which improves local engagement in remote NT projects. Typical laterite soil widely available in Australia's Northern Territory (NT) remote areas was used for making mudbricks for potential application in remote housing. The sieve analysis test results showed presence of 47% of silt and clay in the soil sample. Standard Proctor compaction test, compression test and erosion resistance tests were conducted on three mix designs including, 0%, 5% and 10% cement to soil weight. Following conclusions could be drawn from the obtained results:

- Since the soil used in this study is the common soil in NT remote areas, satisfactory compressive strength and erosion resistance of the mudbricks made from this soil suggest that mudbrick has the potential to be used in NT remote housing.
- Results showed that there is a positive correlation between the percentages of cement inclusion and maximum dry density, compressive strength, and resistance to erosion in tested mudbrick samples while cement content is suggested to be capped at 12%.
- Standard deviation of samples in compression and erosion resistance tests decreased by introducing more cement in the mix suggesting that design safety factors could be moderated for mudbricks with higher cement content.
- Comparison of compressive strength results with that in other studies show that common soil in NT naturally has a right composition for making local mudbrick.

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.

Table 5
Summary of the erosion test results.

Brick type	Average pit depth in millimetre after 60 min of water spray as per HB 195 Australian earth building handbook (mm)	Average rate of pitting (mm/min)	Coefficient of variation (%)
No cement	12	0.20	3.6
5% Cement	9.5	0.16	2.7
10% Cement	6.4	0.11	2.0

Table 6
Compressive strength comparison between earth blocks made in different studies.

Mix name – See Fig. 8 for comparison	Stabiliser and fibre	Density kg/m^3	Place of soil sourcing	Gravel %	Sand %	Silt %	Clay %	Gravel and sand %	Silt and clay %	Compressive strength (MPa)
A (current study)	0% cement, 0% fibre	1950	Darwin, Australia	30	23	37	12	53	47	2.25
B (current study)	5% cement, 0% fibre	2130	Darwin, Australia	30	23	37	12	53	48	3.04
C (current study)	10% cement, 0% fibre	2280	Darwin, Australia	30	23	37	12	53	49	3.34
D [a] [37]	0% cement, 0% fibre	1870	NIT Hamirpur, India	NR	NR	NR	NR	NR	NR	0.32
E [a] [37]	2.5% cement, 2% Grewia Optiva fibre	1800	NIT Hamirpur, India	NR	NR	NR	NR	NR	NR	0.36
F [b] [70]	6% cement, 0% sugarcane ash	1930	Aveiro, Portugal	17	81	NR	NR	98	1.2	0.7
G [b] [70]	6% cement, 8% sugarcane ash	2020	Aveiro, Portugal	17	81	NR	NR	98	1.2	1.54
H [b] [70]	12% cement, 0% sugarcane ash	2020	Aveiro, Portugal	17	81	NR	NR	98	1.2	3.13
I [b] [70]	12% cement, 8% sugarcane ash	2040	Aveiro, Portugal	17	81	NR	NR	98	1.2	2.89
J [c] [73]	0% cement, 0% fibre	1863	Germany	NR	NR	45	12	43	57	5.21

NR: Not Reported.
[a] Soil is reported as sandy clay with low compressive strength.
[b] Silt and clay altogether are reported around 1.2%.
[c] Exact location of material source is not reported.

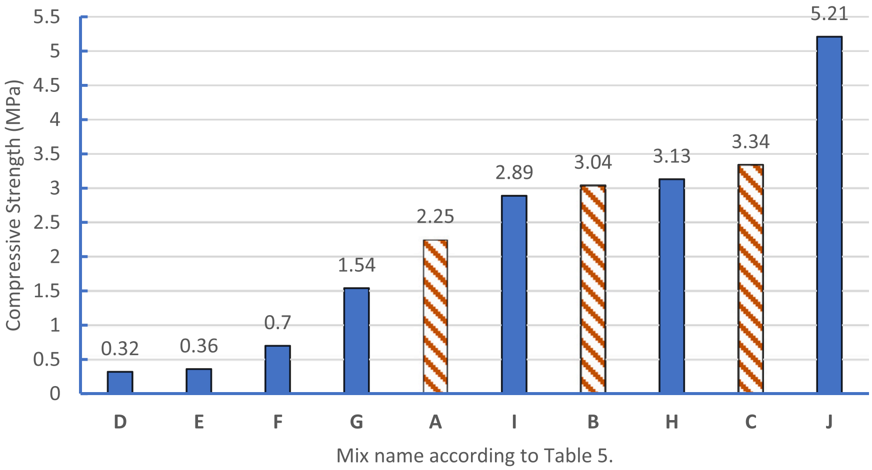

Fig. 8. Mean compressive strength of earth bricks in different studies. Mix names are according to Table 6. Results in the current study are shown in bars A–C.

References

[1] R. Porter, Towards a Hybrid Model of Public Housing in Northern Territory Remote Aboriginal Communities?, Citeseer, 2009.
[2] A. Lowell, et al., The 'invisible homeless'–challenges faced by families bringing up their children in a remote Australian Aboriginal community, BMC Public Health 18 (1) (2018) 1–14.
[3] J. Fien, E. Charlesworth, 'Why isn't it solved?': factors affecting improvements in housing outcomes in remote Indigenous communities in Australia, Habitat Int. 36 (1) (2012) 20–25.
[4] R.S. Bailie, K.J. Wayte, Housing and health in Indigenous communities: key issues for housing and health improvement in remote Aboriginal and Torres Strait Islander communities, Aust. J. Rural Health 14 (5) (2006) 178–183.
[5] J. Stewart, M. Anda, R.J. Harper, Low-carbon development in remote Indigenous communities: applying a community-directed model to support endogenous assets and aspirations, Environ. Sci. Policy 95 (2019) 11–19.
[6] E. Cox, Work with us not for us' to end the Indigenous policy chaos, The Conversation, 2014.
[7] K. Seemann, D. Marinova, Desert settlements: Towards understanding the mutuality of influence and scale-free network concepts, J. Econ. Soc. Policy 13 (2) (2010) 5.

[8] DRD, Resilient Families, Strong Communities: A Roadmap for Regional and Remote Aboriginal Communities. Regional Services Reform Unit, Department of Regional Development, Perth, Australia, 2016.
[9] A. Hay, et al., Lessons learned from managing a remote construction project in Australia. in: Proceedings of the 20th International Symposium on Advancement of Construction Management and Real Estate, Springer, 2017.
[10] M. Moran, et al., The Transformation of Assets for Sustainable Livelihoods in A Remote Aboriginal Settlement, Desert Knowledge CRC, 2008.
[11] P. Burgess, R. Bailie, A. Mileran, Beyond the mainstream: health gains in remote Aboriginal communities, Aust. Fam. Phys. 37 (12) (2008) 986.
[12] R. McDermott, et al., Beneficial impact of the homelands movement on health outcomes in central Australian Aborigines, Aust. N. Z. J. Public Health 22 (6) (1998) 653–658.
[13] K.G. Rowley, et al., Lower than expected morbidity and mortality for an Australian Aboriginal population: 10–year follow-up in a decentralised community, Med. J. Aust. 188 (5) (2008) 283–287.
[14] N. Purdie, G. Milgate, H.R. Bell, Two way teaching and learning: toward culturally reflective and relevant education, 2011.
[15] C. Kutay, Knowledge elicitation with aboriginal Australian communities, Aust. J. Inf. Syst. (2021) 25.
[16] J.C. Morel, et al., Building houses with local materials: means to drastically reduce the environmental impact of construction, Build. Environ. 36 (10) (2001) 1119–1126.
[17] D. Nash, Aboriginal Plant Use and Technology, Australian National Botanic Gardens, ACT, Australia, 2000.
[18] O. Powell, R.J. Fensham, P. Memmott, Indigenous use of spinifex resin for hafting in North-Eastern Australia, Econ. Bot. 67 (3) (2013) 210–224.
[19] F.F. Udoeyo, A.O. Cassidy, S. Jajere, Mound soil as construction material, J. Mater. Civ. Eng. 12 (3) (2000) 205–211.
[20] H. Schroeder, C. Ziegert, P. Fontana, The new German standards for earth blocks and earth masonry mortar, in: Proceedings of the 9th IMC-International Masonry Conference 2014, 2014.
[21] M.J. Munir, et al., Development of eco-friendly fired clay bricks incorporating recycled marble powder, J. Mater. Civ. Eng. 30 (5) (2018), 04018069.
[22] P. Taylor, M.B. Luther, Evaluating rammed earth walls: a case study, Sol. Energy 76 (1) (2004) 79–84.
[23] P. Downton, Rammed Earth, Australia's Guid to Environmentally Sustainable Homes, 2013 [cited 2020; 2020].
[24] ebaa, Earth Building Association of Australia, 2022.
[25] B. Lawson, D. Rudder, Building Materials Energy and the Environment: Towards Ecologically Sustainable Development, Royal Australian Institute of Architects Red Hill, ACT, 1996.
[26] D.E. Smith, Estimating Northern Territory Government Program Expenditure for Aboriginal People: Problems and Implications, Centre for Aboriginal Economic Policy Research (CAEPR), The …, Canberra, ACT, 2018.
[27] K.A. Heathcote, Durability of earthwall buildings, Constr. Build. Mater. 9 (3) (1995) 185–189.
[28] H. Barnard, et al., The preservation of exposed mudbrick architecture in Karanis (Kom Aushim), Egypt, J. Field Archaeol. 41 (1) (2016) 84–100.
[29] Q.B. Bui, et al., Durability of rammed earth walls exposed for 20 years to natural weathering, Build. Environ. 44 (5) (2009) 912–919.
[30] F. Pacheco-Torgal, S. Jalali, Earth construction: lessons from the past for future eco-efficient construction, Constr. Build. Mater. 29 (2012) 512–519.
[31] D. Friesem, et al., Degradation of mud brick houses in an arid environment: a geoarchaeological model, J. Archaeol. Sci. 38 (5) (2011) 1135–1147.
[32] K.N. Brooks, P.F. Ffolliott, J.A. Magner, Hydrology and the Management of Watersheds, John Wiley & Sons, 2012.
[33] K.B. Ren, D.A. Kagi, Upgrading the durability of mud bricks by impregnation, Build. Environ. 30 (3) (1995) 433–440.
[34] C. Atzeni, et al., Surface wear resistance of chemically or thermally stabilized earth-based materials, Mater. Struct. 41 (4) (2008) 751–758.
[35] M. Lanzón, et al., Use of zinc stearate to produce highly-hydrophobic adobe materials with extended durability to water and acid-rain, Constr. Build. Mater. 139 (2017) 114–122.
[36] E. Quagliarini, S. Lenci, The influence of natural stabilizers and natural fibres on the mechanical properties of ancient Roman adobe bricks, J. Cult. Herit. 11 (3) (2010) 309–314.
[37] V. Sharma, H.K. Vinayak, B.M. Marwaha, Enhancing compressive strength of soil using natural fibers, Constr. Build. Mater. 93 (2015) 943–949.
[38] S. Ismail, Z. Yaacob, Properties of laterite brick reinforced with oil palm empty fruit bunch fibres, Pertanika J. Sci. Technol. 19 (1) (2011) 33–43.
[39] S. Muguda, et al., Durability and hygroscopic behaviour of biopolymer stabilised earthen construction materials, Constr. Build. Mater. 259 (2020), 119725.
[40] F.F. Khorasani, M.Z. Kabir, Experimental study on the effectiveness of short fiber reinforced clay mortars and plasters on the mechanical behavior of adobe masonry walls, Case Stud. Constr. Mater. 16 (2022), e00918.
[41] S.N. Malkanthi, W.G.S. Wickramasinghe, A.A.D.A.J. Perera, Use of construction waste to modify soil grading for compressed stabilized earth blocks (CSEB) production, Case Stud. Constr. Mater. 15 (2021), e00717.
[42] L. Baker, S. Lawrence, A. Page, Australian Masonry Manual, Deakin University Press, 1991.
[43] G.F. Middleton, L.M. Schneider, Earth-wall construction, 1987.
[44] ASTM, D-559-03. Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures, American Society for Testing and Materials, West Conshohocken, Pennsylvania, USA, 2003.
[45] T.L. Webb, T. Cilliers, N. Stutterheim, The Properties of Compacted Soil and Soil-cement Mixtures for Use in Building, National Building Research Institute = Nasionale Bounavorsingsinstituut, 1950.
[46] P. Walker, Standards Australia, The Australian Earth Building Handbook, HB 195, Standards Australia International Ltd, Sydney, 2002.
[47] A.P. Sturman, N.J. Tapper, The Weather and Climate of Australia and New Zealand, Oxford University Press, USA, 1996.
[48] G.G. Caitcheon, et al., The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) Rivers, Geomorphology 151 (2012) 188–195.
[49] E. Quagliarini, M. D'Orazio, S. Lenci, The properties and durability of adobe earth-based masonry blocks, in: Eco-efficient Masonry Bricks and Blocks, Elsevier, 2015, pp. 361–378.
[50] S. Alausa, et al., Thermal characteristics of laterite-mud and concrete-block for walls in building construction in Nigeria, Int. J. Eng. 4 (4) (2013) 8269.
[51] H. Binici, O. Aksogan, T. Shah, Investigation of fibre reinforced mud brick as a building material, Constr. Build. Mater. 19 (4) (2005) 313–318.
[52] Z. Saing, et al., Mechanical characteristic of ferro laterite soil with cement stabilization as a subgrade material, Int. J. Civ. Eng. Technol. (IJCIET) 8 (3) (2017) 609–616.
[53] M. Karan, et al., The Australian SuperSite Network: a continental, long-term terrestrial ecosystem observatory, Sci. Total Environ. 568 (2016) 1263–1274.
[54] D. Abrecht, No-till crop establishment on red earth soils at Katherine, Northern Territory: effect of sowing depth and firming wheel pressure on the establishment of cowpea, mung bean, soybean and maize, Aust. J. Exp. Agric. 29 (3) (1989) 397–402.
[55] J. Kirkpatrick, et al., A transect study of the Eucalyptus forests and woodlands of a dissected sandstone and laterite plateau near Darwin, Northern Territory, Aust. J. Ecol. 12 (4) (1987) 339–359.
[56] S. Malkanthi, N. Balthazaar, A. Perera, Lime stabilization for compressed stabilized earth blocks with reduced clay and silt, Case Stud. Constr. Mater. 12 (2020), e00326.
[57] F. Arooz, R. Halwatura, Mud-concrete block (MCB): mix design & durability characteristics, Case Stud. Constr. Mater. 8 (2018) 39–50.
[58] S. Burroughs, Recommendations for the selection, stabilization, and compaction of soil for rammed earth wall construction, J. Green. Build. 5 (1) (2010) 101–114.
[59] ASTM-C136/C136M-14, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, American Society for Testing and Materials Philadelphia, PA, USA, 2014.
[60] K.-L. Lin, et al., Waste brick's potential for use as a pozzolan in blended Portland cement, Waste Manag. Res. 28 (7) (2010) 647–652.
[61] A. Dass, S.K. Malhotra, Lime-stabilized red mud bricks, Mater. Struct. 23 (4) (1990) 252–255.
[62] F. Bell, Lime stabilization of clay minerals and soils, Eng. Geol. 42 (4) (1996) 223–237.
[63] E. Obonyo, J. Exelbirt, M. Baskaran, Durability of compressed earth bricks: assessing erosion resistance using the modified spray testing, Sustainability 2 (12) (2010) 3639–3649.

[64] S.N. Bhavsar, A.J. Patel, Analysis of swelling & shrinkage properties of expansive soil using brick dust as a stabilizer, Int J. Emerg. Technol. Adv. Eng. 4 (2014) 303–308.
[65] U. Khalid, Z. ur Rehman, Evaluation of compaction parameters of fine-grained soils using standard and modified efforts, Int. J. Geo-Eng. 9 (1) (2018) 1–17.
[66] S. Bhairappanavar, R. Liu, A. Shakoor, Eco-friendly dredged material-cement bricks, Constr. Build. Mater. 271 (2021), 121524.
[67] O. Sealetsa, R. Moalosi, A survey of musculoskeletal disorder prevalence in the Kiln brick moulding industry in Botswana, J. Ergon. S4 (2014) S4–S010.
[68] C. ASTM, Standard test method for compressive strength of masonry prisms, Masonry test methods and specifications for the building industry, 2012.
[69] D. Ribeiro, R. Néri, R. Cardoso, Influence of water content in the UCS of soil-cement mixtures for different cement dosages, Procedia Eng. 143 (2016) 59–66.
[70] S.A. Lima, et al., Analysis of the mechanical properties of compressed earth block masonry using the sugarcane bagasse ash, Constr. Build. Mater. 35 (2012) 829–837.
[71] D. Silveira, et al., Mechanical properties of adobe bricks in ancient constructions, Constr. Build. Mater. 28 (1) (2012) 36–44.
[72] D. Ciancio, P. Jaquin, P. Walker, Advances on the assessment of soil suitability for rammed earth, Constr. Build. Mater. 42 (2013) 40–47.
[73] L. Miccoli, U. Müller, P. Fontana, Mechanical behaviour of earthen materials: a comparison between earth block masonry, rammed earth and cob, Constr. Build. Mater. 61 (2014) 327–339.