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Corrosion protection of steel embedded in cement-stabilised rammed earth

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HIGHLIGHTS

- Cement-stabilised rammed earth protects embedded carbon steel from corrosion.
- Carbonation deteriorates the initially-passive embedded steel environment.
- Low capillary absorption and rapid desorption inhibit corrosion.
- Corrosion potential higher than −200 mV SCE indicates negligible corrosion.

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ABSTRACT

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

1. Introduction

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

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

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corrosion is occurring and whether the wall will retain the same capacity for which it was designed.

Very limited research regarding corrosion of reinforcement in any rammed earth variants is present in the literature. CSRE has been studied here as this is the most commonly used variant of modern stabilised rammed earth in Australia. It should be noted that reinforcement is not recommended in unstabilised rammed earth due to a lack of anchorage [2]. A significant body of research regarding corrosion of reinforcement in concrete structures does however exist. Given that CSRE and concrete share a number of similarities such as components (e.g. aggregate and cement as stabiliser) and relevant properties for durability aspects (e.g. pH, density, pore structure), it is potentially reasonable to assume that the reinforcement is exposed chemically to a comparable environment in both.

The service life of a structure reinforced with steel will depend on the corrosion "initiation" and "propagation" phases [3]. In concrete, the high alkalinity of cement paste protects steel reinforcement from corrosion as a passivating layer develops on the surface of the steel. Despite providing initial protection, over time this passivating layer can deteriorate through ingress of aggressive agents such as carbon dioxide (CO_2) or chloride ions (the latter particularly in coastal areas). Carbonation, caused by the reaction of carbon dioxide (CO_2) from the air with alkaline components in the cement paste, is the most common cause of degradation in reinforced concrete. As less-alkaline calcium carbonates are formed during carbonation, pH of the affected cementitious material is lowered to a value around 9, depassivating the steel once the carbonation front penetrates the cover depth. The carbonation reaction depends on environmental factors (such as humidity, temperature and CO_2 concentration) and material penetrability which is determined by pore network connectivity: the more pores that are connected to the outside surface, the greater the penetration. The time taken to lose the steel passivation due to carbonation is the initiation phase. Once the material is no longer protecting reinforcement from corrosion, i.e. the steel is depassivated, the propagation phase will depend on presence of moisture and oxygen on the surface of reinforcement. Capillary absorption generally controls availability of moisture in a steel reinforced material and is also the main transport mechanism controlling ingress of aggressive agents (such as chlorides).

One particular case of a reinforced CSRE wall in Perth, Western Australia (WA) was investigated by Beckett and Ciancio [4]. The wall was built around 1970 in Cottesloe, a coastal suburb of Perth. The parent sandy soil (<7% fines) was stabilised with 7% Portland cement by dry mass of soil. The wall comprised a 200 mm buried portion atop a rammed earth footing; the remainder (~1800 mm) was exposed to incident rainfall with little or no surface protection. The wall was demolished in 2012 and sections showing no surface damage were extracted for analysis. Investigations revealed that the uncoated mild steel reinforcement was highly corroded in the 200 mm buried region between the footing and exposed wall surface, due to groundwater ingress, whilst the remainder was in as good a condition as when it was first installed (Fig. 1). Although an extreme case, being an external wall with no roof protection and in a coastal environment, this example highlights that extensive damage is possible without necessarily being revealed by the state of the wall's surface.

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

Fig. 1. Corroded reinforcement from 30-year-old CSRE wall.

Firstly, carbonation resistance and capillary absorption of different CSRE mixes were measured as these material properties strongly influence corrosion protection. Subsequently, the CO_2-induced corrosion behaviour of carbon steel bars embedded in the different CSRE mixes studied in this work when exposed to various environments was compared. Based on material properties and corrosion behaviour, an assessment is made of whether corrosion may impact the service life of the material. In the absence of specific CSRE tests, existing concrete and masonry testing was used: the appropriateness of these tests for CSRE was also assessed.

2. Experimental program

2.1. Materials and characterisation

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

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

- CL was selected as this is commonly used in WA as the 'earth' component of rammed earth in preference to the local soil. It is inert and generally well-graded, with subrounded particles. It is a readily available quarried material in WA.
- RCA is a popular soil substitute in WA for CSRE construction due to its environmentally-friendly properties as a waste material [8]. The soil classification of RCA differs significantly to that of the other soils used; it is poorly graded with angular particles, a far greater proportion of crushed rock (~50% >4.75 mm) and minimal fine to medium sized materials (Fig. 2).
  Being a waste material, each RCA mix may differ in terms of characteristics such as mineralogy, angularity and PSD, depending on the original concrete product and level of processing. Furthermore, RCA may include some unhydrated cement particles from the manufacture of the concrete for its initial use; the presence of unhydrated cement was not considered to impinge on testing presented here.