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Rammed Earth incorporating Recycled Concrete Aggregate: a sustainable, resistant and breathable construction solution

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ABSTRACT

Construction and demolition debris, mainly concrete and masonry rubble, represent a significant share of municipal waste. Recycling crushed concrete aggregates and using them as substitutes for natural ones might therefore be determinant in reducing landfilling and mineral resource depletion. An innovative way to give new value to Recycled Concrete Aggregates (RCAs) is to ram them in layers to form load-bearing walls for stabilised Rammed Earth (RE) applications. However, the success of those few existing RE projects using RCA is mainly due to the knowledge and experience of the contractors rather than official standards or guidelines or scientific literature. The objective of this study was to further the knowledge of this building technique by determining the effect of different RCA replacements on the material's mechanical resistance, sustainability and hygroscopic properties: indicative of the structure's structural, environmental and hygrothermal performance. Mechanical resistance was assessed by means of the Unconfined Compressive Strength (UCS, commonly used for rammed earth-like materials), hygroscopic properties via Moisture Buffer Value (MBV) and sorption isotherms while the sustainability was assessed via consequential Life Cycle Assessment (LCA). Microstructural investigations via mercury intrusion porosimetry, nitrogen adsorption-desorption isotherms, scanning electron microscopy and X-ray diffraction were performed to understand and explain material mechanical and hygroscopic behaviour. The building technique, already proven to be durable, was demonstrated to be resistant (from 4 to 12 MPa at 28 days depending on the RCA replacement and cement content), sustainable (down to 25 kg CO_2-eq. of embodied carbon per square meter of load-bearing wall) and to have good moisture buffering abilities (0.88 g/(m2%RH) for mixtures containing only RCA). Strength appeared to be more related to the particle size distribution of the mix rather than to the percentage of RCA added. The amount and type of stabiliser added to the mix and the distance covered by the RCA during its lifetime strongly affected the environmental sustainability of the mixture; to maximise the potential of this building technique, reducing the amount of cement in the mixture by using alternative stabilisers should be the main priority.

1. Introduction

Maximising reuse and recycling of waste materials is one of the main paradigms of a circular economy. To boost the transition towards more sustainable economic growth, different governments are adopting strategies to reduce the amount of waste landfilled and to increase recycling rates. The European Commission, for instance, adopted a Circular Economy Package, which includes legislative proposals such as targets for recycling 65% of municipal waste and to reduce its landfilling to a maximum of 10% by 2030 (European Commission, 2015): as it currently stands, only 35% of the non-compostable fraction of municipal waste is recycled and almost 30% is still committed to landfill (Eurostat, 2018).

A significant share of municipal waste is occupied by construction

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Abbreviations: BET, Brunauer, Emmett and Teller; BJH, Barrett, Joyner and Halenda; CDW, Construction and Demolition Waste; CEM, Cement; CL, Crushed Limestone; ES, Engineered Soil; FA, Fly Ash; GHG, Greenhouse Gas; LCA, Life Cycle Assessment; LL, Liquid Limit; MBV, Moisture Buffer Value; MDD, Maximum Dry Density; MIP, Mercury Intrusion Porosimetry; OWC, Optimum Water Content; PL, Plastic Limit; PSD, Particle Size Distribution; RCA, Recycled Concrete Aggregate; RE, Rammed Earth; RH, Relative Humidity; RRCA, Rammed Recycled Concrete Aggregate; SEM, Scanning Electron Microscopy; SRE, Stabilised Rammed Earth; UCS, Unconfined Compressive Strength; XRD, X-Ray Diffraction

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and demolition debris (approximately 35% in Europe (Eurostat, 2014)), which in turn mainly comprise concrete and masonry rubble. In Europe, it is estimated that roughly 1350 M t of concrete is produced annually (approximately 2.7 tonnes per inhabitant) and about 350 M t of concrete debris are generated (European Commission and BIO Intelligence Service, 2011). Global figures are even more astonishing: worldwide concrete production was estimated to be 10 billion m^3 in 2012 (i.e. approximately 1.4 m^3 per person), with Asia and particularly China being the primary consumers (Miller et al., 2016). Data concerning global concrete waste generation and recycling is harder to obtain. Several developed countries already reuse or recycle most of the waste originating from demolished structures: in the Netherlands, for example, more than 95% of the Construction and Demolition Waste (CDW), mainly composed of concrete aggregates, is recycled (BIO Intelligence Service, 2015). However, the same cannot be said for many other countries in Europe, where only between 30% (Johnson, 2014) and 60% (European Commission and BIO Intelligence Service, 2011) of concrete is in fact estimated to be recycled. Figures for CDW recycling have a wide geographical variation in the rest of the world too: in Taiwan, for instance, the recovery rate is higher than 90% (Cement Sustainability Initiative, 2009), while in Australia more than 30% is still disposed of by landfill (Randell et al., 2014) and in China only about 5% of total CDW is reused or recycled (Duan and Li, 2016).

Concrete can be either re-used in its original form or, most commonly, it can be reprocessed into coarse or fine aggregates. Once sorted and processed, coarse Recycled Concrete Aggregates (RCAs) can be used for road works as base or sub-base (Paranavithana and Mohajerani, 2006), reintroduced into the manufacturing of concrete as a substitute for natural aggregates (Fraile-Garcia et al., 2017) or used as backfilling material in quarries, foundations, etc. (Vieira and Pereira, 2015). Incorporating RCAs in new concrete structures may reduce the latter's enormous environmental impact (Hossain et al., 2016); more than 4% of total greenhouse gas (GHG) emissions over the past decade were in fact related to concrete manufacturing (IPCC, 2014). Although using RCA may not make significant CO_2 emission savings, substituting natural aggregates with recycled ones might be determinant in terms of curbing waste production and natural mineral resource depletion (Kleijer et al., 2017). Moreover, recovering the demolished concrete leads to considerable cost advantages to the contractor by eliminating charges for waste disposal (Mah et al., 2018). The environmental and cost benefits of employing RCAs might be particularly true for cases where the supply of gravel is constrained (Ioannidou et al., 2017).

An innovative way to reuse demolished concrete is to ram it into layers to form load-bearing walls for stabilised rammed earth (SRE) applications (Hall and Swaney, 2005). Rammed earth (RE) is an ancient construction procedure where walls are built by compacting an earthen mixture between formwork. SRE is a modern form of rammed earth that involves the addition of a (usually cementitious) binder to the earth mix to improve the material's mechanical resistance (Walker et al., 2005). Right now, the most used stabiliser is cement but alternative, more environmentally friendly binders such as by-products (e.g. fly ash (da Rocha et al., 2014), calcium carbide residue (Arrigoni et al., 2017c)) or natural polymers (e.g. (Achenza and Fenu (2006); Eires (2012)) are being explored. RCA can partially or entirely substitute the sub-soil typically used for earthen construction. However, the success of those RE projects that have used RCA is due to the knowledge and experience of the contractors involved in the projects (for example the design of the deep elevated beam shown in Fig. 1), rather than the presence of any official or rigorous standards or guidelines on this topic. In contrast to concrete, where the use of RCA has been extensively investigated (Behera et al., 2014), the research currently available in literature on the use of RCA for SRE applications is almost non-existent. The first attempt to populate the scientific database with information was done by Taghiloha, who explored the effect on the mechanical properties of SRE caused by a partial replacement of the larger particles (i.e. gravel and sand) with RCA (Taghiloha, 2013). SRE mixes incorporating RCA proved to have an acceptable (but lower) compressive strength than the counterpart with natural aggregates. Advancing on the same topic, Jayasinghe et al. tested the compressive and flexural strength of SRE incorporating building demolition waste in order to find an optimum proportion. Results indicated a mix proportion of 1:5:5 of cement:soil:demolition waste (by mass or volume was not specified) as the best combination to form a new building material with satisfactory load bearing properties (Jayasinghe et al., 2016).

Building on these works, the mechanical behaviour of SRE samples with different RCA replacement percentages was investigated here with the goal of understanding whether a diffusion of this innovative technique might be desirable. Additionally, durability and environmental sustainability results, which were first examined in a previous study (Arrigoni et al., 2017a), were integrated with new information covering the hygroscopic and microstructural properties of the material to create a full characterisation of the construction technique.

2. Materials and methods

2.1. Materials

2.1.1. Recycled Concrete Aggregate

RCA was obtained from demolished structures in the metropolitan area of Perth, Western Australia. Aggregate sizes were predominantly between 0.6 and 19 mm (i.e. sand and gravel grains). Specimens tested either comprised solely RCA and stabiliser or a mixture of RCA, "artificial" soil (described in the following sections) and stabilisers. The entire grading was used when RCA was the only constituent; when RCA was paired with soil, RCA size fraction smaller than 6 mm and greater than 19 mm were discarded for a better control of the final granulometry. X-Ray Diffraction (XRD) analyses on RCA samples (Fig. 2) revealed the presence of Quartz (SiO_2), Calcite ($CaCO_3$), Anorthite ($CaAl_2Si_2O_8$), and traces of Larnite (C_2S, Ca_2SiO_4) phase. The latter indicates the presence of residual un-hydrated cement in the RCA, while the presence of Anorthite could be attributed to the presence of bricks or other ceramic contaminants (Ahmad and Iqbal, 2016).

2.1.2. Mixtures

The primary constituent of traditional RE is inorganic sub-soil taken from deposits found beneath organic topsoil. As soil characteristics are site specific and highly variable, for this study it was decided to create artificial earth mixes to allow for repeatable results. To determine the effect of RCA substitution on RE compressive strength two testing groups, each comprising one artificial soil and varying amounts of RCA, were established. Each group consisted of a benchmark mix (0% RCA replacement) and 3 mixes with respectively 25, 50 and 75% by mass of RCA substitution. Furthermore, batches made only of RCA were tested. A summary of all the mixtures prepared is also presented in Table 1. The first benchmark was a Crushed Limestone (CL) typically used in Western Australia in RE projects, owing to its ready availability. The second benchmark mix was an "engineered" soil created using Kaolin clay (10%, PL = 27%, LL = 61% (Cocjin et al., 2014)), silica flour (to simulate silt particles, 20%), clean sand (50%) and 10-mm blue aggregate (20%) and will be referred to as Engineered Soil (ES). The Particle Size Distribution (PSD) curves of the benchmark mixes are reported in Fig. 3. Portland cement (CEM, 7% by dry mass) was added to all materials to improve the mechanical resistance of the mixtures. For the batches comprising only RCA, additional mixtures comprising a different amount of cement (i.e. 10%) or by partial replacement of cement with fly ash (i.e. 5% cement + 5% fly ash) were also investigated. Fly Ash (FA) is the residue from coal power plants and its addition to the mixture was here considered due to its good performance as cement replacement and its environmental friendliness (Xu and Shi, 2018). FA used in this study was classified as class F according to its calcium content (ASTM, 2015). The chemical analysis showed that the material comprised 58.7% SiO_2, 27.4% Al_2O_3, 8.1% Fe_2O_3,