

1 Title: **Corrosion protection of steel embedded in cement-stabilised rammed earth**

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## 11 **Abstract**

12 Cement-stabilised rammed earth (CSRE) reinforced with steel is a modern adaptation of an ancient  
13 construction technique, permitting the use of a wider range of structural forms and applications  
14 than those used traditionally. However, corrosion behaviour of steel embedded in CSRE is not yet  
15 understood, casting doubt on the longevity of these structural solutions. In this paper, we assessed  
16 the ability of a range of CSRE mixes stabilised with 10% cement to protect embedded steel against  
17 carbonation-induced corrosion by using electrochemical measurements and considering also  
18 material alkalinity, carbonation resistance and capillary absorption. Results demonstrated that the  
19 pH of the CSRE mixes was sufficiently alkaline to provide the appropriate environment for  
20 passivation of steel reinforcement. Based on the experimental results, carbonation would most likely  
21 have reached the reinforcement within approximately 5-15 years (50 mm cover) or 30-75 years (150  
22 mm cover), depassivating the reinforcement within the design life span. The findings demonstrated  
23 that a corrosion potential of -200 mV SCE indicates conditions of negligible corrosion of steel in  
24 CSRE. As behaviour varied little between the four tested soil mixes (of varying granularity), it is  
25 reasonable to expect that findings presented here also apply to other soil mixes stabilised with 10%  
26 cement.

## 27 **Key words**

28 Rammed earth; cement-stabilised; corrosion potential; sustainable building; carbonation; capillary  
29 absorption; passivation

30 **Abbreviations:** CL, crushed limestone; CSRE, cement-stabilised rammed earth; HCP, half-cell  
31 potential; IRA, initial rate of absorption; MDD, maximum dry density; OMC, optimum moisture  
32 content; PSD, particle size distribution; RCA, recycled concrete aggregate; SCE, saturated calomel  
33 electrode; SM1, Soil mix 1; SM2, Soil mix 2; UCS, unconfined compressive strength; WA, Western  
34 Australia

## 35 1.0 Introduction

36 Rammed earth has been used in many forms throughout history, with cement-stabilised rammed  
37 earth (CSRE) being one of the more common modern variants. Steel reinforcement (“rebar”) is now  
38 often specified in CSRE structures, however there is limited understanding of the long-term  
39 behaviour of the composite material. Having been placed in the formwork with the loose CSRE mix  
40 prior to compaction, the deformed bar becomes embedded within the material due to the  
41 compaction force during ramming. The rebar is introduced to increase tensile capacity and ductility  
42 as well as to enable roof and slab tie-downs. Despite its frequent inclusion, it is unknown whether  
43 the reinforcement is likely to corrode and either negate its addition or damage the structure in the  
44 long term. As a result, design is conservative; for example, some standards specify using expensive  
45 galvanised reinforcement to provide corrosion protection (NZS 4298:1998). While there are no  
46 reports of reinforced rammed earth structures built over the last few decades showing signs of  
47 external deterioration as a result of corrosion, it is unknown whether issues will arise in the future,  
48 i.e. whether corrosion is occurring and whether the wall will retain the same capacity for which it  
49 was designed.

50 Very limited research regarding corrosion of reinforcement in any rammed earth variants is present  
51 in the literature. CSRE has been studied here as this is the most commonly used variant of modern  
52 stabilised rammed earth in Australia. It should be noted that reinforcement is not recommended in  
53 unstabilised rammed earth due to a lack of anchorage [2]. A significant body of research regarding  
54 corrosion of reinforcement in concrete structures does however exist. Given that CSRE and concrete

55 share a number of similarities such as components (e.g. aggregate and cement as stabiliser) and  
56 relevant properties for durability aspects (e.g. pH, density, pore structure), it is potentially  
57 reasonable to assume that the reinforcement is exposed chemically to a comparable environment in  
58 both.

59 The service life of a structure reinforced with steel will depend on the corrosion “initiation” and  
60 “propagation” phases [3]. In concrete, the high alkalinity of cement paste protects steel  
61 reinforcement from corrosion as a passivating layer develops on the surface of the steel. Despite  
62 providing initial protection, over time this passivating layer can deteriorate through ingress of  
63 aggressive agents such as carbon dioxide (CO<sub>2</sub>) or chloride ions (the latter particularly in coastal  
64 areas). Carbonation, caused by the reaction of carbon dioxide (CO<sub>2</sub>) from the air with alkaline  
65 components in the cement paste, is the most common cause of degradation in reinforced concrete.  
66 As less-alkaline calcium carbonates are formed during carbonation, pH of the affected cementitious  
67 material is lowered to a value around 9, depassivating the steel once the carbonation front  
68 penetrates the cover depth. The carbonation reaction depends on environmental factors (such as  
69 humidity, temperature and CO<sub>2</sub> concentration) and material penetrability which is determined by  
70 pore network connectivity: the more pores that are connected to the outside surface, the greater  
71 the penetration. The time taken to lose the steel passivation due to carbonation is the initiation  
72 phase. Once the material is no longer protecting reinforcement from corrosion, i.e. the steel is  
73 depassivated, the propagation phase will depend on presence of moisture and oxygen on the  
74 surface of reinforcement. Capillary absorption generally controls availability of moisture in a steel  
75 reinforced material and is also the main transport mechanism controlling ingress of aggressive  
76 agents (such as chlorides).

77 One particular case of a reinforced CSRE wall in Perth, Western Australia (WA) was investigated by  
78 Beckett and Ciancio [4]. The wall was built around 1970 in Cottesloe, a coastal suburb of Perth. The  
79 parent sandy soil (<7% fines) was stabilised with 7% Portland cement by dry mass of soil. The wall

80 comprised a 200 mm buried portion atop a rammed earth footing; the remainder (~1800 mm) was  
81 exposed to incident rainfall with little or no surface protection. The wall was demolished in 2012 and  
82 sections showing no surface damage were extracted for analysis. Investigations revealed that the  
83 uncoated mild steel reinforcement was highly corroded in the 200 mm buried region between the  
84 footing and exposed wall surface, due to groundwater ingress, whilst the remainder was in as good a  
85 condition as when it was first installed (Figure 1). Although an extreme case, being an external wall  
86 with no roof protection and in a coastal environment, this example highlights that extensive damage  
87 is possible without necessarily being revealed by the state of the wall's surface.



88  
89 *Figure 1: Corroded reinforcement from 30-year-old CSRE wall*

90 This casts doubt on the effectiveness of steel reinforcement in existing rammed earth structures and  
91 the design life and/or safety of these structures. It also calls into question whether it is worth  
92 specifying steel reinforcement in rammed earth structures if its longevity cannot be guaranteed.  
93 Therefore, in order to provide some certainty for reinforced rammed earth design, it is essential to  
94 understand whether the rammed earth can provide adequate protection for steel reinforcement  
95 against carbonation-induced corrosion: the subject of our paper.

96 Firstly, carbonation resistance and capillary absorption of different CSRE mixes were measured as  
97 these material properties strongly influence corrosion protection. Subsequently, the CO<sub>2</sub>-induced  
98 corrosion behaviour of carbon steel bars embedded in the different CSRE mixes studied in this work  
99 when exposed to various environments was compared. Based on material properties and corrosion  
100 behaviour, an assessment is made of whether corrosion may impact the service life of the material.

101 In the absence of specific CSRE tests, existing concrete and masonry testing was used: the  
102 appropriateness of these tests for CSRE was also assessed.

## 103 2.0 Experimental program

### 104 2.1 Materials and characterisation

105 It is well-established from cementitious materials research that the ability of both air- and  
106 water-borne aggressors to penetrate a material is dependent on both pore volume and geometry  
107 [5]. A number of properties affect CSRE pore structure, such as specific surface area of the soil(s),  
108 density of the rammed earth, compaction conditions (water content and density) and stabiliser  
109 hydration [6]. This study therefore used four different rammed earth mixes stabilised with cement  
110 (see Table 1) and typical of construction around the world to evaluate their influence on the  
111 corrosion behaviour of carbon steel in CSRE, as well as to facilitate correlations between durability  
112 performance and soil mix characteristics.

113 The four base soils used were crushed limestone (CL), recycled concrete aggregate (RCA), a natural  
114 soil from the Dampier Peninsula, WA (Soil mix 1, SM1) and a blend of crushed limestone and kaolin  
115 clay (SM2). Particle size distributions of base soils (PSD; according to AS 1289.3.6.1—2009 [7]) are  
116 shown in Figure 2. United soil classification system designation of each base soil is included in  
117 Table 1.

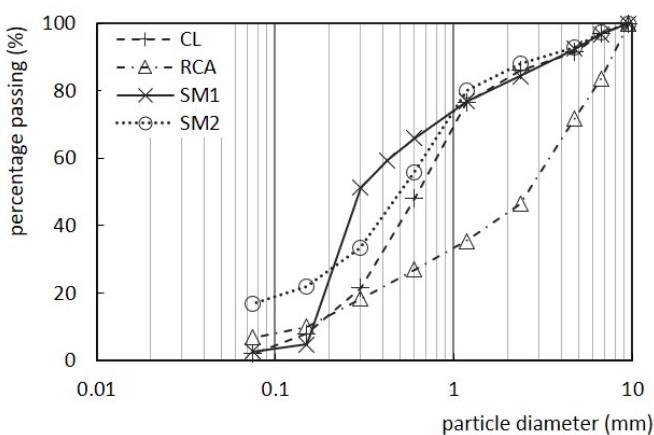
- 118 • CL was selected as this is commonly used in WA as the ‘earth’ component of rammed earth  
119 in preference to the local soil. It is inert and generally well-graded, with subrounded  
120 particles. It is a readily available quarried material in WA.
- 121 • RCA is a popular soil substitute in WA for CSRE construction due to its environmentally-  
122 friendly properties as a waste material [8]. The soil classification of RCA differs significantly  
123 to that of the other soils used; it is poorly graded with angular particles, a far greater

124 proportion of crushed rock (~50% >4.75 mm) and minimal fine to medium sized materials  
125 (Figure 2).

126 Being a waste material, each RCA mix may differ in terms of characteristics such as  
127 mineralogy, angularity and PSD, depending on the original concrete product and level of  
128 processing. Furthermore, RCA may include some unhydrated cement particles from the  
129 manufacture of the concrete for its initial use; the presence of unhydrated cement was not  
130 considered to impinge on testing presented here.

- 131 • Soil mix 1 (SM1) largely consisted of fine sand with little gravel, coarse sand or fines. This  
132 was selected to broaden the range of soils being used as, like RCA, it was poorly graded but  
133 with disparate predominant particle sizing.
- 134 • An “engineered” (i.e. artificial) soil mix, referred to as Soil mix 2 (SM2), was created from a  
135 blend of 85% CL and 15% kaolin clay. The kaolin used was an anhydrous aluminium silicate  
136 (PL 27%, LL 61%; [9]). Addition of kaolin increased the fines content (Figure 2), intended to  
137 modify the CL pore structure. As both components of SM2 were commercially available, mix  
138 mineralogy and grading was highly repeatable.

139 All soils were stabilised with 10% cement (relative to dry soil mass) as this is common practise  
140 around the world [10].



141

142 *Figure 2: Dry PSD of each base soil (refer Table 1)*

143 All specimens were manufactured at optimum moisture content (OMC) and maximum dry density  
144 (MDD). These parameters were established for each soil mix in accordance with AS 1289.5.2.1—  
145 2003 [11] using a modified compactive effort, selected as it produced densities similar to those used  
146 in the field (obtained using pneumatic rammers) [12]. As stabilisers had been added, each test was  
147 completed within 45 minutes of adding water to ensure adequate workability and accuracy of  
148 results prior to stabiliser hydration [1]. Specimen dry density was measured throughout testing to  
149 track variation.

150 UCS testing was completed as a quality control measure to ensure each CSRE mix was representative  
151 of those suitable for RE construction. Testing was carried out as per AS 5101.4—2008 [13].

152 Specimens were manufactured by combining adequate base soil and 10% anhydrous stabiliser to  
153 form a homogenous mix. Base soils were sieved prior to mixing, using only the material passing the  
154 9.5 mm sieve to ensure diameter of any aggregates was less than ten times the minimum mould  
155 diameter. Water was then added to meet OMC for each mix. As for compaction testing, specimen  
156 preparation was completed within 45 minutes of stabiliser addition. Specimens were compacted in  
157 five layers in a mould of height 200 mm, diameter 104 mm. To ensure MDD was met, soil mass for  
158 one layer was calculated and compacted to a depth of 40 mm using a volume-controlled rammer  
159 head. Four specimens of each mix were manufactured with the exception of SM1 (one specimen  
160 due to insufficient material). Results for each mix, tested after 28 days' curing in a humidity-  
161 controlled room ( $94 \pm 2\%$  relative humidity,  $21 \pm 1^\circ$  temperature), are given in Table 1. Results  
162 showed that all soil mixes would be suitable for low-rise rammed earth building per NZS 4298:1998  
163 [1] requirements of greater than 1.3 MPa (7-16 MPa; averages shown in Table 1).

164 Specimen pH and available pore volume (apparent porosity) were examined to support the study of  
165 corrosion behaviour. The pH of each stabilised CSRE mix was tested at manufacture as per the Eades  
166 and Grim procedure [14] to verify that CSRE was sufficiently alkaline to promote passivation. pH was  
167 tested again following the curing phase (see Table 1) to view any possible evolution.

168 Available pore volume of each specimen type was evaluated using an immersed absorption test,  
 169 measured at 5 weeks from manufacture and at 30 weeks. A specimen of each CSRE mix was  
 170 immersed in water and weighed at fixed time intervals until constant mass was reached. Available  
 171 pore volume was then calculated as:

$$p = \left\{ \frac{(m_s - m_d)}{\delta_w} \left( \frac{1}{V_{sp}} \right) \right\} 100 \quad (1)$$

172 where  $m_s$  and  $m_d$  are respectively saturated ( $s$ ) and oven dry ( $d$ ) specimen masses ( $m$ ) (kg),  $\delta_w$  is  
 173 density of water ( $\text{kg/m}^3$ ) and  $V_{sp}$  is volume of the specimen ( $\text{m}^3$ ). Calculated available pore volume  
 174 for each CSRE mix is also given in Table 1.

175 *Table 1: Summary of CSRE mix preparation details and properties*

CSRE mix: Base soil + 10% cement	Base soil (United soil classification system designation)	MDD ( $\text{kg/m}^3$ )	OMC (%)	UCS avg (MPa)	pH		Available pore volume (%)	
					Manufacture	After curing	@5 wks	@30 wks
CL	Crushed limestone (SW)	1950	12	14.0	12.0	13.0	17.1	15.7
RCA	Recycled concrete aggregate (GP)	1995	13	8.9	11.6	12.9	19.4	17.2
SM1	Dampier Peninsula natural soil (SP)	2040	9	12.9	11.9	12.9	14.3	12.6
SM2	85% Crushed limestone + 15% kaolin clay (SC)	2075	11	10.0	11.7	12.7	18.5	16.8

176

177 No tests to investigate corrosion susceptibility exist specifically for CSRE. In this work, it was  
 178 assumed that tests developed for durability-related properties in concrete could be adapted to suit  
 179 CSRE; the success of this assumption is discussed later in this paper.

## 180 2.3 Carbonation resistance

181 For concrete, the rate at which the carbonation front develops can generally be described by



$$d = kt^{1/n} \quad (2)$$

182 where  $k$  is the carbonation coefficient and  $t$  is time (years) [3].  $k$  (mm/year<sup>1/n</sup>) can be calculated for  
183 a given material to specify cover depth for protection of reinforcement from carbonation-induced  
184 corrosion for the life of the structure.

185 100 mm cube specimens of the four CSRE mixes were manufactured for carbonation testing. These  
186 were compacted in two 50 mm layers of known mass compacted to the target density using a  
187 jackhammer and a volume-controlled rammer head. Compacted surfaces were scarified to promote  
188 amalgamation of the two layers. Each was weighed and then cured for 28 days at a high humidity to  
189 provide an appropriate environment for cement hydration (in accordance with AS 5101.4—2008  
190 [13]).

191 Carbonation testing was carried out across a six-month period to assess whether the relationship  
192 which described CO<sub>2</sub> penetration with time in concrete might be applied to those CSRE mixes  
193 studied in order to determine their carbonation coefficients (Table 2). Testing was undertaken after  
194 14 days (half-curing period), 5 weeks, 15 weeks and 30 weeks from manufacture. Excepting those  
195 tested at 14 days, specimens were removed from the curing room after 28 days and exposed to  
196 ambient air conditions. Testing at 5 weeks was carried out to allow a week for the specimens to  
197 equilibrate to the ambient environment: the lower humidity with respect to the curing room  
198 progressively reduces the water in the pores thereby favouring access to CO<sub>2</sub>. Air temperature  
199 throughout the experimental program varied between 11.7 °C and 25.1 °C with an average of  
200 18.2 °C. Relative humidity varied between 43.3% and 83.9% with an average of 63.2%.

201 Specimens were tested by breaking them in half along the ramming line, using compressed air to  
202 remove any detached particles (to ensure no cross-contamination between carbonated and  
203 uncarbonated areas). In order to evaluate carbonation depth by colorimetric test, each broken face  
204 of the specimen was then sprayed with a 1% alcoholic solution of phenolphthalein as per  
205 I.S. EN 13295:2004 [15]. The pH indicator is colourless in areas where material is carbonated (pH ≤ 9)

206 and magenta where there is alkaline reserve. Measurements for carbonation progression were taken  
 207 on four sides of each specimen and averaged. Specimens were exposed to atmospheric CO<sub>2</sub> only,  
 208 rather than an accelerated CO<sub>2</sub> environment, to be more representative of likely site conditions.  
 209 Additional SM2 carbonation specimens were manufactured to a lower density of 1800 kg/m<sup>3</sup> at a  
 210 water content of 10% to examine the effect of reduced density on carbonation performance.  
 211 Besides that, specimen components, preparation and exposure conditions were identical to those  
 212 described above.

213 *Table 2: Summary of specimens for each test*

Soil	Test	Age of specimen (weeks from manufacture)													
		2	4	5	7	8	11	15	20	25	30	44	47	52	
CL	Carbonation	1	1					1		1				1 <sup>1</sup>	
	IRA	2	5					3		5					
	HCP dry & immersed unless noted			2	2	2	2	2	2	2, 2 <sup>2</sup>	2 <sup>3</sup>	2 <sup>4</sup>	2		
	otherwise (UNO)														
RCA	Carbonation	1	1					1		1				1 <sup>1</sup>	
	IRA		5					3		5					
	HCP dry & immersed UNO		2	2	2	2	2	2	2	2, 2 <sup>2</sup>	2 <sup>3</sup>	2 <sup>4</sup>	2		
SM1	Carbonation	1	1					1		1				1 <sup>1</sup>	
	IRA		5					3		5					
	HCP dry & immersed UNO		1	1	1	1	1	1	1	1, 1 <sup>2</sup>	1 <sup>3</sup>	1 <sup>4</sup>	1		
SM2	Carbonation (MDD)	1	1					1		1				1 <sup>1</sup>	
	Carbonation (low density)		1	1	1		1								
	IRA		5					3		5					
	HCP dry & immersed UNO		2	2	2	2	2	2	2	2, 2 <sup>2</sup>	2 <sup>3</sup>	2 <sup>4</sup>	2		

214 <sup>1</sup>HCP specimen, <sup>2</sup>immersion followed by drying, <sup>3</sup>humidity room, <sup>4</sup>rainfall simulation

## 215 2.4 Initial rate of absorption (IRA)

216 Initial rate of absorption (IRA) is a measure of the ease of ingress of water, and therefore any water-  
217 borne aggressors, under atmospheric conditions. Although developed for masonry and concrete,  
218 Hall and Djerbib [16] showed that these methods can be extended to CSRE.

219 100 mm x 100 mm x 50 mm specimens were manufactured for IRA testing. These specimens  
220 comprised a single rammed layer but were otherwise identical to carbonation specimens. IRA testing  
221 was undertaken at 5 weeks (4 weeks' curing, 1 week ambient), 15 weeks and 30 weeks from  
222 manufacture (Table 2). Testing was carried out according to AS/NZS 4456.17:2003 [17] with slight  
223 variations for rammed earth as described by Hall and Djerbib [18]. Specimens were placed on a wick  
224 of florists' foam (80 mm dia.; a material with negligible capillary resistance) in water. That the  
225 contact area with florists' foam was smaller than the specimen face allowed for a more realistic 3D  
226 water uptake. Specimens were weighed each minute to 0.01 g for five minutes, then at ten minutes,  
227 followed by ten-minute intervals up to 60 minutes.

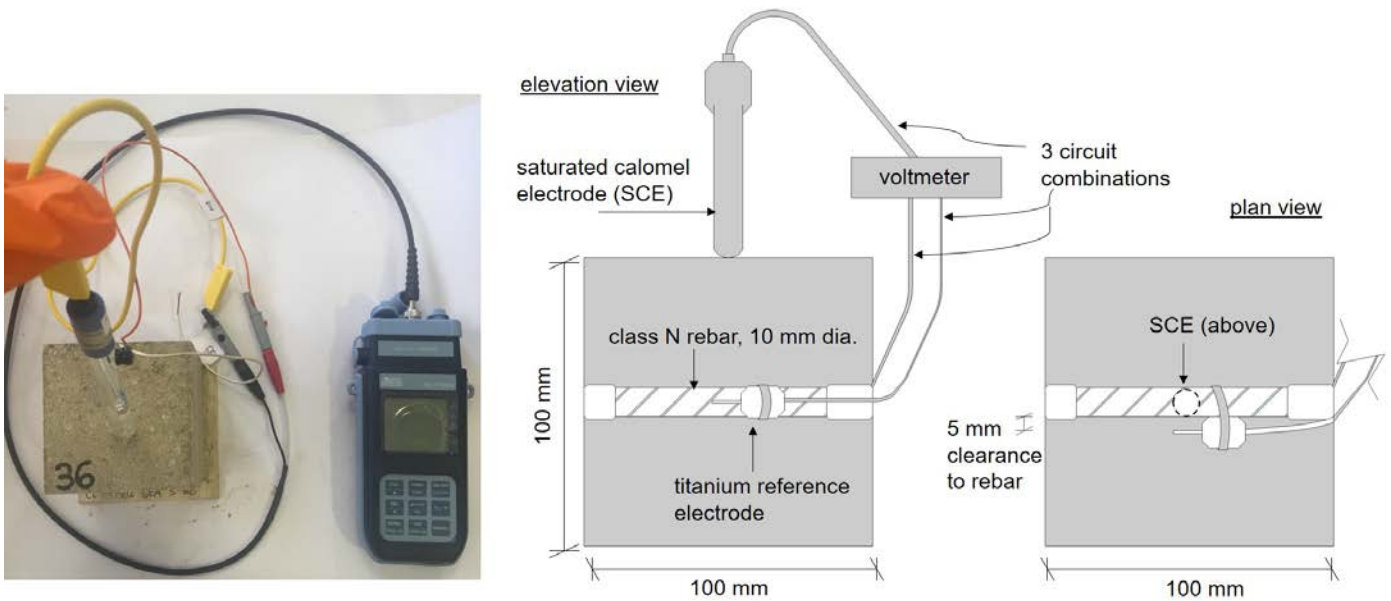
228 Testing reported by Ciancio et al. [19] indicated that exposure to high temperatures during oven  
229 drying accelerates stabiliser hydration. Therefore, specimens were not oven dried prior to IRA  
230 testing but were tested from equilibrium at ambient conditions to avoid alteration to material  
231 behaviour. Testing from ambient lab conditions meant that these measurements may be more  
232 representative of possible exposure conditions.

## 233 2.5 Half-cell potential (HCP)

234 Half-cell potential (HCP) testing is one of several electrochemical techniques that exist for  
235 monitoring and assessing corrosion in reinforced concrete. This non-destructive test can be used  
236 either *in situ* or in a lab environment. HCP was used in this study to measure corrosion potential of  
237 steel embedded in the various CSRE mixes in a number of different environments. This test was  
238 completed in accordance with ASTM C876-91 [20] using a calomel reference electrode (SCE) placed  
239 on the concrete surface. As well as the steel bar, specimens were also instrumented with an internal

240 electrode of activated titanium which can be used as an alternative to the SCE electrode  
 241 (measurements made versus activated titanium are not reported in this paper). Potential readings  
 242 were taken with a high-impedance voltmeter. A schematic of an instrumented specimen is shown in  
 243 Figure 3.

244 Two 100 mm cube specimens were made for HCP testing per soil mix (excepting SM1, for which only  
 245 one was prepared due to a lack of material) in a similar manner to carbonation specimens. In  
 246 addition to the carbonation specimen manufacturing process described in Section 2.3, a titanium  
 247 reference electrode and 90 mm length of reinforcement were embedded between the two  
 248 compacted layers as shown in Figure 3. Cables to complete the HCP circuit exited each specimen at  
 249 the interface of the two layers.



250

251 *Figure 3: HCP test set-up (photo courtesy of G. Orfeo)*

252 Class N, 500 MPa, deformed bar reinforcement (10 mm dia.) was used as this is commonly used for  
 253 CSRE reinforcement in Australia. Bars were sandblasted to be free of oxides prior to specimen  
 254 manufacture. Bar ends were covered with thermal tape to leave an exposed length of 80 mm within  
 255 each specimen whilst avoiding corrosion on the bar ends (as shown in Figure 3). A number of studies  
 256 [21,22] found that HCP can vary significantly as a function of exposure conditions and have

257 suggested that an individual HCP measurement cannot be taken to indicate corrosion state of  
258 embedded reinforcement but that, when used as a comparative measure (e.g. between different  
259 areas of a structure exposed to the same conditions), corroding areas can be found through  
260 potential mapping. In the same way, results in this study will give indications of whether the various  
261 rammed earth mixes provide a better or worse environment for steel reinforcement when  
262 compared with one another, given equivalent exposure conditions, type of steel reinforcement and  
263 experimental specimen. For the same reason, it is recommended to be used in combination with  
264 other methods and/or destructive testing to confirm results [20]. Following completion of corrosion  
265 testing, reinforced specimens used in this experimental work were split in half to allow a visual  
266 assessment of the corrosion state to compare to the HCP readings.

267 An initial HCP test was carried out immediately after the curing phase (i.e. on reinforced CSRE  
268 specimens maintaining equilibration to high humidity conditions). Specimens were then air dried  
269 until reaching constant mass in ambient conditions, after which testing was repeated approximately  
270 once per month over a six-month period and then again at 11 and 12 months from manufacture.  
271 Each test consisted of one reading on the reinforced specimens while they were exposed to dry  
272 conditions followed by readings taken after 1, 3, 8 and 24 hours while the specimens were immersed  
273 in water.

274 To evaluate differences in terms of corrosion behaviour of steel in CSRE when exposed to laboratory  
275 condition and high humidity environments, at 30 weeks from manufacture, reinforced specimens  
276 were placed in the humidity room and their corrosion potential and mass tested periodically until  
277 reaching equilibrium (Table 2). They were then returned to ambient laboratory conditions.

278 To study corrosion behaviour during desorption, specimens remained immersed until reaching  
279 constant mass and were then left in ambient conditions to dry. Mass and HCP were measured  
280 throughout the exposure period to determine how quickly the material re-equilibrated on  
281 emergence and to assess changes in corrosion behaviour both during extended immersion and

282 desorption. Alternative wetting and drying cycles provided the worst-case environment for steel in  
283 rammed earth in case of risk of carbonation-induced corrosion. HCP was also carried out on  
284 reinforced specimens with only one face exposed to water to understand corrosion behaviour in  
285 more realistic conditions (representative of incident rainfall, Table 2). Test setup followed the same  
286 configuration as for IRA testing but with a controlled volume of water applied. A volume of water  
287 corresponding to the daily rainfall in the Perth region over a two week period during July 2016  
288 (wettest fortnight of 2016 [23]) was placed in a covered tray with each specimen enabling each to  
289 absorb the full amount over 24 hours. In reality, it is likely significant surface runoff would occur  
290 from a (typically vertical) rammed earth surface whereas in this test, specimens had unlimited  
291 exposure to the simulated rainfall volume. Although extreme, it is nevertheless a potentially more-  
292 realistic scenario for corrosion likelihood than full immersion.

293 Quantitative information on the corrosion state of steel in cementitious materials can be obtained  
294 by considering also other electrochemical techniques in addition to its corrosion potential (such as  
295 the measurement of corrosion rate estimated by polarization resistance). For steel reinforcement in  
296 concrete, a corrosion rate of  $1 \text{ mA/m}^2$  (an approximate thickness reduction of  $1.17 \text{ }\mu\text{m/year}$ ) is the  
297 limit below which corrosion is considered negligible (e.g. [5,24]). A previous preliminary CSRE  
298 corrosion study (carried out at the Department of Chemistry, Materials and Chemical Engineering of  
299 Politecnico di Milano by the authors) found a correlation between corrosion potential and corrosion  
300 rate of steel embedded in CSRE: a negligible corrosion rate of  $1 \text{ mA/m}^2$  corresponded to  
301 approximately  $-200 \text{ mV SCE}$  [25]. Measures of corrosion potential of the steel bar versus calomel  
302 electrode obtained in the CSRE mixes studied in this research when exposed to different conditions  
303 were compared both with this CSRE specific value ( $-200 \text{ mV SCE}$ ) and with those found for concrete,  
304 given in ASTM C876-91 [20] (see Table 3, taking into account that indicative potentials have been  
305 converted from a Copper/Copper Sulfate electrode [CSE] to a Saturated Calomel [SCE] electrode).

306 Potential differences were assessed for three circuit combinations: between the (i) reinforcing bar  
 307 and the calomel electrode; (ii) between the bar and the internal titanium electrode; and (iii)  
 308 between the titanium electrode and the calomel electrode. Following corrosion potential testing,  
 309 carbonation depth of HCP specimens was also measured at 12 months from manufacture as  
 310 described in the previous sections.

311 *Table 3: Indicative potential brackets for likelihood of corrosion*

Corrosion potential $E_{corr}$ (mV, converted from CSE to SCE)	Likelihood of corrosion
$E_{corr} > -200$ mV	Specific potential criteria for corrosion of reinforced CSRE [25]
$E_{corr} > -125$ mV	Corrosion conditions <10% probability at time of measurement [20]
$-275$ mV < $E_{corr}$ < $-125$ mV	Unknown probability [20]
$E_{corr} < -275$ mV	Corrosive conditions >90% probability [20]

312

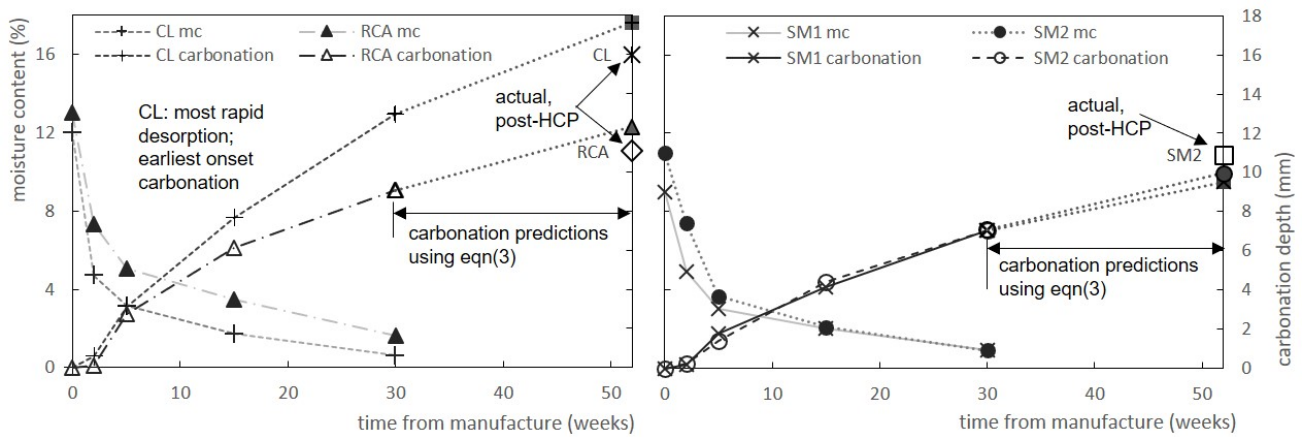
313 Throughout exposure to all environments, mass of specimens was measured concurrently with all  
 314 HCP measurements to enable any potential correlation between corrosion potential and moisture  
 315 content above equilibrium. Following all other testing at the various specimen ages, specimens were  
 316 oven dried, giving absolute moisture content as per AS 1289.5.2.1—2003 [11].

317 A summary of all tests, the number of specimens and test times is provided in Table 2. Specimen  
 318 numbers for each test were selected to give an accurate representation of material behaviour whilst  
 319 keeping overall specimen numbers to a reasonable level.

320 **3.0 Results and Discussion**

321 **3.1 Carbonation**

322 Carbonation depths with time are shown in Figure 4. At manufacture, specimens present the highest  
 323 point of water content, rendering the carbonation rate negligible. As water content reduced,  
 324 carbonation commenced. Initial carbonation rate was highest for CL. In agreement, CL also had the  
 325 most significant water content reduction in the first two weeks; carbonation can only commence  
 326 once CO<sub>2</sub> can penetrate the pore network.



327  
 328 *Figure 4: Carbonation depth and moisture content across time; extrapolation to 52 weeks shown in comparison to actual*  
 329 *measured carbonation following completion of HCP testing (CL, RCA, SM2)*

330 Carbonation was measured over 30 weeks to determine progression rates. Carbonation rates ranged  
 331 between 8-16 mm/year<sup>0.67</sup>, for the different CSRE mixes, calculated as:

$$k = \frac{d}{t^{1/n}} \quad (3)$$

332 where  $k$  is carbonation coefficient,  $d$  is depth of cover (mm) minus 5 mm (Yoon et al. [26] showed  
 333 that material is no longer protected from corrosion if the carbonation front closes to within 5 mm of  
 334 the reinforcement) and  $t$  is time (years) (e.g. [3]). Curing time was disregarded in calculation of  
 335 carbonation rates as results in Figure 4 suggest that carbonation progresses only after equilibrium  
 336 with ambient conditions has been reached. The relationship given in Equation ( 3 ) assumes that the



337 CO<sub>2</sub> concentration is constant. In reality, the rate of carbonation over time will depend on  
 338 environmental factors (such as temperature, humidity and CO<sub>2</sub> concentration) and factors related to  
 339 cementitious materials (mainly alkalinity and permeability). The exponent  $n$  is often approximately  
 340 equal to two for ordinary concrete but may be greater than two for dense concrete [5]. This study  
 341 found an exponent of  $n = 1.5$  to be a better fit for the tested CSRE. This indicates that, although the  
 342 established concrete testing methods are valid, the CSRE carbonation depth versus time relationship  
 343 is faster than in concrete. In particular, the carbonation rate was lower for CSRE mixes made with  
 344 SM1 and SM2 soils than those with RCA and CL.

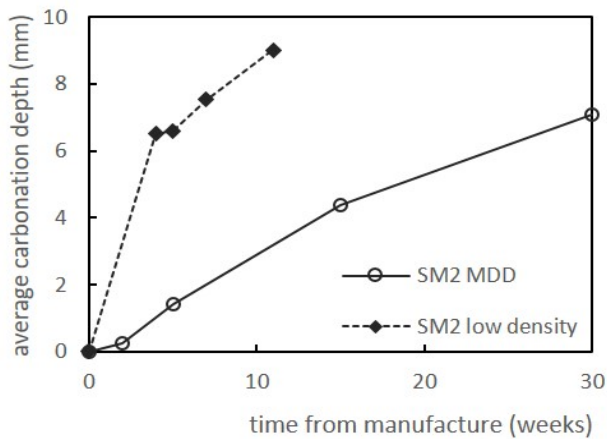
345 Table 4 shows time until an indicative cover depth would be breached, calculated using  
 346 Equation ( 3 ) extrapolated over the depth of interest. For typical cover depths, carbonation was  
 347 estimated to reach the reinforcement within the design life span (50 years). Historically, rammed  
 348 earth walls were commonly >300 mm thick. With central reinforcement, time to breach such cover  
 349 may exceed the design life dependent on mix characteristics. Modern rammed earth structures  
 350 however are more frequently being built as insulated panels (e.g. [27]) which significantly reduces  
 351 the cover to reinforcement.

352 *Table 4: Years to carbonation front breaching illustrative cover depths*

Cover (mm)	Time to carbonation breach of cover (years)			
	CL	RCA	SM1	SM2
50	4.9	9.3	12.7	11.0
150	28.6	53.6	73.2	63.5

353  
 354 A general relationship between available pore volume and carbonation rate for CSRE could not be  
 355 established due to other uncontrolled variables associated with the soil types (e.g. soil specific  
 356 surface area, grading, angularity, mineralogy). However, a relationship between carbonation rate  
 357 and density was evident when contrasting specimens of a given soil type, as shown in Figure 5 (only  
 358 SM2 shown for clarity as other CSRE mixes behaved similarly): lower density specimens carbonated

359 at a faster rate due to the increased ease of CO<sub>2</sub> penetration. For results shown in Figure 5,  
360 carbonation rate of the low-density specimens was 28.5 mm/year<sup>0.67</sup>, approximately three times  
361 faster than specimens compacted to MDD (9.1 mm/year<sup>0.67</sup>). Given that final RE density on site is  
362 controlled largely by operator experience, consequences of poor density control should be  
363 considered when designing CSRE reinforcement.



364  
365 *Figure 5: Carbonation depth comparison of SM2 low density and MDD specimens*

### 366 Carbonation depth following HCP tests

367 Twelve months after manufacture, final carbonation measurements were taken on selected HCP  
368 specimens. Figure 4 shows measured data to 30 weeks followed by both the predicted extrapolation  
369 to 52 weeks using Equation ( 3 ) and actual carbonation measurements of HCP specimens. Despite  
370 approximate monthly wetting during HCP testing, carbonation progressed similarly to relationships  
371 found using carbonation-specific specimens. Such a result indicates that the periodic wetting cycles  
372 were insufficient to stall carbonation for any significant time: specimens were able to desaturate  
373 sufficiently rapidly for CO<sub>2</sub> to continue penetrating the material. As such, it would not be expected  
374 that incident rainfall would slow the penetration of carbonation in a CSRE structure. Given that  
375 specimen carbonation rates in the curing room were low, it may be that exposing HCP specimens to  
376 higher humidity conditions would have affected carbonation rate. However, as such a process was  
377 not representative of the outside environment, this was not investigated.

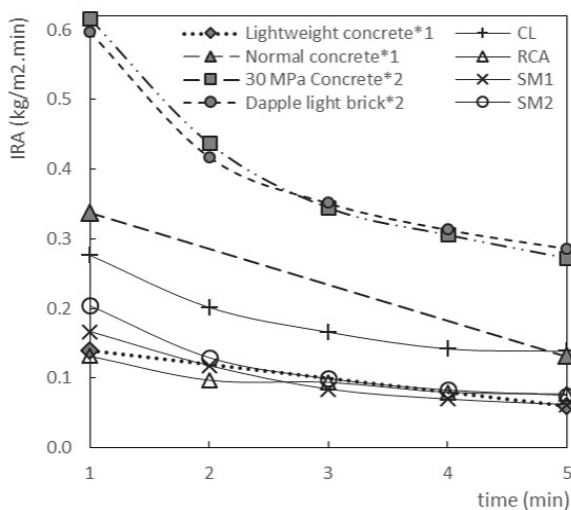
378 **3.2 Capillary absorption**

379 Initial rate of surface absorption of the four tested soil mixes is shown in Figure 6 (5-week specimens  
 380 only for clarity), presented as the mass of water absorbed per unit surface area per minute. Results  
 381 for porous materials investigated by previous authors are also shown for comparison. Absorption in  
 382 porous materials has previously been demonstrated to be linear with respect to the square root of  
 383 time, according to

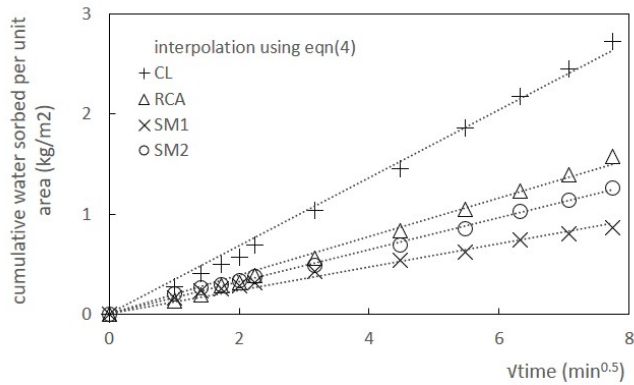
$$i = S\sqrt{t} \tag{4}$$

384 where  $i$  is the cumulative absorption ( $\text{kg}/\text{m}^2$ ),  $S$  the sorptivity ( $\text{kg}/\text{m}^2 \cdot \text{min}$ ) and  $t$  the time (minutes)  
 385 (e.g. [5,18]). As shown in Figure 7, this relationship adequately described CSRE specimen absorption  
 386 in this study.

387 As shown in Figure 4, specimen water contents roughly halved over the testing period. However, no  
 388 significant change in absorptivity was found between specimens of various ages – 5, 15 and 30  
 389 weeks – suggesting that water content changes were not sufficiently extreme to appreciatively  
 390 affect capillary forces. 5-week specimens were therefore suitable to indicate long-term CSRE  
 391 absorptivity.



392  
 393 *Figure 6: Initial rate of absorption over 5 minutes; CSRE and comparative materials (<sup>1</sup>Byrami 2006; <sup>2</sup>Hall & Djerbib 2004)*



394

395 *Figure 7: Water sorption over 60 minutes; CSRE (5 weeks from manufacture)*

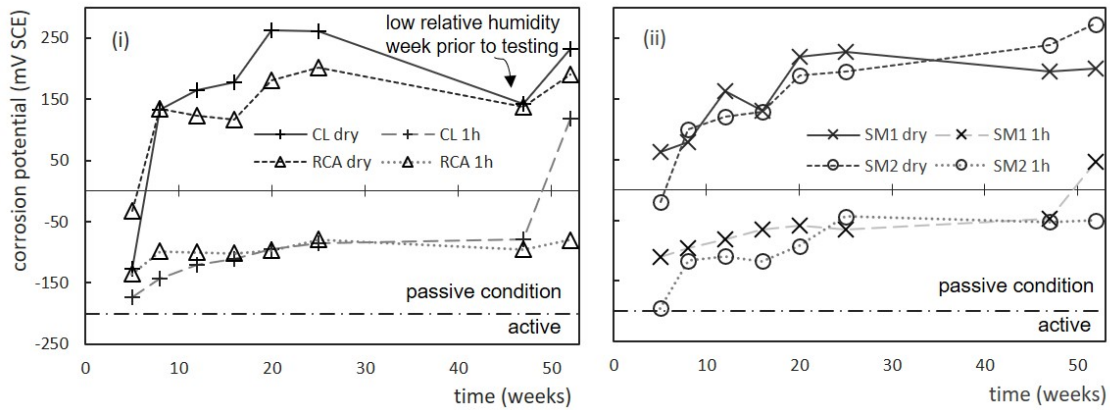
396 CSRE specimens consistently showed lower IRA and cumulative sorption values than materials tested  
 397 by Hall and Djerbib [18]. However, specimens in that work were oven-dried (at 105°C) prior to  
 398 testing. It is well known that increased temperatures impart greater suction to the pore structure,  
 399 i.e. capillary forces are higher; that our specimens achieved lower IRA and cumulative sorption  
 400 values was therefore expected. Sorption values presented in Figure 6 and Figure 7 are therefore  
 401 suggestibly more indicative of “real-world” values expected for CSRE materials exposed to water  
 402 ingress.

403 It is anecdotally believed that rammed earth materials are particularly susceptible to moisture  
 404 ingress (e.g. [29]); contrariwise, Figure 6 shows that realistic CSRE sorption rates are comparatively  
 405 low with respect to other construction materials considered. The absorption parameter cannot,  
 406 however, be used as an absolute measure of quality of alternative construction materials but can be  
 407 useful for comparing the different mixtures of CSRE made in this study at equal water/cement ratio  
 408 and compaction method. As aggressive ions such as chlorides move most effectively in pore water  
 409 by diffusion, low sorption rates could improve chloride resistance. However, since chloride  
 410 penetration in cementitious materials also depends on other factors (e.g. cement content), it’s not  
 411 possible to draw conclusions on chloride resistance based only on the results obtained in terms of  
 412 capillary measurements. A more detailed future study specifically addressing chloride resistance of  
 413 CSRE would be worthwhile.

414 **3.3 Corrosion potential**

415 When CSRE is reinforced with steel bars, the protection of embedded steel can be studied by  
 416 monitoring its corrosion potential in different exposure conditions.

417 **Twelve-month dry (ambient laboratory) and immersed HCP testing**



418

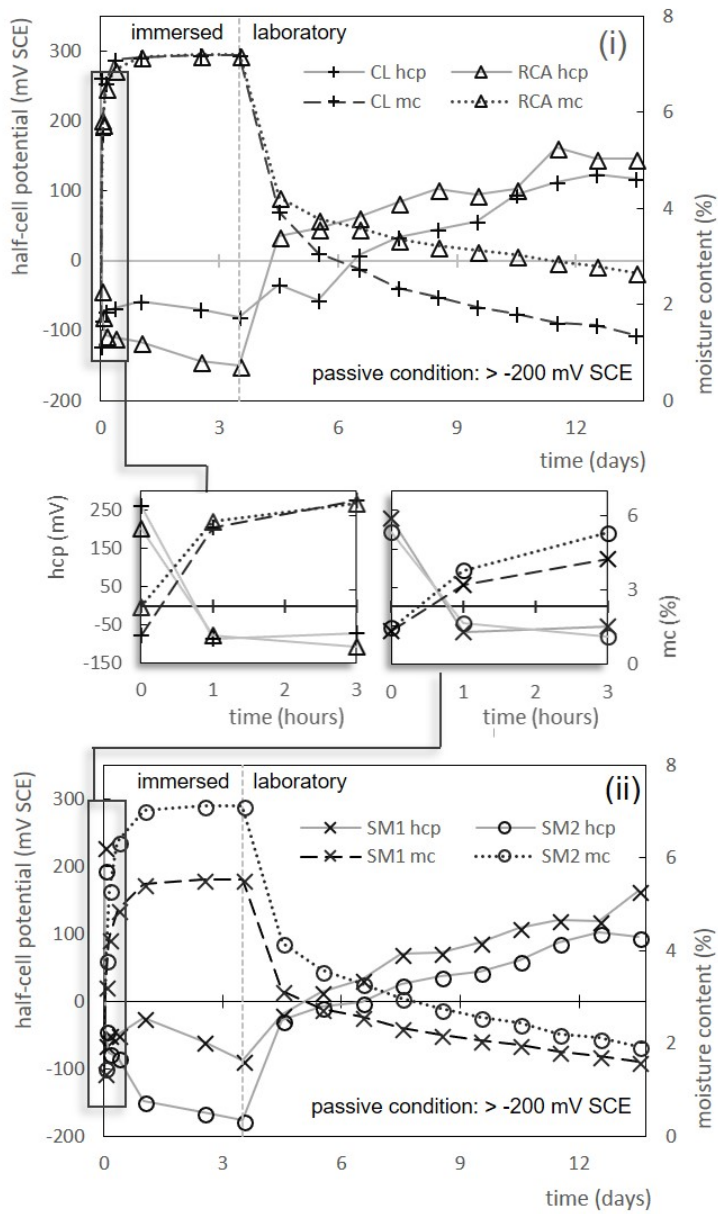
419 *Figure 8: HCP in dry condition (beginning of each HCP test) and after 1h immersion of: (i) CL and RCA, (ii) SM1 and SM2. HCP*  
 420 *value indicating passive condition for steel in CSRE (>-200 mV SCE) is shown*

421 Figure 8 shows the results of electrochemical monitoring of corrosion potential of steel embedded in  
 422 CSRE specimens of the various mixes (measured using saturated calomel electrode, 'SCE' noted after  
 423 unit). Measurements of corrosion potential carried out while specimens were dry are reported, as  
 424 are measurements following 1-hour of immersion. Except for the first measurement, made 5 weeks  
 425 from manufacture, at which time specimens were still drying (corrosion potential values around  
 426 -100 mV SCE), corrosion potential in dry conditions reached positive values ranging between  
 427 +100-+250 mV SCE confirming steel was in a passive state. A similar but less pronounced pattern was  
 428 also found for the measurements repeated monthly on the same reinforced specimens after  
 429 immersion in tap water for one hour; for these specimens, corrosion potential reached stable, but  
 430 more negative, values than those in dry conditions. For CSRE immersion in tap water, the diminished  
 431 supply of oxygen to the steel surface brought the potential down to values around -100 mV SCE but  
 432 still above the corrosion limit. Hence, corrosion potential of passive steel, if in alkaline CSRE, is  
 433 determined by the availability of oxygen at the surface of the rebars.

434 Although readings were taken over 24 hours, only dry and 1-hour immersion measurements are  
435 presented in Figure 8: corrosion potential dropped significantly in the first hour while immersed (as  
436 observed in Figure 9 (i) and (ii) insets), after which potential became more stable.

#### 437 Extended immersion and desorption testing

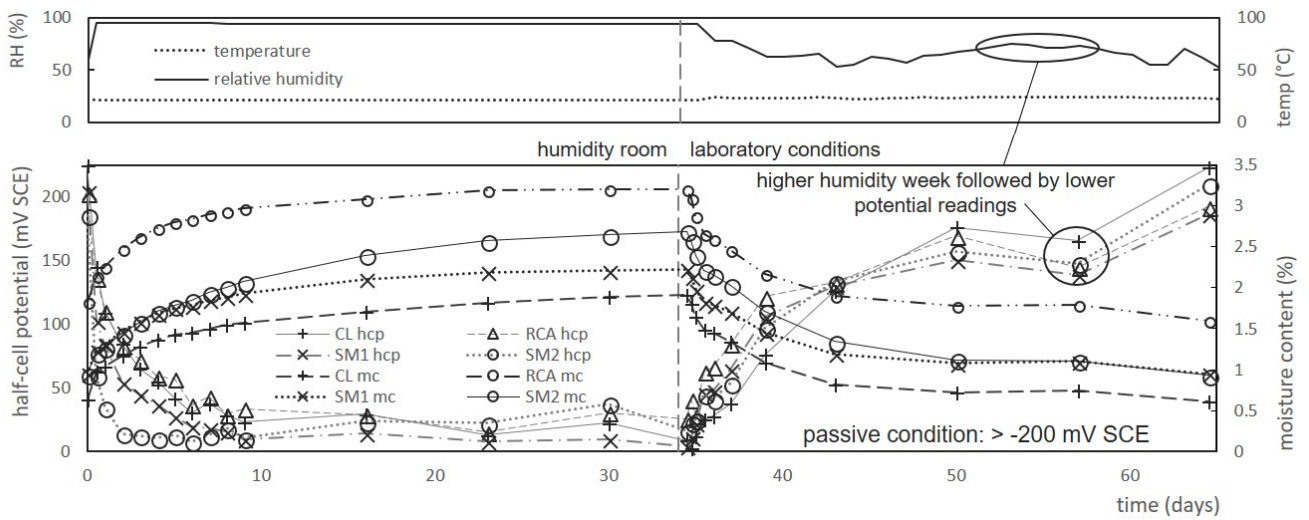
438 At the completion of the 6<sup>th</sup> wetting and drying cycle (i.e. that which commenced at 25 weeks),  
439 reinforced specimens were fully immersed in tap water until mass equilibrium was reached (taking  
440 roughly 3 days). Corrosion potential was measured during prolonged wetting and as samples  
441 reequilibrated to ambient conditions (Figure 9). Steel embedded in CSRE made with CL and SM1  
442 remained comfortably in the passive condition throughout testing while steel in the RCA mix  
443 approached but did not exceed the threshold value of -200 mV SCE. Only steel embedded in SM2  
444 reached the corrosive limit on some occasions once immersed for at least 8 hours, however  
445 recovered to the passive state within one day of being removed from the water. Changes in HCP  
446 measurements were strongly correlated with those in water content for all specimens; RCA and  
447 SM2, which absorbed the greatest amount of water, achieved the worst corrosion potential.  
448 Complete immersion is an extreme scenario for a rammed earth structure but, were it to occur (e.g.  
449 during flash flooding), the rapid desorption and increase in corrosion potential on removal from  
450 water shown in Figure 9 suggest that the material would quickly recover (noting that results here do  
451 not account for other potentially-negative effects of submergence, for example slaking).



452

453 *Figure 9: Desorption following immersion to constant mass of: (i) CL and RCA, (ii) SM1 and SM2*

454 High humidity testing



455

456 *Figure 10: HCP testing in high-humidity environment and re-equilibration to laboratory conditions*

457 HCP results for specimens exposed to high humidity conditions following desorption testing (i.e. on  
 458 reaching week 30 in Table 2) are shown in Figure 10. HCP testing was completed until equilibrium  
 459 with the high humidity air was reached, whereupon specimens were re-exposed to the lower  
 460 humidity (ambient laboratory) conditions. Although corrosion potential dropped significantly  
 461 (around 200 mV) on exposure to high air humidity, all specimens remained in the passive state  
 462 throughout equilibration. Corrosion potential increased sharply on re-exposure to laboratory  
 463 conditions, varying with the inverse of humidity as indicated in Figure 10.

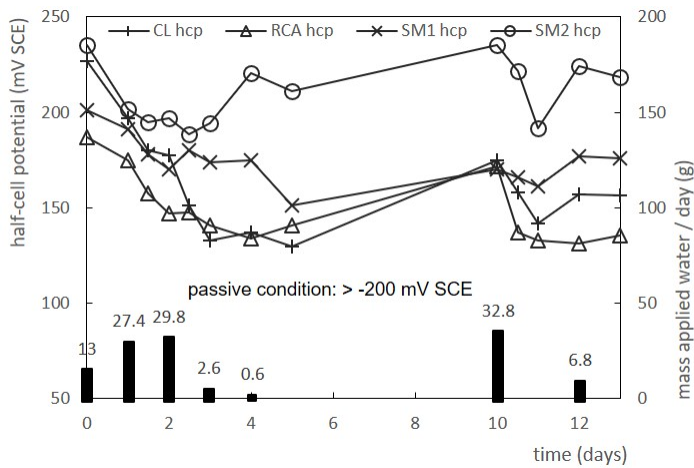
464 Simulated rainfall

465 HCP results for specimens exposed to water on one side only (at 44 weeks, i.e. after completion of  
 466 high humidity testing) are shown in Figure 11. The amounts of water added to simulate July 2016  
 467 rainfall in Perth are also given. As for fully immersed (1h), extended immersion (3d) and high-  
 468 humidity specimens, HCP reduced on wetting, but all specimens remained in passive condition at all  
 469 times.

470 All specimens absorbed the full amount of water during the first 2 days' exposure except for SM1,  
 471 which had the lowest IRA value. Results presented in Figure 12 indicate that SM1 could absorb up to

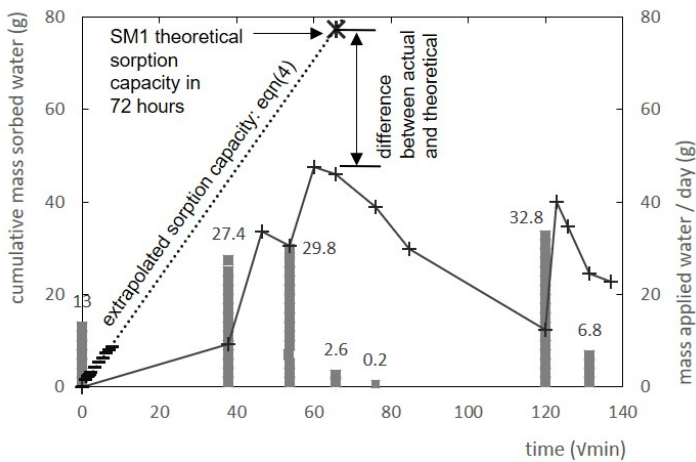


472 77 g in 72 hours: a greater amount than the applied 70.2 g. That SM1 could not fully absorb this  
 473 amount was due to periodic exposure, rather than the instantaneous (and so maximum) exposure  
 474 used for IRA testing.



475

476 *Figure 11: HCP testing and simultaneous rain simulation*



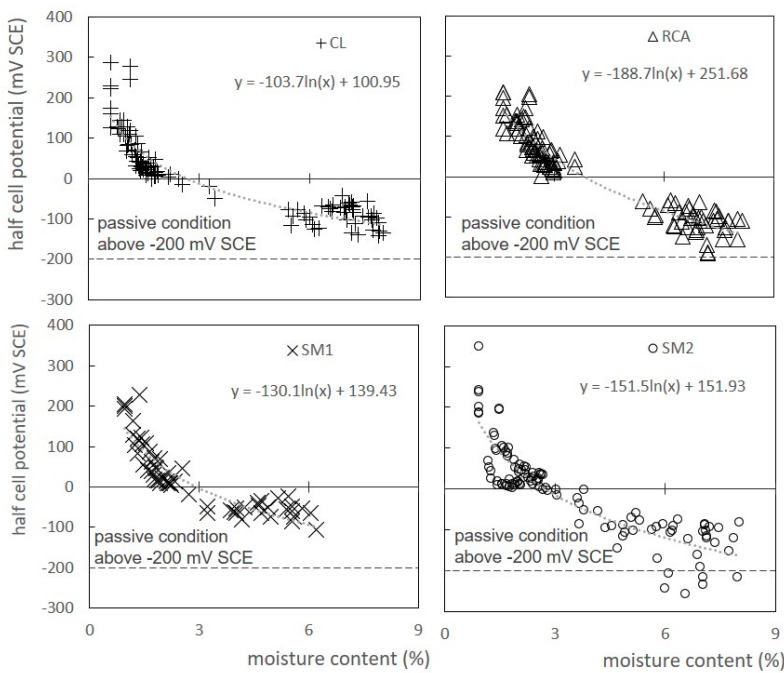
477

478 *Figure 12: SM1 theoretical sorption potential, applied water and actual sorbed mass*

### 479 3.4 Moisture content correlation

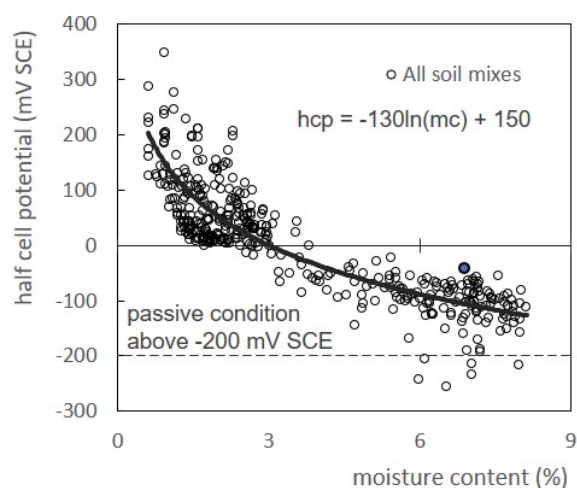
480 The experiments described above indicated a relationship between HCP and specimen water  
 481 content. Corrosion potential values and water contents from all HCP tests are shown in Figure 13  
 482 (each soil mix separately) and Figure 14 (all soil mixes combined). As shown, there is an influence of  
 483 moisture content of CSRE on HCP measurement, regardless of environment and material. For CSRE

484 in highest moist conditions, the diminished supply of oxygen to the surface of steel can bring the  
 485 potential down to more negative value. However, all CSRE specimens tested were comfortably more  
 486 positive than the -200 mV SCE corrosion limit in dry ambient laboratory conditions (Figure 8), in the  
 487 humidity room (Figure 10) and during simulated rainfall HCP testing (Figure 11) implying a negligible  
 488 corrosion rate in each of these environments [25]. During immersed testing, most specimens  
 489 remained above -200 mV SCE throughout confirming that moisture content cannot change the  
 490 corrosion behaviour of steel during initiation phase. Only SM2 readings dropped below -200 mV SCE  
 491 on a few occasions (shown in Figure 13 (iv)) and only once specimens had a moisture content greater  
 492 than 6%, having been immersed in tap water for a minimum of 8 hours: a highly unlikely scenario for  
 493 a rammed earth structure. Local groundwater level and other potential causes of long-term wetting  
 494 should be considered in design, particularly if considering a base soil high in clay. The corrosion  
 495 potentials below -200 mV of SM2 specimen could be associated to local loss the passive condition of  
 496 steel bar; Figure 13 (iv) shows that corrosion was activated on SM2 specimens only in high moist  
 497 conditions.



498

499 *Figure 13: HCP vs moisture content for CL (i), RCA (ii), SM1 (iii) and SM2 (iv) specimens in various environments*



500

501 *Figure 14: HCP vs moisture content for all soil mixes in various environments*

502 For those results collated in Figure 14, the relationship between moisture content and HCP can be  
 503 described as

$$HCP \approx -130\ln(mc) + 150 \quad (5)$$

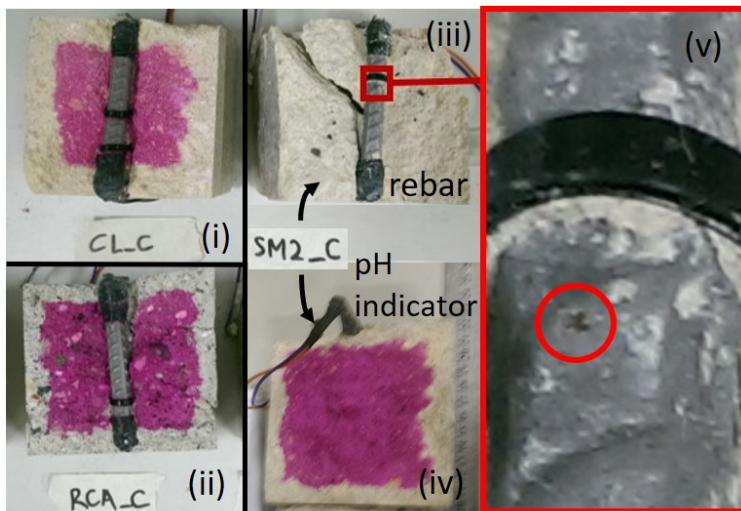
504

505 Using Equation ( 5 ), a moisture content of 15% would be required for HCP to drop  
 506 below -200 mV SCE. Consulting the 30-week available pore volume data given in Table 1, SM1 will  
 507 never reach the corrosive limit even at saturation, demonstrating that as long as CSRE is alkaline and  
 508 without chlorides on the steel surface, moisture content doesn't affect the passive state. SM2  
 509 becomes more negative than -200 mV SCE once at 88% saturation probably because steel bars  
 510 present a localised breakdown of the passive film.

511 These results suggest that the tested CSRE mixes provide corrosion protection to the steel  
 512 reinforcement so long as the material remains alkaline (in the absence of chlorides). Once steel is  
 513 depassivated by carbonation or chlorides, the corrosion potential behaviour depends on the  
 514 moisture content of CSRE.

515 **3.5 Destructive testing**

516 Twelve months post-manufacture, one specimen of each soil mix except SM1 was broken in half to  
517 allow visual inspection of the rebar. As shown in Figure 13, throughout testing in all environments,  
518 RCA and CL specimens maintained a corrosion potential more positive than -200 mV SCE at all times  
519 whereas SM2 dropped below this (i.e. to potentials at which corrosion activity may occur) on several  
520 occasions. These results were supported by the destructive testing shown in Figure 15: the final  
521 conditions of the extracted rebar matched those surmised from HCP testing – CL and RCA showed no  
522 sign of corrosion while SM2 had one fleck of rust visible. This suggests that the value of -200 mV SCE  
523 was a reasonable indicator of the loss of passive state for the tested CSRE specimens. However,  
524 further investigation considering a large exposition time and a greater number of specimens could  
525 be of use.



526  
527 *Figure 15: Visual inspection of rebar and carbonation measurement 12 months from manufacture; i) CL, rebar inspection &*  
528 *carbonation measurement; ii) RCA, rebar & carbonation; iii) SM2, rebar only (no pH indicator); iv) SM2, carbonation only*  
529 *(with pH indicator); v) SM2, inset showing fleck of rust*

530 12-month carbonation testing (shown in Figure 15) confirms that the reinforced specimens  
531 remained in the passive condition throughout testing. Work assessing corrosion behaviour of  
532 depassivated carbon steel in carbonated CSRE is ongoing.

## 533 4.0 Conclusions

534 Steel reinforcement is an example of a modern adaptation to traditional rammed earth building  
535 techniques. However, little is known about how steel in such an environment interacts with its  
536 surroundings. This study assessed the ability of a range of CSRE mixes to provide corrosion  
537 protection to carbon steel, using testing methods described in ASTM C876-91 [20] and a corrosion  
538 potential lower limit of -200 mV SCE [25].

539 pH of the CSRE mixes studied in this work were all sufficiently alkaline to provide the appropriate  
540 environment for passivation of steel reinforcement; in fact, the hydrated cement paste of CSRE is  
541 initially alkaline in the same way as for conventional concrete. However, the resistance to  
542 carbonation of CSRE is also of primary importance in relation to the protection of embedded steel.  
543 This experimental study has shown that for typical cover depths, carbonation would most likely have  
544 reached the reinforcement within approximately 5-15 years (50 mm cover) or 30-75 years (150 mm  
545 cover) depending on the CSRE mix considered. Therefore, although the initial CSRE environments  
546 tested may be adequate for passivation, rebar will be depassivated within the design life span.  
547 Specimens compacted to MDD performed better than those compacted to a lower density, given  
548 which, a target density for site work should be specified and monitored if particular characteristics  
549 are required.

550 A correlation between corrosion potential and moisture content was found, regardless of  
551 environment and soil mix. For CSRE in highest moist conditions, the diminished supply of oxygen to  
552 the surface of steel brought the potential down to a more negative value. However, all CSRE  
553 specimens tested were comfortably more positive than the -200 mV SCE corrosion limit both in dry  
554 ambient laboratory conditions and in moist conditions, implying a negligible corrosion rate in each of  
555 these environments. During immersed testing, most specimens remained above -200 mV SCE  
556 throughout, confirming that moisture content cannot influence the corrosion behaviour of steel in  
557 CSRE that is both alkaline and without chlorides near to the steel surface; thus, the moisture

558 condition doesn't affect passive state. Only for steel embedded in SM2 specimen, a corrosion  
559 potential more negative than -200 mV SCE was measured in immersion conditions, probably because  
560 steel bars had a localised breakdown of the passive film as confirmed from the small rust spot  
561 observed by destructive testing. However, a rapid desorption was found to be typical of the CSRE  
562 specimens, meaning the material would dry quickly if exposed to a temporarily detrimental  
563 environment such as heavy rain or flooding. Given rapid desaturation, it is likely that corrosion  
564 propagation of steel in SM2 specimen would remain negligible. Destructive tests of all other  
565 reinforcing bars show no sign of corrosion due to their being protected in alkaline CSRE.

566 These results suggest that the tested CSRE mixes provide corrosion protection to the steel  
567 reinforcement so long as the material remains alkaline (in the absence of chlorides). Once steel is  
568 depassivated by carbonation or chlorides, the corrosion potential behaviour depends on the  
569 moisture content of CSRE.

570 As behaviour varied little between the four tested soil mixes (of varying granularity), it is reasonable  
571 to expect that findings presented here also apply to other soil mixes stabilised with 10% cement.  
572 However, as SM2 performed most poorly, the performance of mixes manufactured with base soils  
573 high in clay (>15%) may be worthy of further investigation.

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