Eco+Rceb

Eco-efficient recycled cement compressed earth blocks

FCT Project

PTDC/ECI-CON/0704/2021

Report Eco+RCEB/R3

Characterisation of materials: fine construction and demolition waste as recycled material for earth replacement

March 2023

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA E DO ENSINO SUPERIOR Portugal

Eco-efficient recycled cement compressed earth blocks

FCT Project

PTDC/ECI-CON/0704/2021

Report Eco+Rceb/R3

Characterisation of materials: fine construction and demolition waste as recycled material for earth replacement

Acknowledgements

The authors wish to thank the Portuguese Foundation for Science and Technology (FCT) for funding this research through project PTDC/ECI-CON/0704/2021, CERIS for supporting this research, Oficinas do Convento – Montemor-o-Novo and SECIL for supporting the experimental work and suppling the materials for the experimental campaign.

Written by

This report has been written by: Sofia Real, Ricardo Cruz and José Alexandre Bogas.

Information

Main Contractor:

Instituto Superior Técnico, Technical University of Lisbon

Department of Civil Engineering and Architecture

Av. Rovisco Pais, 1049-001 Lisbon, Portugal

Main Research Unit:

CERIS is an FCT-registered research unit, hosted by the Department of Civil Engineering, Architecture and Georesources (DECivil) of Instituto Superior Técnico (IST), University of Lisbon (ULisboa).

Table of Contents

List of Figures

List of Tables

Preface

Although it is estimated that more than 30% of the world's population still inhabit earthen dwellings, in the last two centuries earth has fallen into disuse, due to the emergence of new building materials and construction techniques. However, in line with the increasing demand of more sustainable and eco-friendly building materials, earth construction has regained interest. The low environmental impact and embodied energy, the high availability of raw material, the recyclability, the high hygrothermal comfort, the improved indoor environmental quality, with nearly zero hazardous emissions, and the advances in new construction methods and in the materials science, are some reasons that contributed to the resurgence of earth construction.

A promising approach to earth building materials is the compressed stabilised earth blocks (CSEB), increasing the processing speed and showing improved mechanical strength and durability when stabilised with cementitious materials, such as ordinary Portland cement or hydraulic lime. However, despite its adequate behaviour in real exposure conditions, this type of CSEB fails to address the sustainability issue, since it requires a considerable amount of non-eco-friendly stabilisers.

Alternative more sustainable natural stabilisers have been explored by various investigators, but they are still far from being technically viable and from providing comparable mechanical and durability performance as cementitious materials.

In this context, the low-carbon thermoactivated recycled cement is expected to be a very promising alternative for CSEB stabilisation, potentially providing adequate binding properties with reduced environmental impact. Comparing to conventional cement stabilisers, the new eco-efficient binder contributes to a lower consumption of natural resources and, potentially, over 60% reduction of CO_2 emissions, while adequately repurposing construction and demolition waste.

Therefore, the main objective of this project is the innovative production and characterisation of more eco-friendly CSEB, by using low embodied energy recycled cement from concrete waste as a more sustainable stabiliser. The idea is to also explore the incorporation of construction and demolition waste as partial earth replacement, further increasing the CSEB sustainability.

The new CSEB will be characterised in terms of their main physical, mechanical, thermal and durability properties by means of laboratory tests, as well as in-situ tests involving the long term exposure of various CSEB walls to different natural environments.

In addition, the project also aims the development and characterisation of new more eco-efficient masonry earth mortars for CSEB joints, using recycled cement.

Finally, the best compromise between the technical performance and eco-efficiency of this new CSEB product is assessed by economic and environmental life-cycle analysis.

For the accomplishment of these objectives, a comprehensive experimental program was defined involving the following six main tasks: production of compressed earth blocks stabilised with recycled cement; masonry earth mortar characterisation and CSEB wall production; physical, mechanical and microstructural characterisation of CSEB; thermal performance of CSEB; durability of CSEB; life-cycle cost and life-cycle assessment of CSEB.

1. Introduction

This report outlines a component of the FCT research project, PTDC/ECI-CON/0704/2021, which aims to produce and characterise eco-efficient compressed stabilised earth blocks as part of an effort to promote the use of earth materials in sustainable construction practices. Specifically, this report focuses on the characterisation of fine recycled aggregates that will be used as partial earth replacement in the production of unstabilized and stabilized compressed earth blocks (CEB). Due to the anticipated shortage of natural resources, the application of recycled aggregates will origin more sustainable CEB solutions, enhancing their economic and environmental advantages.

2. Characterisation of fine recycled aggregates

In this study, the aim was to characterise two types of commercial construction and demolition waste (CDW), as well as a high-quality recycled sand (HQRS) innovatively produced in our lab, for potential use as partial earth replacement in CSEB. Coarse and fine sand were also characterised for comparison purposes. CDW-MIX, obtained from Vimajas - Sociedade de Construções e Obras Públicas, and CDW-CONCRETE, provided by Zircom SA, were the two types of CDW characterized in this study. The HQRS, which ranged in size between 150 μm and 500 μm, was obtained from the patented process for waste concrete separation developed in Instituto Superior Técnico (IST) [1]. The sand and HQRS were characterised based on particle size distribution, particle density and water absorption, while the 2 types of CDW was also characterised in terms of their composition.

2.1 Particle size distribution

The preparation of test specimens required the reduction of samples according to NP EN 932-2 [2]. The samples were dried in a ventilated oven until constant mass, as illustrated in Figure 1, followed by reduction using a quartering machine. To ensure that laboratory characterization was feasible and prevent agglutination of particles due to bituminous material, the CDW samples were dried at temperatures below 40°C.

Figure 1 - Drying of the sample in a ventilated oven and reduction of it by quartering

According to the EN 933-1 [3] standard, particle size analysis was conducted on the samples under study. The CDW samples, with a maximum size (D_{max}) of less than 8 mm (D_{max} ≤ 8 mm), were weighed at approximately 0.6 kg. As the HQRS samples have a maximum particle size of less than 4 mm, the sample weight is around 0.2 kg. The samples were placed in a container with water and shaken vigorously to ensure complete separation and suspension of the fine material. They were then washed through a No.200 sieve until the water was clear, and the retained material was dried until a constant mass was achieved. The material that was washed and dried was then introduced into a column of sieves (Figure 2a and Figure 2b), which consisted of a series of sieves including No. 2.5, No. 3.5, No. 5, No. 10, No. 18, No. 35, No. 60, No. 120, and No. 230, arranged in decreasing order of size. The column was manually agitated while the retained mass on each sieve was recorded (Figure 3). A scale with an accuracy of ±0.1% was used for weighing (Figure 4). The granulometric curves obtained for each of the samples studied are presented in **Error! Reference source not found.** and Figure 5. Note that due to the separation method procedure, the HQRS was produced and tested in two fractions (150-250 μm; 250-500 μm)

Figure 2 - Sieve column: a) No. 2.5, No.3.5, No. 5, No. 10 and No. 18; b) No. 35, No. 60, No. 120 and No. 230

Figure 3 - Retained mass in each sieve for CDW-MIX

Figure 4 – Scale used

Table 1 – Particle size distribution

Sieve aperture (mm)	Cumulative percentage of passing material (%)					
	CDW-MIX	CDW-CONCRETE	HQRS150-250	HQRS250-500	Coarse Sand	Fine Sand
8	100.0	100.0	100.0	100.0	100.0	100.0
5.6	97.8	100.0	100.0	100.0	98.9	100.0
4	91.6	100.0	100.0	100.0	96.6	100.0
2	78.7	91.6	100.0	100.0	83.9	100.0
1	60.8	70.5	100.0	100.0	50.0	99.4
0.5	41.2	48.2	100.0	100.0	14.9	82.2
0.250	23.3	25.9	99.2	28.2	3.7	20.5
0.125	15.7	12.3	25.5	9.6	1.4	1.2
0.063	12.5	6.2	15.8	9.0	1.0	1.0

From the analysis of the presented granulometric curves, it can be observed that the HQRS150-250 presented the smaller maximum particle size. CDW materials showed a continuous and extensive particle size distribution, including all particle sizes in between. The cumulative percentage passing through the 0.063mm mesh size allows the identification of the fine content. In this case, the HQRS150-250 sample had the highest value - 15.8%. The remaining CDW samples had values between 12.5% and 6.2%. Fine and coarse sand had negligible fine content (<1%).

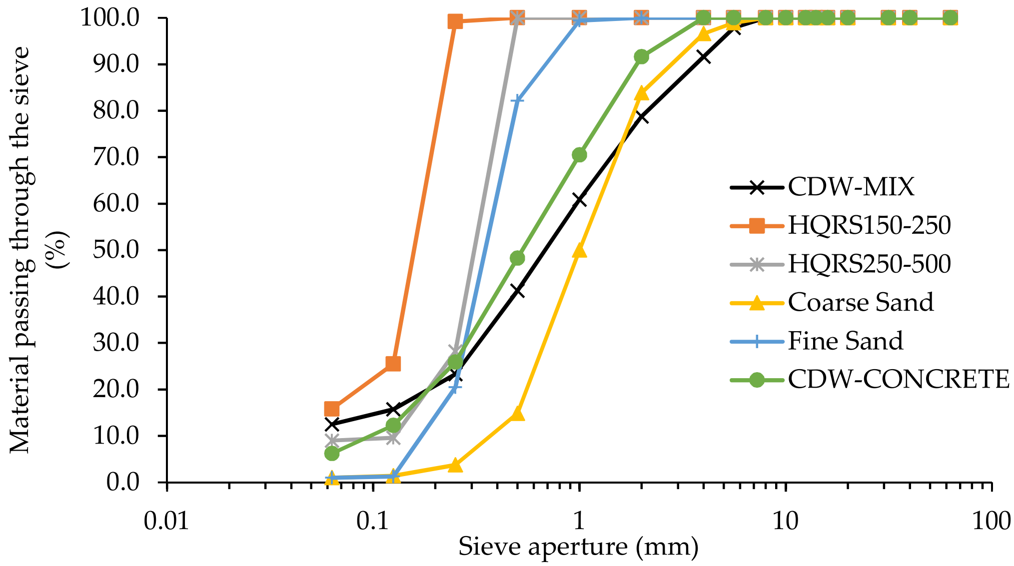

Figure 5 - Particle size curves of recycled aggregates and fine and coarse sand

2.2 Particle density and water absorption

In accordance with the directives outlined in NP EN 1097-6 [4], the assessment of water absorption and particle density were performed. As indicated in this standard, only the 0.063/4 mm fraction was evaluated. The pycnometer technique was employed to determine the particle density.

The samples were sieve on a 4 mm sieve and the retained material was discarded. The passing material was washed on a 0.063 mm sieve to remove finer particles and dried until constant mass (Figure 6). The retained material was immersed in distilled water at 22 ± 3 ^{o}C in the pycnometer (Figure 6). The entrapped air was removed by gently rolling and jolting the pycnometer. Then the pycnometer was stand in a water bath at 22 ± 3 ^{o}C for 24 hours. After this period, the pycnometer was overfilled with water and the cover was placed on top without trapping air. Then, the pycnometer was dried on the outside and weighted (m_2). After this, the pycnometer was emptied into a tray (Figure 6). The pycnometer was refilled with water, dried on the outside and weighted (m_3). The soaked test portion was spread uniformly into a tray and exposed to a current of warm air (Figure 6). The test portion was stirred at frequent intervals to ensure unform drying until no free surface moisture could be seen and the aggregate particles no longer adhere to one another. To assess whether the surface dry state was achieved, the metal cone mould (Figure 6) was hold with its largest diameter face downwards on the bottom of the tray and filled with part of the drying test portion. Then, a tamper was used to lightly tamp the surface 25 times through the hole at the top of the mould. After this the mould was lifted. This process was repeated until almost complete collapse occurred, but the peak of the cone was still visible (Figure 6). The saturated and surface dry test portion was weighted (m_1) and dried in a ventilated oven until constant mass (m_4).

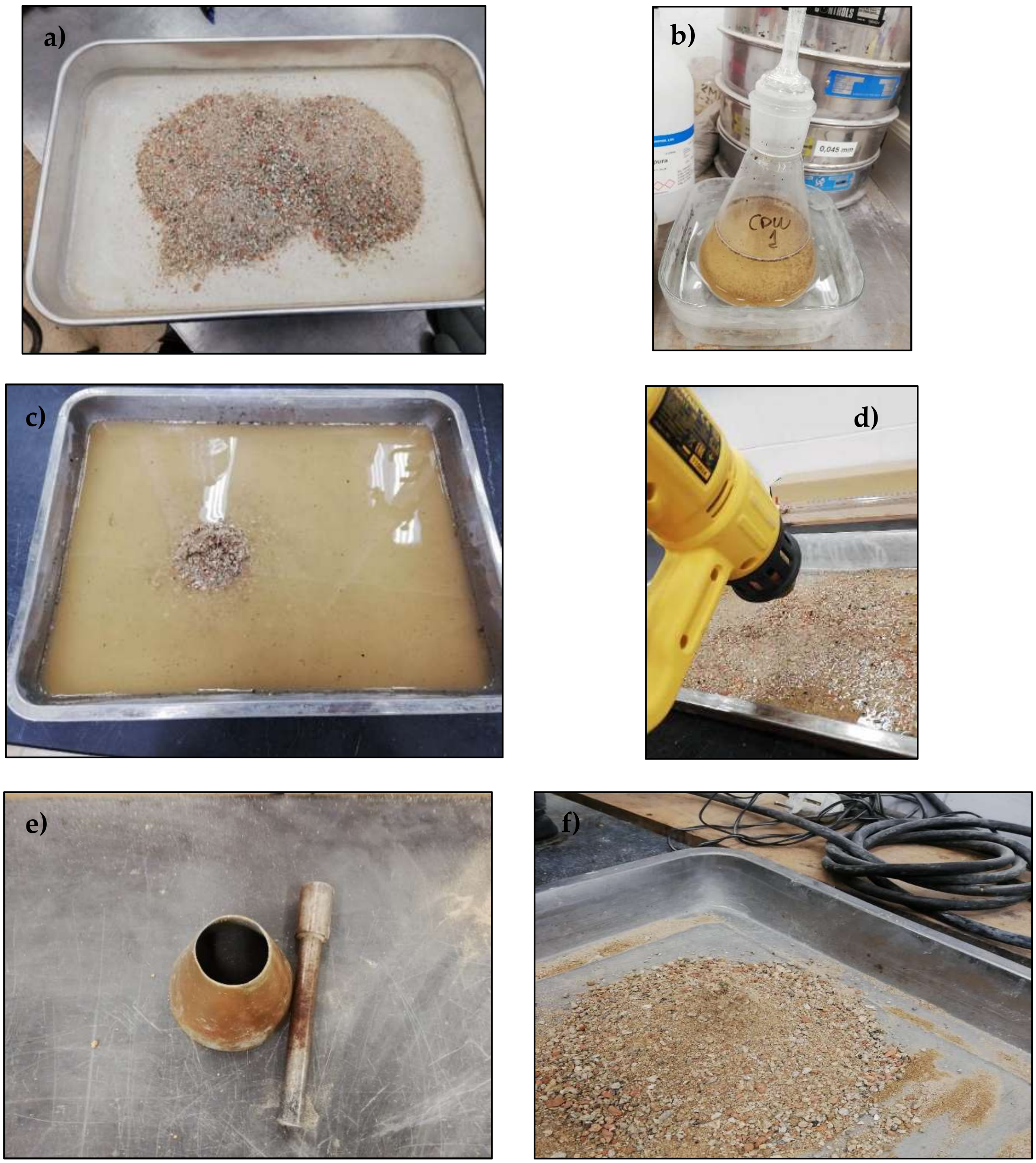

Figure 6 – Determination of particle density and water absorption: a) dried sample; b) immersion of the sample in distilled water in a pycnometer; c) soaked test sample emptied in a tray; d) exposure of the soaked test sample to a current of warm air; e) metal cone mould and tamper; f) samples on a saturated and surface dried phase

The particle densities and water absorption were calculated in accordance with the following equations:

$$Apparent\ particle\ density, \rho_a = \rho_w \frac{m_4}{m_4 - (m_2 - m_3)} \tag{1}$$

$$Particle\ density\ on\ an\ oven\ dried\ basis, \rho_{rd} = \frac{m_4}{m_1 - (m_2 - m_3)} \tag{2}$$

$$Particle\ density\ on\ a\ saturated\ and\ surface\ dried\ basis, \rho_{ssd} = \frac{m_1}{m_1 - (m_2 - m_3)} \tag{3}$$

$$Water\ absorption, WA = \frac{(m_1 - m_{4)}}{m_4} * 100 \tag{4}$$

Table 2 summarizes the values obtained for the different types of aggregates under study.

Table 2 – Particle density and water absorption

Aggregates	ρ_a (kg/m³)	ρ_{rd} (kg/m³)	ρ_{ssd} (kg/m³)	WA (%)
CDW-MIX	2559	2304	2403	4.3
CDW-CONCRETE	2464	1957	2162	10.5
HQRS250-500	2469	2271	2351	3.5
HQRS150-250	2580	2395	2467	3.0
Coarse sand	2573	2548	2558	0.4
Fine sand	2600	2575	2585	0.4

Among the water absorption values presented in the Table 2, the sample CDW-CONCRETE stands out with a value higher than 10%. Values obtained for natural aggregates are generally lower than 1% [5]. Regarding the density values, CDW presented lower values than those observed for natural aggregates, as expected.

2.3 Composition

The identification and classification of the constituents of the recycled aggregates under study, was carried out according to the NP EN 933-11 [6]. It should be stated that this methodology cannot be applied to fine aggregates (with a maximum particle size lower than 4 mm). Therefore, the identification and composition of the constituents of

HQRS250-500, HQRS150-250 and CDW-CONCRETE was not performed, because they come directly from concrete.

The CDW-MIX sample was collected in accordance with NP EN 932-1 [7] and reduced in accordance with NP EN 932-2 [2] until a 20 kg specimen was obtained. Then, the sample was dried at 40±5 °C until constant mass. The dried sample was sieve manually on the sieve No. 230 and No.5 agitating with sufficient vigour to ensure the complete separation of particles larger than 4 mm. The mass of the retained material on the No.5 sieve was recorded as m_1. The clay and soil were separated from the other test portion. The remaining test portion was immersed into a filled watertight tank and stirred to wash the particles and release the floating ones. These floating particles were collected, and their volume (V_{FL}) was recorded. For this purpose the floating particles were dried using dry absorbent paper and then introduced into a graduated cylinder filled with a known volume of water to assess the resulting volume increase (Figure 7). The non-floating particles were collected (Figure 8) and dried until constant mass. Then, the dried particles were spread on a flat surface and separated by hand those belonging to miscellaneous materials such as metals, non-floating wood, plastic, rubber and gypsum plaster. These materials were put together in a tray with the soil and clay and then weighted and recorded as m_X. The remaining non-floating particles were weighted and recorded as m_2. Its constituents were separated by hand (as defined in Table 3), weighted and recorded (Table 4 and Figure 8).

Figure 7 – Floating particles volume determination

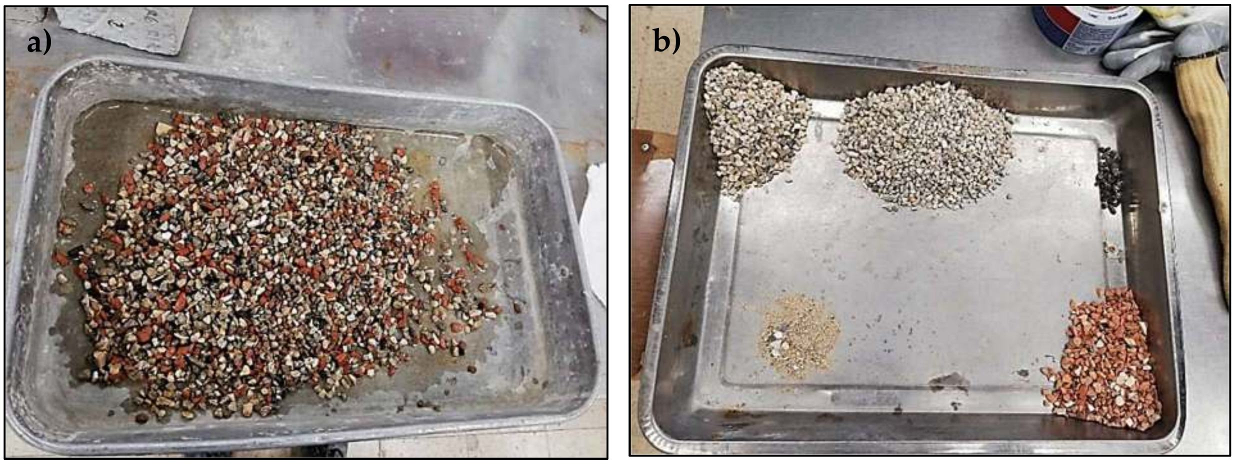

Figure 8 – Non-floating particles: a) before drying; b) after drying and separation by hand

Table 3 - Non-floating constituents of coarse recycled aggregates

Constituent	Description
Rc	Concrete, concrete products, mortar Concrete masonry units
Ru	Unbound aggregate, natural stone
Rb	Clay masonry Calcium silicate masonry Aerated non-floating concrete
Ra	Bituminous materials
Rg	Glass

Table 4 - Constituents of recycled aggregate samples (CDW-MIX)

Recycled aggregate	Constituents						
	V_{FL} (cm^3)	Rc (%)	Ru (%)	Rb (%)	Ra (%)	Rg (%)	X (%)
CDW-MIX	1.00	45.25	27.87	16.36	2.15	0.03	8.34

The sample is composed of several constituents, the most significant ones, accounting for 45.25%, are concrete, concrete products, mortar and concrete masonry units. The amount of natural stone and ceramic material is also relevant, with 27.9% and 16.4%, respectively.

Conclusions

Currently, there is a growing interest in the use of recycled aggregates due to the foreseeable shortage of natural resources, as well as the clear environmental advantages of reusing materials that would otherwise be disposed of. However, the experience with the application of this type of material in compressed earth blocks is still limited.

This report presented the study related to the laboratory characterization of recycled aggregates, including their classification and determination of geometric, mechanical, and physical properties, using standards commonly employed for natural aggregates. Additionally, for comparative purposes, fine and coarse sand were also characterized in terms of their geometric, mechanical, and physical properties.

From the results presented in this report, the following considerations can be made:

- The CDW-MIX consists mostly of concrete products, mortar, cement paste, fired clay bricks and natural stone. Other CDW used in this project results from concrete waste, namely CDW-CONCRETE and HQRS.
- The conducted tests revealed that CDW-CONCRETE had a significantly higher water absorption (10.5%) in comparison to the other recycled aggregates (3.0-4.3%) and natural aggregates (0.4%). Consequently, the usage of this aggregate in CEB would require a higher amount of mixing water and a more difficult control of the final mixture composition and CEB characteristics.

Acknowledgments

The authors wish to thank the Portuguese Foundation for Science and Technology (FCT) for funding this research through project PTDC/ECI-CON/0704/2021, and under the unit project UIDB/ECI/04625/2020 (CERIS). The authors also wish to acknowledge Vimajas and Zircom for providing the CDW used during the experimental campaign.

References

[1] J. Bogas, M. Pereira, A. Carriço, S. Hu, and R. Sousa, “Process for separating the components of hardened concrete waste for producing recycled cement,” WO 2021/173022 A1, 2021

[2] NP EN 932-2, “Ensaios das propriedades gerais dos agregados. Parte 2: Métodos de redução de amostras laboratoriais,” 2002.

[3] NP EN 933-1, “Ensaios das propriedades geométricas dos agregados. Parte 1: Análise granulométrica. Método da peneiração,” 2014.

[4] NP EN 1097-6, “Ensaios das propriedades mecânicas e físicas dos agregados. Parte 6: Determinação da massa volúmica e da absorção de água,” 2000.

[5] F. Branco, “Levantamento das Características dos Agregados produzidos em Portugal,” 2009.

[6] NP EN 933-11, “Ensaios das propriedades geométricas dos agregados. Parte 11: Ensaio para classificação dos constituintes de agregados grossos reciclados,” 2014.

[7] NP EN 932-1, “Ensaios para determinação das propriedades gerais dos agregados. Parte 1: Métodos de amostragem,” 2002.

Lisbon, 26 of March 2023

Authors

Ricardo Cruz

PhD student
(IST)

Sofia Real

Researcher
(IST)

José Alexandre Bogas

Associate Professor with Habilitation
(IST)