FINANCIAL AND ECONOMIC PERFORMANCE OF COMPRESSED EARTH BLOCKS STABILIZED WITH RECYCLED CEMENT

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ABSTRACT

Sustainability and cost efficiency is driving the revival of "modern" earth construction solutions, such as compressed earth blocks (CEB). However, the need to resort to Portland cement (PC) to enhance their mechanical and durability to meet present requirements impacts significantly on their environmental and economic performance. The present research assesses the financial and economic performance of using recycled cement (RC) produced with novel technology bases on magnetic separation as stabilizer in compressed earth blocks. The technology allows extracting the hydrated cement paste from concrete waste, unlocking the possibility of producing RC in practice. In absolute terms, the BTC produced with RC are more cost effective than those produced with PC, particularly when accounting for the benefits from diverting the hydrated cement paste from lower grade waste management alternatives and including natural raw material tax on PC. Normalizing by the mechanical performance of the BTC, the RC stabilized CEB are 0.02€ to 0.07€ more expensive than the best performing PC stabilized BTC.

Keywords

recycled cement; compressed earth block; financial assessment; economic assessment

1 INTRODUCTION

The European Union set ambitious goals towards evolving to a circular economy. This encompasses several changes in all sectors of activity, including increasing the use natural renewable resources, adopting low energy/carbon technologies and enhancing waste reuse and recycling among others. Considering the high resources consumptions and waste generation associated with the construction industry, it is one of the eight key areas in this policy (EU 2020).

In Europe, 40% of energy consumption takes place in buildings and housing alone is responsible for between 35% (EUROSTAT 2025) to 50% (EEA 2024) of the material used, depending on the indicator adopted (raw material consumption vs material footprint). Yeheyis et al. (2013) reported a worldwide value of 32%, aligned with the estimates for Europe. At the same time, the construction sector is also responsible for 35% of the total waste generation in the European Union (EU 2020). Despite the high recycling and reuse rate of construction and demolition waste (CDW) recorded in most European Union countries, the EEA (2020) indicates that the majority corresponds to the use of waste as filling material or recycled aggregates in applications such as pavement sub-bases. A similar scenario is reported in the United States (EPA 2009, 2020) and worldwide (Soto-Paz et al. 2023). Furthermore, Haas et al. (2015) indicate that the level of circularity in construction is very low (<6%). Thus, the inherent value of the materials in the CDW is lost, the qualitative aspects of recycling are not taken into account, and recycling does not occur in a closed loop.

Among the materials most widely used in construction, concrete stands out. With an estimated production of more than 14 billion cubic meters in 2020 (GCCA 2026), it is the second most consumed material in the world, surpassed only by water (Monteiro et al. 2017). Consequently, it also represents a significant share of the CDW generated, being the largest fraction in the European Union (>50% - Caro et al. 2024) and in the United States (>60% - EPA 2020). As a whole, concrete has relatively low specific embodied energy and carbon emission when compared with other common construction materials, such as steel, glass, bricks, or even some wood-based products (Mynt and Shafique 2024; Seyedabadi et al. 2024). However, the contribution of its main components is very distinct (Miller et al. 2018): cement accounts for more than 80% of the embodied energy and more than 90% of greenhouse gas (GHG) emissions, while aggregates are responsible for only 4% and 2%, respectively. The remainder results from the mixing and transportation of the components and of the concrete itself (Miller et al. 2018). Still, cement only represents 15% to 20% of the total mass of concrete (Mehta and Monteiro 1993).

Within this context, two technologies are highlighted herein: i) earthen construction; and ii) recycled cement (RC). The former is an ancestral construction technique still used in many regions of the globe (Reddy et al. 2022) and the modern rammed earth or compressed earth blocks (CEB) technics are receiving a renewed interest in the more developed countries (Mechtcherine and Gleiser 2025). The main driver for adopting earth as a construction material is mostly motivated by the environmental benefits of using a natural, local and renewable material (Arrigoni et al. 2017; Christoforou et al. 2016; Melià et al. 2014), but it also brings socio-economic benefits (Morel 2001; Anokie 2026). RC concept emerged from the observation that rehydration of the dehydrated cement paste exposed to high temperatures was possible (Crook and Murray 1970; Alonso and Fernandez 2004). However, since cement is mostly used in concrete, the bottleneck for exploring RC potential is the difficulty in extracting the hydrated cement paste from concrete waste. Carriço et al. (2021) developed a patented (Bogas et al. 2021) magnetic separation-based technology, unlocking the potential for using RC in practice.

CEB represent an evolution of traditional adobe blocks, using a press to increase soil stability through mechanical stabilization (Mansour et al. 2016). However, the traditional option of using Portland cement (PC) to enhance its mechanical performance and durability, particularly against water, and render it compatible with modern requirements hinders both its susceptibility and cost effectiveness. The present research effort assesses the financial and economic performance of using RC as a chemical stabilizer in BTC production.

2 MATERIAL AND METHODS

2.1 COMPRESSED EARTH BLOCK

The CEB were produced in Montemor-o-Novo, where one of the few facilities operating in Portugal is located. The plant production process entails the following stages: i) materials preparation; ii) material mixing; iii) CEB molding and compression; and iv) CEB curing. Typically, the major benefit underlying earth construction is the possibility of using material available on site. In the material preparation stage, the soil undergoes disaggregation and sieving to remove impurities and produce a material adequate for mixing. Since not all natural soils are suitable, it may be necessary to add materials to correct its properties. Herein, the soil was corrected with clay powder waste (CPW) from a tile plant. CDW was also included in the mix to assess the viability of its incorporation in CEB. PC, namely CEM I 42.5R (OPC) and Cement CEM II/B-L 32.5N (LPC), and RC were used as stabilizers, along with potable water from the public network. The selected materials were dosed and mixed in a mechanical mixer to produce 295x140x90 mm CEB in a hydraulic press. The CEB were left to cure in a shelter, protected from rain and sun. The curing stage only requires space since all handling is manual.

Table 1 details the mix composition of the different types of CEB produced and some of their main physical (fresh - and dry bulk density) and mechanical (unconfined compressive strength in laboratory conditions - $f_{c,un,LC}$) properties.

Table 1 – CEB mix composition and main physical and mechanical properties

Designation	Soil (kg/m³)	CPW (kg/m³)	PC (kg/m³)	RCC (kg/m³)	CDW (kg/m³)	$Water_{Tot}$ (kg/m³)	ρ_f (kg/m³)	$\rho_{28,LC}$ (kg/m³)	$f_{c,un,LC}$ (MPa)
OPC	1244	153	144	-	400	211	2155	2064	7.9
LPC	1244	153	144	-	400	211	2157	2071	6.4
RC	1139	138	-	197	367	256	2114	2018	5.5
OPC80_RC20	1235	151	114	43	398	211	2122	2039	7.2
OPC50_RC50	1222	149	71	105	394	211	2118	2047	6.4
UCEB	1253	272	-	-	438	216	2188	2001	2.1
UCEB_CDW0	1623	351	-	-	-	205	2195	2075	1.8

Reference CEB were produced with 8% PC (OPC or LPC) and 9% water by weight of solids. On the other hand, RC-stabilised CEB had to be produced with a higher stabiliser content (12%) due to the binder–aggregate contamination, and with increased water dosage (12%) to account for the greater water demand of RC (Carriço et al. 2020). CEB were also produced with partial replacement of PC by RC (20% and 50%) to obtain intermediate products. Unstabilised blocks (UCEB) were included for comparison purposes, although they are unsuitable for unprotected outdoor applications. All CEB contained 25% of the earth replaced with CDW, except for UCEB_CDW0, which was produced without CDW. More details of the experimental campaign can be found in Bogas et al. (2023).

2.2 METHODOLOGY

The assessment developed herein aims to address the financial and some of economic costs associated with the production of BTC. The methodology comprises simply in correcting the baseline official sale price of unstabilized CEB with materials exclusively from the Montemor-o-Novo, Portugal, CEB plant. For blocks with 300x150x80 mm, the official sale price is 1.2€/CEB (https://oficinasdoconvento.com/wp-content/uploads/2024/12/OC_OCT.pdf). The value is consistent with the 1.75€/CEB to 2.20€/CEB, for blocks ranging from 295x10x70 mm to 295x140x105 mm, from a plant located in Emmen, The Netherlands (https://oskam-vf.com/en/clay-products/compressed-earth-blocks/clay-blocks-brown-ocher).

The RC production cost estimates are presented in Table 2. The methodology used to estimate these costs is detailed in Sousa et al. (2026).

Table 2 –RC production costs

Resource	Consumption	Units	Cost	Units	Cost	Units
Raw material						
Recycled aggregates	1.22	t/t	3.54	€/t	4.31	€/t
Release						
Electricity	0.48	kWh/t	230.91	€/MWh	0.11	€/t
Fuel	0.56	l/t	1.58	€/l	0.88	€/t
Separation						
Electricity	7.20	kWh/t	230.91	€/MWh	1.66	€/t
Capital	1	-	0.48	€/t	0.48	€/t
Transportation	150	Km	0.046	€/tkm	6.95	€/t
Reactivation						
Resource	Consumption	Units	Cost	Units	Cost	Units
Thermal	395.22	kWh/t	71.37	€/MWh	28.21	€/t
Electricity	8.90	kWh/t	230.91	€/MWh	2.06	€/t
Capital	1.00	-	4.48	€/t	5.47	€/t
Other	1.00	-	12.32	€/t	15.03	€/t
Total					65.15	€/t

CEMBUREAU (2021), indicate PC production costs ranging from 46€/t to 58€/t for PC with an average clinker to cement factor of 74%. The values are similar to the 35-72€/t range, with an average of 48€/t, estimated by Moya and Boulamanti (2016) based on 2011 and 2012 data. The cost estimates exclude the capital costs, only encompassing the fixed and variable operation costs. Moya and Boulamanti (2016) also indicate that the capital costs represent roughly 12% of the total production cost, meaning that the average PC total production cost is 54.5€/t. This value is consistent with Rootzén and Johnsson (2017) total production cost of PC estimate of 58.4€/t, but higher than the 46€/t reported in Agora Energiewende and Wuppertal Institute (2021).

Comparing RC and PC productions costs appears to indicate that the latter is cheaper, despite using natural raw materials and requiring far less energy. This is explained by two major factors: i) inflation; and ii) fuel used for thermal processing.

Regarding the former, considering the official cost index for price revision in public construction contract in Portugal (IMPIC 2026), cement price increased 82% between 2012 and 2025. Considering the average total production cost in the EU in 2012 (54.5€/t) and assuming that the manufacturers margin didn't change in this period, the updated production price would be 99.2€/t.

In the RC production cost estimation, it was assumed the use of natural gas for the thermal processing, whereas the cement industry uses a mix of fuels. According to the environmental product declaration of the average grey cement in Portugal (DAPHabitat 2023), alternative fuels make up 40% of the mix. However, these alternative fuels are not disclosed nor their costs. Regarding the fossil fuels, petcoke is the most commonly used in Portugal. For comparison purposes, in 2025, the use of natural gas as the fuel in PC production would yield a thermal energy cost of 57.5€/t (2.9 GJ of thermal energy required and a clinker to cement ratio of 77.9% - DAPHabitat 2023). PC production requires also 147.5 kWh//t, for a clinker to cement ratio of 77.9%, corresponding to 34.1€/t. So, in similar conditions, PC energy costs alone would amount to 91.6€/t, which is explain partly by the energy prices increase in recent years (Figure 1). Since the energy costs make up 24% of the total PC production cost (EC 2018), the remaining costs are 41.4€/t. Consequently, the total PC production costs amount to 133.0€/t.

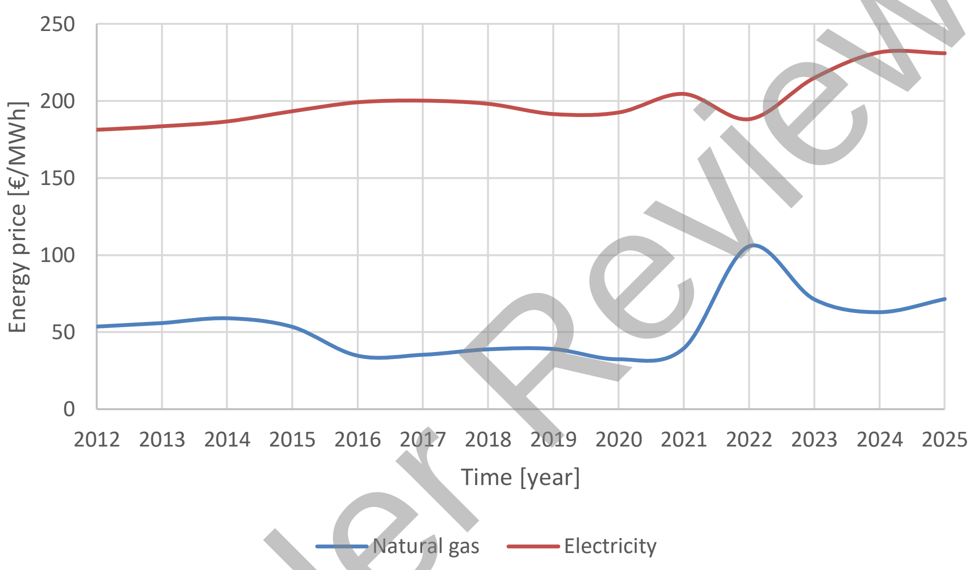

Figure 1 – Energy prices evolution in Portugal

Assuming that the average of the PC cost estimates presented represent the production cost of LPC (116.1€/t), the OPC production cost is estimated at 141.6€/t based on the clinker to cement ratio alone. These estimates are compatible with the bulk LPC and OPC sale prices directly from Portuguese manufacturers of 145€/t and 170€/t, respectively, in 2025.

The components that are not at the CEB production plant need to be transported by road. Long-haul transportation costs in Portugal is 1.13€/km for a 40 tonne HGV truck (CNR 2022a). This estimate is based on international transportation data, considering that 90% of the fuel (diesel) was purchased in Spain. This situation occurs due to the small size of Portugal and difference in fuel prices between both neighbouring countries, with the diesel price in Spain averaging 1.47€/l, without the excise duty discount (CNR 2022b), whereas in Portugal it averaged 1.80€/l (DGEG 2026b). Transportation cost in mainland Portugal can be estimated at 0.038€/tkm with the following assumptions (CNR 2022a,b; DGEG 2026b): i) a 40 tonne HGV truck is used ant it has an average load capacity of 30 t; ii) the diesel price averaged 1.58€/l in 2025; and iii) the government offers a discount of 0.30€/l up to 35 t of diesel and 0.20€/l onwards for freight road transportation. A deduction of 120% of the fuel expenses on the deducible profit is also available for the companies, but this was disregarded because it depends also on the company's revenues.

Concerning the economic analysis, the fact that RC is produced with CDW was considered to estimate other benefits from RC. Recycling CDW represents an economic benefit that can be directly estimated due to the existence of a waste management tax for landfilling. In Portugal, the waste management landfilling tax has been steadily increasing (Figure 2) and, in 2025, was 35€/t. This surcharge does not account for the landfill's capital and operational costs, which are presently critically reaching their capacity (APA 2020). From 2026 onwards, an additional fee will be defined by the government (Law-Decree n.º 102-D/2020). These costs represent the social burden of not managing adequately CDW.

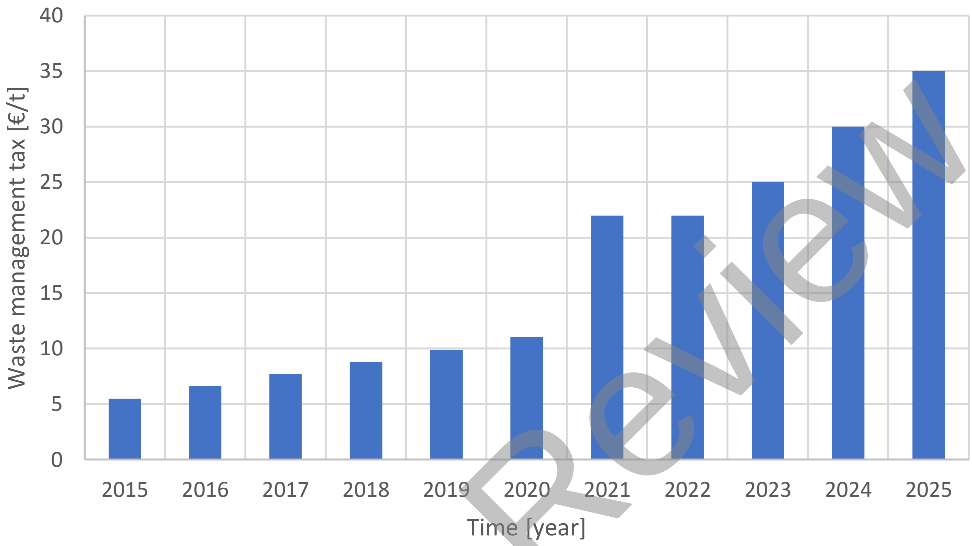

Figure 2 – Evolution of waste management tax in Portugal (Law-Decree n.º 102-D/2020)

CDW management data is far from consistent. A primary source of variability is if excavation soils and dredging spoils are included. A typical reference found in the academic literature (e.g., Jin et al. 2018; Ruiz et al. 2020; Moschen-Schimek et al. 2023) and official sources alike (e.g., EC 2021; Garcia et al. 2024) is that CDW make up between 35% to 40% of the waste generated in the European Union. The total CDW generated in the European Union is reported around 820-862 million tonnes (e.g., Gálvez-Marto et al. 2018; Saéz and Ormandi 2019; EUROSTAT 2025) of the 2 226 million tonnes (e.g., EUROSTAT 2025). However, excavation soils and dredging spoils make more than 50% of the CDW (EC 2017). This creates some confusion with other references reporting CDW amounts to around 300-350 million tonnes (e.g., Gálvez-Marto et al. 2018), some without explicitly indicating that it excludes excavation soils and dredging spoils (e.g., Zhang et al. 2022). Furthermore, some official statistics report yet another category, the CDW excluding mineral fraction, which corresponds to an even a lower amount (39.8 million tonnes according to EUROSTAT 2025). A second source of variability is the classification of CDW management alternatives, in particular, if backfilling use should be accounted as recovery and reuse. A substantial proportion of the CDW generated is used primarily in backfilling or low-grade recovery (EC 2024; Garcia et al. 2024) and several academic (e.g., Zhang et al. 2022) do not make this distinction explicit like most official reports (e.g., ECSO 2019). Additionally, the CDW management performance results are strongly related to the nature of the CDW generated, which can be highly variable. In Portugal, concrete, brick, tiles and ceramics make nearly 70% of the CDW, which corresponds to the largest proportion amongst the countries analysed in Deloitte (2017). On the other end, only a little over 20% of the CDW in Estonia are concrete, brick, tiles and ceramics (Deloitte 2017). Finally, there all also substantial differences on how CDW management information is collected, hindering an accurate assessment and comparison of the data available (Moschen-Schimek et al. 2023).

3 RESULTS AND DISCUSSION

3.1 FINANCIAL ANALYSIS

Since the production cost distribution of the CEB is not available, the lower soil content of the stabilized CEB is disregarded. Therefore, a constant value of 1.2€/CEB is adopted for all alternative compositions and only the additional cost of the components is accounted for. The cost of the components includes the transportation considering a distance of 100 km between the supplier and the CEB plant. This corresponds to a transportation cost of 7.6€/t for a 200 km journey (back and forth). The total cost and specific cost per CEB are detailed in Table 3. The specific cost accounts for the differences in the mechanical performance of the various CEB, corresponding to the total cost divided by the respective compressive strength.

Table 3 – CEB unit and specific financial cost

CEB	COST [€/CEB]							SPECIFIC COST [€/CEB.MPa]
	Base	OPC	LPC	RC	CDW	CPW	TOTAL	
OPC	1.2	0.77	0.00	0.00	0.11	0.04	2.12	0.27
LPC		0.00	0.64	0.00	0.11	0.04	1.99	0.31
RC		0.00	0.00	0.52	0.10	0.04	1.85	0.34
OPC80_RC20		0.61	0.00	0.11	0.11	0.04	2.08	0.29
OPC50_RC50		0.38	0.00	0.28	0.11	0.04	2.00	0.31
UCEB		0.00	0.00	0.00	0.12	0.07	1.39	0.66
UCEB_CDW0		0.00	0.00	0.00	0.00	0.10	1.30	0.72

For cement stabilized CEB construction in the USA, Kumar et al. (2018) estimated a cost of 0.96-1.01USD/CEB for 356x254x90 mm blocks with and without holes, respectively. Based on the estimates, labour represents 39-40%, equipment 23-24% and material (cement) 37-35%. The Auroville Earth Institute estimate that a 5% cement stabilised CEB has the following cost distribution (AEI ND): i) 45% for labour (soil sieving and block making); ii) 27% for raw materials (soil and sand extraction and water); iii) 25% for cement; and iv) 3% for equipment. The values obtained are more aligned with the former, with OPC, LPC and RC combined representing between 28% and 38% of the total CEB cost. Even disregarding the transportation costs of CDW and CPW, that increase the total CEB cost and, therefore, decrease the binder cost fraction, the range is similar (30% to 40%). However, it should be noticed that while the base value of the CEB is a price (includes profit), the remaining components only include cost.

3.2 ECONOMIC ANALYSIS

In Portugal, as well as many other countries in Europe, concrete, brick, tiles and ceramics CDW are mostly used for backfilling and only a little over 20% of this CDW fraction is recycled Deloitte (2017). Moreover, even the recycling is limited converting the mineral fraction of the CDW into aggregates. Regarding the concrete fraction, these options lose the value associated with the most expensive component, the cement.

The recent review of the Waste Directive introduced the separate reporting of the use of CDW in backfilling, since is the least valuable alternative excluding landfilling. Simultaneously, in Portugal, the use excavated soil and dredging spoil as by-product is being actively promoted, with 80% used in backfilling

(APA 2024). Considering that EC is requesting backfilling to be reported separately, since, in practice, is close to decentralized landfilling, it would not be surprising that some future policies make this connection and impose taxes on using CDW as backfilling. This can be simulated by applying a discount on the RC production cost equivalent to the landfilling tax.

Another option is to impose a tax on the extraction of natural non-renewable materials or increase the ones already in place in several countries in the Europeans Union. Since 1 t of clinker requires the consumption of over 1.5 t of natural raw material and the natural raw material taxes range between 0.5€/t and 2.6€/t (Luciano et al. 2022; Deserno and Sterk 2025), with an average of 1.5€/t, this would represent an increase of the PC production cost of 2.25€/t.

Table 4 details the cost of the CEB from an economic perspective, including both the landfill waste discount on the RC and the natural raw material tax on OPC and LPC.

Table 4 – CEB unit and specific economic cost

CEB	**COST [€/CEB]**							**SPECIFIC COST [€/CEB.MPa]**
	Base	OPC	LPC	RC	CDW	CPW	TOTAL	
OPC	1.2	0.79	0.00	0.00	0.11	0.04	2.14	0.27
LPC		0.00	0.65	0.00	0.11	0.04	2.00	0.31
RC		0.00	0.00	0.27	0.10	0.04	1.61	0.29
OPC80_RC20		0.62	0.00	0.06	0.11	0.04	2.03	0.28
OPC50_RC50		0.39	0.00	0.14	0.11	0.04	1.88	0.29
UCEB		0.00	0.00	0.00	0.12	0.07	1.39	0.66
UCEB_CDW0		0.00	0.00	0.00	0.00	0.10	1.30	0.72

4 CONCLUSIONS

In absolute value, unstabilised CEB are the cheapest option, but normalizing by the mechanical strength they become the worst in both the financial and economic evaluations. Additionally, these CEB are incompatible to use in locations exposed to water, so a direct comparison is misleading. RC stabilized CEB are 24% more expensive than unstabilised CEB, in absolute value, and between 8% (economic) and 25%(financial) more expensive that OPC stabilized CEB, in normalized value. OPC and LPC CEB are the most expensive, with unit costs 7%-33% higher than RC CEB. Still, their better mechanical performance makes them the best options in normalized terms.

Since RC stabilized CEB meet the requirements to use in non-structural walls, the results attest that RC is a cost-effective alternative option to OPC and LPC for CEB production. Furthermore, the solution effectively promotes a circular economy, valuing the component of concrete waste with the highest environmental and financial burden.

ACKNOWLEDGMENTS

The authors acknowledge the Portuguese Foundation for Science and Technology (FCT, https://ror.org/00snfqn58) for funding this research through project PTDC/ECI-CON/0704/2021, and through the project UIDB/06438/2025 (https://doi.org/10.54499/UID/06438/2025) of the research unit CERIS. The authors also acknowledge the support of SECIL, Vimajas, Portuguese Air Force, and Cobert for supplying the materials used during the experimental campaign, and Oficinas do Convento, Montemor-o-Novo, for supporting the production of the CEB.

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