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Earthen plasters hygrothermal and mechanical performance: Effect of adding recycled gypsum from plasterboards and raw hemihydrate

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ABSTRACT

The aim of the present study is to assess if recycled gypsum from plasterboard waste can be added to earth plastering mortars instead of raw calcium sulphate hemihydrate when a mineral binder addition is foreseen to improve durability. Earth mortars with additions of 0 %, 5 %, 10 % and 20 % vol. of raw hemihydrate, gypsum milled from plasterboards with and without thermal treatment were produced and tested. In general, the additions led to an overall improvement in mechanical strength and resistance to water and did not significantly influence the hygroscopicity of the earth plaster. In general, earth mortars with untreated gypsum waste achieved comparable to superior results compared to mortars with treated gypsum waste, indicating the viability of using recycled gypsum from plasterboard without thermal treatment as earthen plaster addition.

1. Introduction

As the world's human population continues to grow, serious problems arise when it comes to exploitation of primary resources. As one of the largest consumers of energy and raw materials, as well as a major contributor to greenhouse gas and pollutant emissions, the building sector has an important impact on resource consumption [1]. To mitigate climate change and develop a more circular economy, the construction sector must work towards greater resource efficiency. Research has gained interest in natural and not so conventional building materials in the past decades because they have low embodied energy, prevent other raw material depletion [2] and reduce energy consumption for production of materials. Earth is a natural and, although used for millennia, nowadays, not so conventional building material. As a building material, earth offers many advantages in terms of sustainability [3]. It is non-toxic (except when contaminated), available locally, needs low energy consumption to be used, has low carbon emissions and is reusable (when not chemically stabilised) and easily recyclable [4].

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Clayey earth-based mortars have been widely used in the past and were probably the first type of mortars used in the history of humankind [5]. During the second half of the 20th century, however, the use of earth mortars, namely as masonry mortars [6] and plasters [7], was largely replaced by cement-based mortars due to the maintenance and labour intensity of the former [2]. With an increase in environmental concerns, on bio-climatic architecture and a need to make the built environment more sustainable, interest in earth plasters has regrown in the past decades. Life cycle assessment (LCA) methodology shows earth plasters to have a low environmental impact compared to plasters based on current binders [2,8]. Other advantages of earth to be used to produce plastering mortars for buildings are related to indoor comfort. Using earth-based plasters can contribute to good indoor air quality since they can act as a passive moisture buffer [9] and an air purifier [10]. As clays have high adsorption and desorption capacities [11], earth-based plasters can strongly contribute to balance the relative humidity (RH) of the indoor air, improving comfort and health of inhabitants [12]. In recent studies, Arris-Roucan et al. [13] presented values of carbon dioxide (CO_2) retention capacity for raw earth, while Ranesi et al. [14] showed its ability to capture ozone, providing evidence of the potential passive regulation capacity of this material. Santos et al. [10] compared the adsorption and desorption capacity as well as the CO_2 capture capacity of an earth and a gypsum-based plaster, with advantages to the former.

Clayish earth is not resistant to contact with water, and repairs of earth-based plasters are therefore easy to undertake [15]. Disadvantages of earth plasters may, however, be related to this poor water resistance as unstabilised earth plasters are susceptible to liquid water [16]. Although the contact of plasters with water is not frequent, it can occur during cleaning actions and when a window is left opened. Furthermore, during drying, clay-rich earth mortars shrink causing cracks [17]. A high number or large drying cracks negatively impacts the durability and aesthetics of earth plasters.

To enhance the performance of earth plasters, additional materials may be added. Sand size aggregates, fibres and binders can be added to the earth to reduce shrinkage and increase durability [4]. However, the latter increases their embodied energy and makes the material non-reusable just by mixing with water.

Hemihydrate (calcium sulphate hemihydrate or bassanite, $CaSO_4.0.5H_2O$) is a gypsum-based binder frequently used in indoor coatings of walls and ceilings, but also as decorative elements, such as crown moulding, and gypsum plasterboards. Hemihydrate is obtained by dehydration of calcium sulphate dihydrate ($CaSO_4.2H_2O$, typically denominated gypsum) during calcination process at 125–180 °C [18]. Due to its reversibility, in contact with water the calcium sulphate hemihydrate transforms again into gypsum (calcium sulphate dihydrate) [19]. When analysing the energy consumption for its manufacture, this binder is environmentally friendly when compared to building limes and cements: the hemihydrate does not release CO_2 during calcination and requires a low calcination temperature when compared to circa 900 °C and circa 1500 °C for air lime and Portland cement, respectively [20,21]. Therefore, it shows great potential to be used as an alternative to other common binders with a higher carbon footprint, contributing to a more sustainable built environment.

Lima et al. [22] analysed illitic earth mortars with addition of 0 %, 5 %, 10 % and 20 % vol. of raw hemihydrate without setting retarder and, in another study, Lima et al. [23] analysed a pre-mixed illtic earth mortar with the addition of 0 %, 5 %, 10 % and 20 % vol. of anhydrite and 20 % of hemihydrate with setting retardant. Both studies showed that the addition of low contents of gypsum-based materials (hemihydrate and anhydrite) improved mechanical performance, without significantly decreasing its adsorption and desorption capacity.

Gypsum and gypsum-based products are widely used in the building industry, resulting in high amounts of waste accumulation such as leftovers from plasterboard cuts of new constructions and used plasterboards from building refurbishments and demolitions. Globally, landfills receive more than 15 million tons of gypsum plasterboard waste each year [24]. Due to the reversibility of the gypsum by either calcination or hydration, this material can be recycled [25–27]. Different types of recycled gypsum, such as gypsum waste from plasterboards, flue gas desulfurization (FGD) gypsum and phosphogypsum, are used in other building products [28–31]. Erbs et al. [26] and Geraldo et al. [27] evaluated the recyclability of gypsum plasterboard waste by analysing the material after multiple hydration and dehydration cycles. Both studies did not observe a significant decrease in mechanical behaviour after each recycling cycle.

Geraldo et al. [27] analysed a recycled gypsum, calcined for 1 h at 150 °C, used after 1, 3 and 5 recycling cycles. Researchers concluded that, after the several consecutive recycling cycles, with low energy consumption, the gypsum waste maintained the chemical characteristics, demonstrating its high recycling potential. Thus, using gypsum waste presents environmental benefits by reducing the consumption of natural resources and the gypsum plasterboards waste disposed in landfills. In this way, the negative environmental impact of using natural gypsum can be reduced when replacing raw gypsum by recycled gypsum.

Camarini et al. [19] studied the energy consumption during gypsum plaster waste calcination using different calcination temperatures (120 °C, 150 °C and 200 °C) and duration (1 h, 2 h, 5 h, 8 h, 16 h and 24 h). Of course the energy consumption was greater the higher the temperature and duration of process.

Some studies evaluated the environmental impacts of gypsum waste recycling [18,29,31,32]. Weimann et al. [18] concluded that gypsum plasterboard waste recycled on an industrial scale can be eco-friendly and environmentally advantageous compared to natural and FGD gypsum. Suárez et al. [31] analysed the influence of 5 % of recycled gypsum (replacing the same percentage of raw gypsum) as a set retarder in ordinary Portland cement and concluded that the recycling gypsum process consumed less than 65 % of energy and emited less than 65 % of greenhouse gases compared to raw gypsum preparation process.

Pedreño-Rojas et al. [29] performed a LCA on the recycling of gypsum plasterboard waste. The authors found that recycled gypsum plasterboards were highly environmentally friendly indoor coating products, demonstrated by Global Warming Potential and Embodied Energy indicators.

The addition of a current binder to earth plasters, due to its high environmental impact compared to earth [2,8], as mentioned previously, suggests a possible increase of the embodied energy of earth-based plasters with the addition of low contents of raw gypsum. However, the good environmental impact of recycled gypsum waste compared to raw gypsum suggests a good environmental performance of these earth-based plasters. Further research on the influence of the addition gypsum-based materials to earth plasters should be carried out.

Camarini et al. [33] referred that the gypsum waste is composed by dihydrate and, depending on the gypsum waste origin, by some impurities, and its dehydration occurs up to 180 °C. To recycle gypsum and gypsum-based products it is important to optimize how the waste should be prepared and which thermal treatment (thermal treatment cycle, including maximum temperature and type of cooling) should be applied. Multiple studies did research into the optimized thermal treatment temperature and time for recycled gypsum waste [19,29,34]. Erbs et al. [34] investigated the physical and mechanical properties of recycled gypsum plasterboard waste's mortars. The researchers cut, crushed and heat-treated gypsum plasterboard waste at 160 °C, 180 °C and 200 °C for 1 h, 2 h, 4 h, 8 h and 24 h. They were able to verify that the granulometry between the samples did not show great variation in function of the treatment temperature. From the results of the mechanical strength tests (flexural and compressive strength), the highest values achieved were in samples heat-treated at 160 °C and 180 °C at 24 h, and 200 °C at 4 h [34]. Camarini et al. [19] studied the energy consumed to recycle gypsum plaster waste in stationary kilns, to establish the best thermal treatment time and temperature. Based on the results, the gypsum heat-treated at the temperatures of 150 °C and 200 °C for 1 h was chosen to be tested in powder, fresh and hardened state. Of the two treatment temperatures, the gypsum heated at 150 °C presented the best performance compared to the reference material. Results shown shorter setting times, good compressive strength, lower permeability and shorter crystals in the microstructure [19]. In another research by Pedreño-Rojas et al. [29], the influence of the heating process on the development of new gypsum composites containing different types and contents of waste was studied. The researchers concluded that thermally treated gypsum-based waste from industrial plasterboard production for 3 h at 150 °C was enough to transform all particles into hemihydrate. Additionally, they investigated recycling gypsum wastes without any heating treatment. These researchers concluded that industrial gypsum plasterboard waste (GPW) could be used in gypsum-based plasters without any heating process, improving the mechanical results compared with the reference material.

Camarini et al. [33] evaluated the effect of citric acid on the properties of a recycled gypsum plaster. The researchers concluded that the citric acid increased the fluidity of the recycled gypsum plasters but decreased the mechanical properties. Finally, Pritzel et al. [35] studied the recycling of gypsum with the presence of retarding agents and other additives. The study concluded that gypsum-based binding materials can be recycled, but that it will change the material performance due to new impurities and effects of additives that could change the morphology, technical properties and particle size and surface of the material.

The aim of the present study is to assess if GPW can be efficient when stabilizing earth plastering mortars. Therefore, GPW was prepared to become a powder and used directly (not re-heated GPW, gypsum), while a fraction was heated (re-heated GPW, hemihydrate). The properties of earth-based mortars produced with different contents of the unheated GPW were compared with mortars produced with the addition of heated GPW, the addition of raw gypsum (hemihydrate), and with an unstabilised earth mortar. It was decided not to add other additions, as plasticizers and retarding agents.

2. Materials, mortars and methods

2.1. Materials description and characterization

2.1.1. Earth, sand and raw gypsum

For the mortars, an earth (Ea) from a central region of Portugal was used. This earth was previously disaggregated and sieved, after drying in the open air, to eliminate big agglomerations.

As this earth is highly clayey and based on previous studies [12,36], siliceous sand (S) was added to control the mortars shrinkage.

A raw calcium sulphate hemihydrate (G) for plastering mortars was used, produced by SIVAL company. This hemihydrate is ready to be mechanically mixed with water and is suited for manual application, with an initial setting time of 12 ± 3 min (SIVAL technical sheet [37]).

2.1.2. Gypsum-based plasterboard waste

The gypsum-based waste used in this study was obtained from gypsum plasterboards collected at building sites in the region of Almada and Seixal, South of the Tagus River, Portugal. The plasterboards' waste was manually crushed to separate the gypsum from the paper and adhesive. After separation, the fraction resulting from board pieces was grinded in a Retsch SK 100 mill to obtain the desired particle size.

Camarini et al. [19] and Geraldo et al. [27] reported that 80 % of the gypsum-based particles they have used passed a sieve with 297 μm opening. Thereby, the gypsum powder obtained was then sieved in a 300 μm opening sieve. Part of the sieved recycled gypsum powder (GPW) was then ready to use – unheated GPW. Other part of this gypsum powder was thermal treated (GPWh).

Camarini et al. [19] referred that gypsum plasters' waste heated at 150 °C for 1 h presented good performance. However, Pedreño-Rojas et al. [29] concluded that a heat treatment at 150 °C for 3 h transformed all the particles of gypsum plasterboard into hemihydrate (see section 1). To verify the most advantageous temperature for the heat treatment and optimize the environmental performance the hourly mass loss of the samples was evaluated. The particles of GPW (samples with approximately 1 cm height placed in three different metal capsules) were heated at 150 °C for 1 h, 2 h and 3 h. The mass loss was evaluated after each period of time by weighing the sample on a balance with 0.01 g of precision. The procedure of removing from the oven and weighing was carried out as quickly as possible to reduce the adsorption of moisture. Heating the gypsum-based powder for 2 h and 3 h did not show a change in the mass loss compared to 1 h of heating. Based on this result, the choice was made to thermally treat the recycled gypsum-based powder at

150 °C for 1 h (GPWh). The GPWh was left in a dry desiccator for approximately 17 h for cooling before being used.

The thermal treatment of the GPWh had the same temperature (150 °C) and time (1 h) than the treatment used by Camarini et al. [19] and consumes less energy when compared to the treatment of Pedreño-Rojas et al. [29] (for 3 h).

2.1.3. Loose bulk density and particle size distribution

The loose bulk density (LBD) was determined for the earth (Ea), sand (S), raw (commercial) gypsum-based product (G) and heated and unheated recycled gypsum (GPWh and GPW, respectively), based on EN 1097-3 [38], and the results are presented in Table 1. G presented higher loose bulk density compared to GPW and GPWh. A decrease of loose bulk density of recycled gypsum plasterboard waste was also reported by Geraldo et al. [27]. The loose bulk density of heated recycled gypsum decreased when compared to the unheated waste. This can be due to the release of water present in the GPW. Geraldo et al. [27], when analysing the recyclability of gypsum waste, also obtained a decreased of loose bulk density after 3 cycles of recycling (thermal treatment at 150 °C for 1 h). In the study of Camarini et al. [19] it is concluded that the temperature of thermal treatment (150 °C and 200 °C for 1 h) did not influence the loose bulk density of the recycled gypsum.

The dry particle size distribution of earth and sand was analysed based on EN 1015-1 [39] and is presented in Fig. 1. The raw gypsum-based (G) particle size distribution is obtained from the product's technical sheet [37]: it presents residue on the 500 μm sieve ≤0.100 % and on the 300 μm sieve ≤0.650 %. The heated and unheated recycled gypsum from plasterboards waste (GPWh and GPW, respectively) passed through the 300 μm sieve.

2.1.4. X-ray diffraction and thermogravimetric analysis

The X-ray diffraction (XRD) analysis was carried out in a AERIS Malvern Panalytical X-ray diffractometer with 40 kV and 15 mA, using Copper Kα radiation (λ = 1.5406 Å). A representative sample of each material (G as it arrived from the producer and E, GPW and GPWh after the preparation described in 2.1.1 and 2.1.2, respectively) was ground with mortar and pestle until all material passed a 106 μm sieve. Diffractograms were then recorded in the range 5–85°2θ, at a step size of 0.20°/s. The diffractograms analysis was made according to an internal procedure based on the test specification LNEC E 403 [40] and using the HighScore Plus software from Malvern Panalytical for the peak identification and for the semiquantitative analysis by Rietveld method. The structural models of the identified minerals for Rietveld refinement were taken from the Crystallography Open Database [41–47].

The mineralogical composition obtained is presented in Table 2. The results show that raw hemihydrate (G) is mainly bassanite (β-hemihydrate), while the unheated gypsum plasterboard waste (GPW) is essentially gypsum (calcium sulphate dihydrate). These results also demonstrate that the heat treatment of the GPW for 1 h at 150 °C was sufficient to convert the gypsum in β-hemihydrate. Comparing with raw hemihydrate (G), GPWh has a higher percentage of β-hemihydrate. These results confirm what was referred to by Geraldo et al. [27]: recycled gypsum presents characteristics similar to raw gypsum, emphasizing its recyclability. The presence of calcite and dolomite in G and GPWh is still verified.

In the work of Pedreño-Rojas et al. [29] the conversion of gypsum in β-hemihydrate was also achieved but with a thermal treatment of the gypsum plasterboard waste for 3 h at 150 °C. In the present study the same result was obtained in 1 h, demonstrating that a lower energy expenditure for this transformation is possible. These differences can be due to different volumes of thermally treated waste gypsum.

The clayish earth (Ea) is mainly composed by illite and quartz, residual kaolinite and vestigial montmorillonite, microcline and calcite. Thus, it is considered an illitic clayish earth.

Thermogravimetry with differential thermal analysis (TGA/DTA) was made using a SETARAM TGA92 simultaneous thermal analyser. The samples were placed in a Pt-Rh crucible and introduced into TGA equipment where they were heated from room temperature to 1000 °C at a uniform rate of 10 $^{\circ}\mathrm{C.min}^{-1}$, with argon atmosphere (3 $\mathrm{L.h}^{-1}$) as carrier gas [48].

TGA/DTA graphs and the derivate thermogravimetric curve (DTG) of gypsum samples (raw and wastes) are presented in Fig. 2.

It is possible to observe that raw hemihydrate (G) and gypsum waste (GPW and GPWh) present weight losses in two regions: the first one between 100 and 200 °C due to the loss of water of crystallization of bassanite or gypsum, and the second between 550 and 950 °C due to the CO_2 loss of carbonates. In the first region, the two loss peaks of two water molecules from the gypsum can be observed in the GPW sample. Besides, the phase change of soluble to insoluble anhydrite can be detected through the exothermic peak between 370 and 400 °C [49].

2.2. Mortars, specimens and methods

2.2.1. Mortars formulation and fresh state characterization

In this study, ten different mortars were prepared. One control unstabilised earth mortar (0 % gypsum-based addition), three reference mortars with 5 %, 10 % and 20 % (in volume) additions of raw hemihydrate binder (G) and six mortars with the same

Table 1
Loose bulk density of the materials.

Materials	Ea	S	G	GPW	GPWh
LBD [kg/dm^3]	0.92 ± 0.02	1.47 ± 0.00	0.64 ± 0.02	0.49 ± 0.00	0.42 ± 0.01

Notation: Ea – earth; S – sand; G – raw hemihydrate; GPW – unheated gypsum-based plasterboard waste; GPWh – heated gypsum-based plasterboard waste ate 150 °C for 1 h.

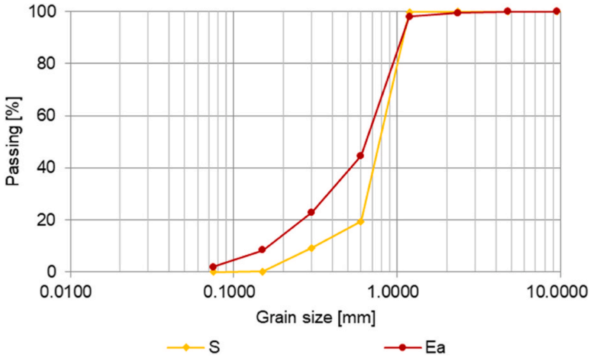

Fig. 1. Particle size distribution of earth (Ea) and sand (S).

Table 2
Mineralogical composition of the clayish earth (Ea), raw gypsum (G) and heated and unheated gypsum-based plasterboard wastes (GPWh and GPW).

	Minerals	wt %			
		Ea	G	GPW	GPWh
Montmorillonite	$(Na,Ca)_{0,3}(Al,Mg)_2Si_4O_{10}(OH)_2.nH_2O$	2.3	–	–	–
Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,H_2O]$	46.3	–	–	–
Kaolinite	$Al_2Si_2O_5(OH)_4$	10.8	–	–	–
Microcline	$KAlSi_3O_8$	2.6	–	–	–
Gypsum	$CaSO_4.2H_2O$	–	–	91.8	–
Bassanite	$CaSO_4 \cdot 0.5H_2O$	–	77.2	4.8	88.8
Anhydrite	$CaSO_4$	–	13.9	0.7	1.5
Calcite	$CaCO_3$	3.3	5.0	1.5	6.4
Dolomite	$CaMg(CO_3)_2$	–	3.4	1.0	2.8
Quartz	SiO_2	34.7	0.5	0.2	0.5

percentual additions of heated (GPWh) or unheated (GPW) recycled gypsum-based binder from plasterboards waste. The control mortar (E) with 0 % gypsum-based addition was formulated with an earth:sand ratio of 1:3 (in volume). In Table 3, the volumetric and mass proportions of these mortars are presented.

The mixing water (in relation to the total solids) was added to guarantee the mortar's workability. All mortars were produced based on DIN 18947 [50]: the dry solid constituents were manually homogenized; the water was placed in the mechanical mixer container and dry solid constituents were added; the mixer was started for 30 s at low speed and then the mixer was changed to high speed for another 30 s; the mixing was stopped for 5 min and the need to add more water to ensure workability was evaluated; lastly, the mortar was mixed for an additional 30 s at high speed. For mortars with gypsum-based additions (G, GPW and GPWh) the 5 min stoppage in mixing was omitted due to the gypsum setting time.

All mortars presented a good workability evaluated by an experienced technician, although some mortars did not meet the flow table consistency defined by the DIN 18947 [50] (175 ± 5 mm) for unstabilised earth plasters. The workability was also evaluated in fresh state by flow table consistence, based on EN 1015-3 [51] but with a flow table not in agreement with the latest version of this standard. In fresh state, the wet bulk density was also determined, based on EN 1015-6 [52], and the water content was determined by the weight loss of the fresh and oven dry mortar sample.

2.2.2. Specimens

Three prismatic and three cylindrical specimens were produced with each mortar. The prismatic specimens with dimensions of 160 mm × 40 mm x 40 mm were mechanically compacted in two layers, each with 20 strokes, on standard metallic moulds, and levelled manually. After 28 days of drying in laboratory conditions (at a temperature of 21 ± 5 °C and 65 ± 2 % of RH), the specimens were used to test the linear drying shrinkage, dry bulk density, dynamic modulus of elasticity and flexural and compressive strengths. The cylindrical specimens, simulating plasters, have a height of 20 mm and diameter of 85 mm and are manually produced with a PVC mould and levelled. These specimens were used to determine the thermal conductivity, surface cohesion, dry abrasion resistance and water vapour adsorption and desorption. For each property, an average and standard deviation from three specimens were obtained for each mortar.

2.2.3. Hardened state characterization

Visual observation – Through visual observation of the specimens of each mortar, it was possible to observe and compare the colour of the different mortars. On the other hand, it was possible to identify any damage on the specimens, allowing to assess whether or not the specimen can be used in mortar characterization tests.

Linear drying shrinkage – The linear drying shrinkage was visually observed, qualitatively assessed when demoulding the specimens

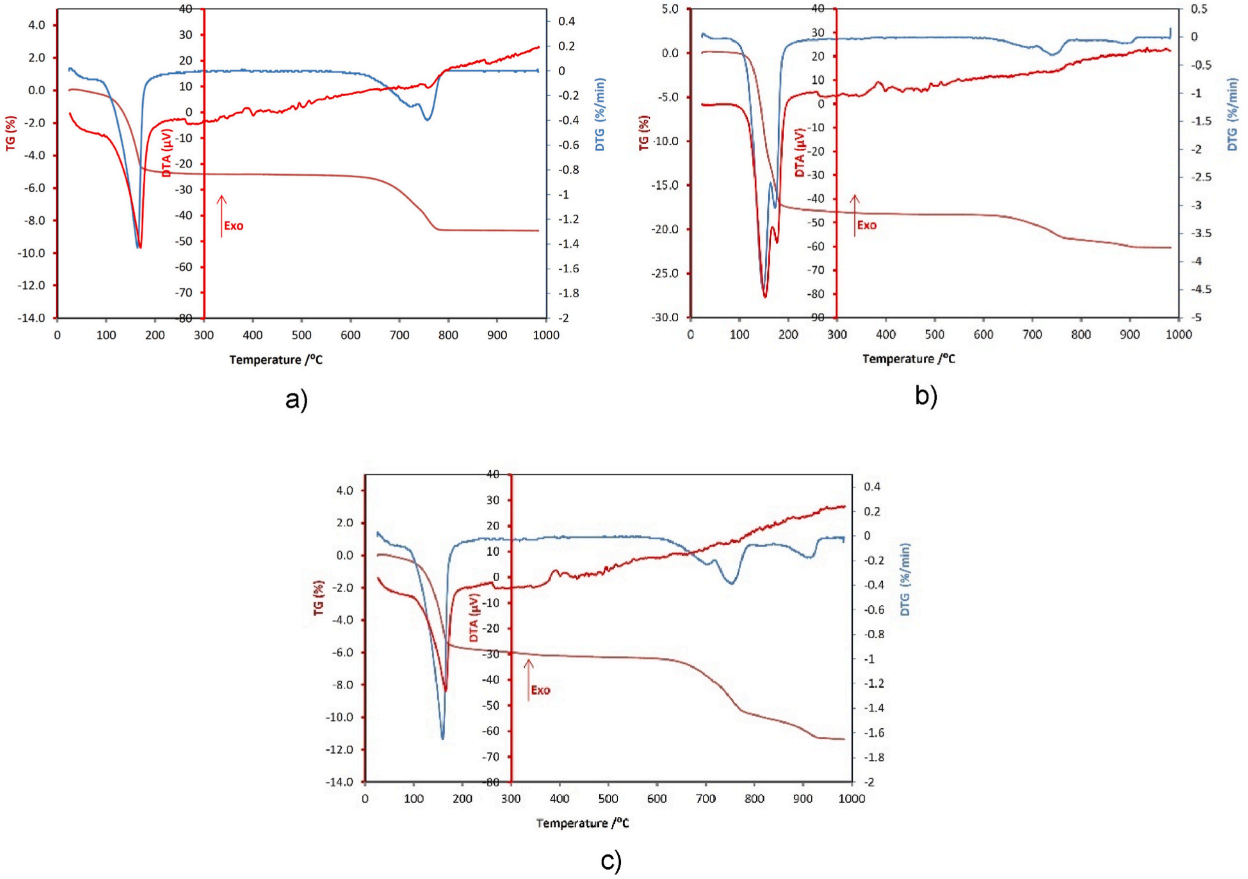

Fig. 2. TGA/DTG/DTA thermographs of: a) raw hemihydrate – G; b) unheated gypsum-based plasterboard waste – GPW; c) heated gypsum-based plasterboard waste – GPWh.

Table 3
Volumetric and mass proportions of mortars, water/solids ratio, water content of the fresh mortars, flow and wet bulk density.

Mortars	Volumetric proportions					Weight proportions					W/s [kg/kg]	Water content [%]	Flow [mm]	Wet bulk density [kg/dm^3]
	Ea	S	G	GPW	GPWh	Ea	S	G	GPW	GPWh				
E	1	3	–	–	–	1	4.8	–	–	–	0.20	21 ± 0.2	175	1.97
E+5G	1	3	0.2	–	–	1	4.8	0.1	–	–	0.20	21 ± 0.1	170	1.92
E+10G	1	3	0.4	–	–	1	4.8	0.3	–	–	0.20	21 ± 0.0	166	1.93
E+20G	1	3	0.8	–	–	1	4.8	0.6	–	–	0.23	24 ± 0.1	170	1.92
E+5GPW	1	3	–	0.2	–	1	4.8	–	0.1	–	0.20	21 ± 0.1	168	1.91
E+10GPW	1	3	–	0.4	–	1	4.8	–	0.2	–	0.20	21 ± 0.1	174	1.90
E+20GPW	1	3	–	0.8	–	1	4.8	–	0.4	–	0.20	22 ± 0.1	167	1.90
E+5GPWh	1	3	–	–	0.2	1	4.8	–	–	0.1	0.21	21 ± 0.3	156	1.92
E+10GPWh	1	3	–	–	0.4	1	4.8	–	–	0.2	0.23	24 ± 0.1	129	1.85
E+20GPWh	1	3	–	–	0.8	1	4.8	–	–	0.4	0.28	29 ± 0.1	173	1.82

Note: W/s – relationship between water added and the sum of solid constituents (Ea, S, G, GPW and GPWh).

and quantitatively performed as defined in the DIN 18947 [50] standard, by the difference of the length of the prismatic specimens in comparison with the mould.

Dry bulk density – The dry bulk density of mortars was performed based on the EN 1015-10 [53], by the ratio of the mass by the volume of each prismatic specimen. The specimens were tested in ambient conditions and were not dried at 105 °C as referred to in the standard.

Thermal conductivity – The thermal conductivity was assessed in each cylindrical specimen using an ISOMET 2114 equipment with a surface probe that measures in the range of 0.3–3.0 W/(m.K). The specimens were in equilibrium with the environment, with the test taking place at a temperature of 24.6 ± 0.5 °C and RH of 55.5 ± 5.5 %.

Dynamic modulus of elasticity – The dynamic modulus of elasticity was obtained based on the EN 14146 [54], using a Zeus

Resonance Meter equipment. The mass and dimensions of each prismatic specimen was introduced in the software and the dynamic modulus of elasticity obtained.

Flexural and compressive strengths – The flexural strength was obtained based on the EN 1015-11 [55] using a Zwick Rowell Z050 equipment with a load cell of 2 kN and velocity of 0.2 mm/min. Each specimen was broken in two. One part of each specimen was used for the compressive strength determination, based on the same standard, using the same equipment with a load cell of 50 kN and a velocity of 0.7 mm/min.

Surface cohesion – The surface cohesion was determined based on procedure defined by Drdácky et al. [56] and with necessary adaptations defined by Faria et al. [57], Santos et al. [58] and Parracha et al. [59,60]: the difference in mass of an adhesive tape with 50 mm × 50 mm weighed on a scale with 0.001 g of precision is evaluated before and after being placed on the surface of the cylindrical specimens, pressed with resilient material (for example, a neoprene tape), with a constant intensity of 2 kg for 2 min.

Dry abrasion resistance – The dry abrasion resistance was obtained based on DIN 18947 [50] and was determined by the loss of material from the surface of cylindrical specimens after 20 rotations with a circular brush with 65 mm of diameter, with a constant pressure of 2 kg applied on the specimen's surface [57,60]. After this the specimen's surface was cleaned. The difference of mass of the specimens before and after the test (measured on a scale with a precision of 0.001 g) are indicative of the dry abrasion resistance of each plaster.

Water vapour adsorption and desorption – Differently to what is defined by DIN 18947 [50], which proposes the use of planar specimens with 1000 cm^2 and 15 mm thickness, kept in metallic moulds ensuring that during the test the water vapour adsorption and desorption occurs only by the exposed upper face, cylindrical specimens were used in the present study. Faria et al. [57] compared the results of the water vapour adsorption and desorption in planar specimens (proposed by DIN 18947 [50]) and in cylindrical specimens, concluding that the specimens present similar behaviour, despite the fact that the cylindrical specimens present less water vapour adsorption and desorption due to the lower plaster area exposed compared to planar specimens. Smaller specimens have also been used by Ranesi et al. [61] when testing earth plasters and other binder-based plasters. However, to ensure that the adsorption and desorption of water vapour only occurred by the upper exposed surface, the lateral and bottom surface of each specimen were waterproofed with silver adhesive tape (Fig. 3).

The hygroscopicity of the plastering mortars was assessed by the adsorption and desorption tests, performed based on the DIN 18947 [50] and the test method defined by Lima et al. [5]: the specimens were stabilised in a climatic chamber at 23 °C and 50 % RH; when specimens are stabilised, the water vapour adsorption phase began, setting the RH inside the climatic chamber to 80 %; in this phase the specimens were weighted at 0 h, 1 h, 3 h, 6 h, 12 h and 24 h.

After 24 h, the adsorption phase is concluded and the desorption begins, following the test method defined by Lima et al. [5]: the RH inside the climatic chamber was set again at 50 %; the specimens of each plaster are weighed in the same periods of time.

Resistance to contact with liquid water – A sample of a specimen of each plaster, after the compressive strength test, was placed in contact with a water height of 5 mm, in a *Petri* dish. The resistance to contact with liquid water was assessed, in a preliminary way, depending on the speed of their degradation: the faster it degrades, the lower the resistance of the plaster to contact with liquid water.

3. Results and discussion

3.1. Fresh state characterization

The flow and wet density, as well as the water content and the water/solids (W/s) ratio of the mortars, are presented in Table 3. From Fig. 4 it is possible to conclude that, to guarantee the workability of the earth-based mortars, it was necessary to maintain or increase the water content with the increase in the incorporation of raw or waste gypsum-based (hemihydrate – G and GPWh – or gypsum – GPW) binder added. Therefore, it is to highlight that the addition of hemihydrate (G and GPWh) and gypsum (GPW) to earth mortars is being compared. Although G and GPWh are both hemihydrates, GPWh contains a higher percentage of bassanite compared to G, as can be seen from the XRD analysis results (section 2.1.4). This higher percentage of bassanite may justify the need for more

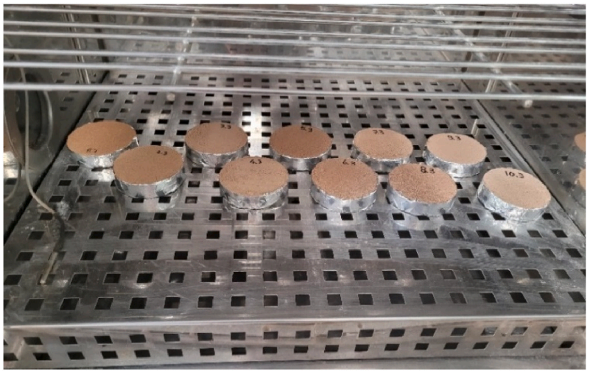

Fig. 3. Circular specimens in the climatic chamber showing the laterals (and base) waterproof with silver adhesive tape.

mixing water to maintain the workability of mortars with GPWh addition, compared to mortars with G addition. The anhydrite content also may influence the fresh characteristics of mortars.

Despite the increases in the water/solids (W/s) ratio, the E+10GPWh mortar presents lower flow compared to other mortars. However, it has good workability; so, it was decided not to increase the water/solids ratio, and consequently the flow, of this mortar. A higher amount of water could also cause an increase in mortars' shrinkage and porosity.

Pedreño-Rojas et al. [29], when analysing the influence of replacing raw gypsum-based binder with 0 %, 25 %, 50 %, 75 % and 100 % of gypsum plasterboard waste (GPW) with or without different heat treatments (with different temperatures and times) in gypsum plasters mixtures, concluded that water/gypsum ratio increased with the incorporation of this waste with or without heat treatments (with water/gypsum ratio of 0.55 for reference mortar). However, the addition of unheated gypsum-based waste (with water/gypsum ratio of 1.0–1.3) promoted a higher increase of water/gypsum ratio compared with the addition of the different heated gypsum-based wastes (with temperature of 100 °C for 6 h and 24 h and of 150 °C for 3 h and 6 h and with water/gypsum ratio of 0.7–1.0). In the present study, the addition of heated gypsum plasterboard waste (GPWh) to earth mortars also increases their water content to maintain workability. Nevertheless, this increase was higher with the addition of heat-treated waste (GPWh) than untreated (GPW), contrary to what was obtained by Pedreño-Rojas et al. [29]. This difference can be related to the combination of gypsum with earth when mixing the earth-based mortar or the bassanite content present in the gypsum plasterboard waste analysed in the present study.

3.2. Visual observation

In Fig. 5 it is possible to observe the difference in colour of earth mortars promoted by the addition of raw hemihydrate (G) and gypsum plasterboard waste (GPW and GPWh). The earth mortar without additions (E) presents a brownish colour like the earth's colour. The addition of gypsum-based materials (raw or waste) causes a slight lightning of the brownish colour of the earthen mortar, compared to the reference mortar (E), due to the whiter colour of the gypsum. Nevertheless, it is considered that the influence of the addition of gypsum-based materials on the colour of the mortars is not significant. No biological growth is visually observed.

Due to the fast-setting time of the raw gypsum (G – hemihydrate, see section 2.1.1), the prismatic specimens of the earth mortars with the addition of 10 % and 20 % of raw gypsum (E+10G and E+20G) were not very homogeneous: the specimens showed big voids (Fig. 6). So, these specimens cannot be used for all the characterization tests of these mortars: only its visual observation and linear shrinkage test were performed. These results reflect the reduced opening time of E+10G and E+20G mortars, and the need to add a retarder when using this binder as an addition to earth mortars. Increasing the water content in these mortars does not seem viable as that would probably lead to increased mortar's shrinkage.

Lima et al. [22] analysed illitic earth mortars with the addition of 5 %, 10 % and 20 % (in volume) of raw hemihydrate, by the same production method, with water content of 20–25 % (in volume) and without setting retarder, having obtained homogeneous specimens for the mortars analysed, which did not happen in the present study. Here, the mortars with addition of raw hemihydrate have water content in the same range (Table 3); so, this factor cannot justify the failure to obtain homogeneous specimens in E+10G and E+20G mortars. The difference can be due to the type of earth used in the two studies or a faster production of specimens from Lima et al. [22]. However, in another study, Lima et al. [23] analysed a pre-mixed illitic earth mortar and added 20 % of hemihydrate together with a setting retardant. In the present study, to avoid adding a variable when comparing the influence of using raw gypsum (hemihydrate) or gypsum-based wastes (unheated or heated), it was decided not to add a setting retardant to the mortars.

It is important to note that, although the water/binder ratio influences the plasters' setting time, other factors can accelerate its hydration reactions: water temperature, raw material, procedure used on the plaster production, or the energy used to mix the plaster mixture [62].

Although the heated gypsum-based plasterboard waste (GPWh) is also mostly composed by hemihydrate (Table 2), such as G, the same behaviour does not occur in mortars with addition of 10 % and 20 % of GPWh. Soluble anhydrite is known to be an accelerator of the hydration [63]. This can justify the faster hydration of mortars with addition of G, since they have a higher amount of anhydrite compared to GPWh (Table 2).

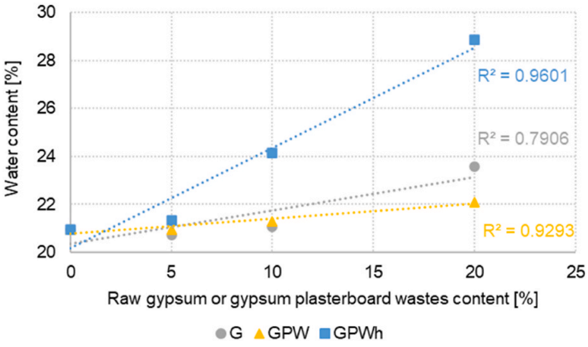

Fig. 4. Relationship between the water content of mortars to ensure workability, the gypsum-based types (G and GPWh – hemihydrate, GPW – gypsum) and content added.

Fig. 5. Colour of mortars with 0 %, 5 %, 10 % and 20 % vol. addition of G, GPW and GPWh. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 6. Specimens of the reference earth mortar (E) and earth mortars with 5 %, 10 % and 20 % vol. of raw hemihydrate (G), showing the lack of compactness of the ones with higher content.

3.3. Linear shrinkage

The linear shrinkage of mortars, qualitatively and quantitatively, is presented in Figs. 7 and 8, respectively. This is different to what commonly occurs on gypsum mortars that often expands and are frequently added air lime, associated to shrinkage, to equilibrate dimension variation [64]. It is possible to conclude that the linear shrinkage of earth-based mortars increases with increasing hemihydrate or gypsum (raw – G, or wastes – GPW and GPWh) content (Fig. 8a and b). This can be justified by the increase of water content necessary to guarantee the workability of earth-based mortars with higher gypsum-based binder content. The earth-based mortar with addition of 20 % of heated gypsum plasterboard waste (E+20GPWh) presents the highest linear shrinkage, but also the highest water content (see 2.2.1), which may justify the higher linear shrinkage.

3.4. Dry bulk density and thermal conductivity

The dry bulk density and thermal conductivity of the mortars are presented in Fig. 9. No clear linear relationship between raw or wastes gypsum-based (hemihydrate – G and GPW – or gypsum – GPW) binder content and the dry bulk density and thermal conductivity of the mortars can be observed. The dry bulk density shows little variation amongst the mortars, with all the mortars within a range of 0.04 kg/m^3 from each other (1.70–1.74 kg/m^3).

Considering the standard deviation associated with the results, there is no significant change in the thermal conductivity with the addition of gypsum-based materials (G, GPW and GPWh). Only the E+20GPWh mortar presents a lower result compared to other mortars. This can be justified by the higher water content of this mortar compared to the others.

Analysing the mortars with additions of hemihydrate and gypsum (GPW and GPWh, unheated and heated waste), it is observed that the same trend occurs: the thermal conductivity increases from 5 % to 10 % and decreases from 10 % to 20 %. Furthermore, the earth mortars with addition of 10 % and 20 % of GPWh present lower thermal conductivity compared with the similar mortars with GPW. This can be justified by the water content of the mortars and, consequently, by their porosity, since mortars with GPWh (hemihydrate) have a higher water content compared to mortars with GPW (gypsum).

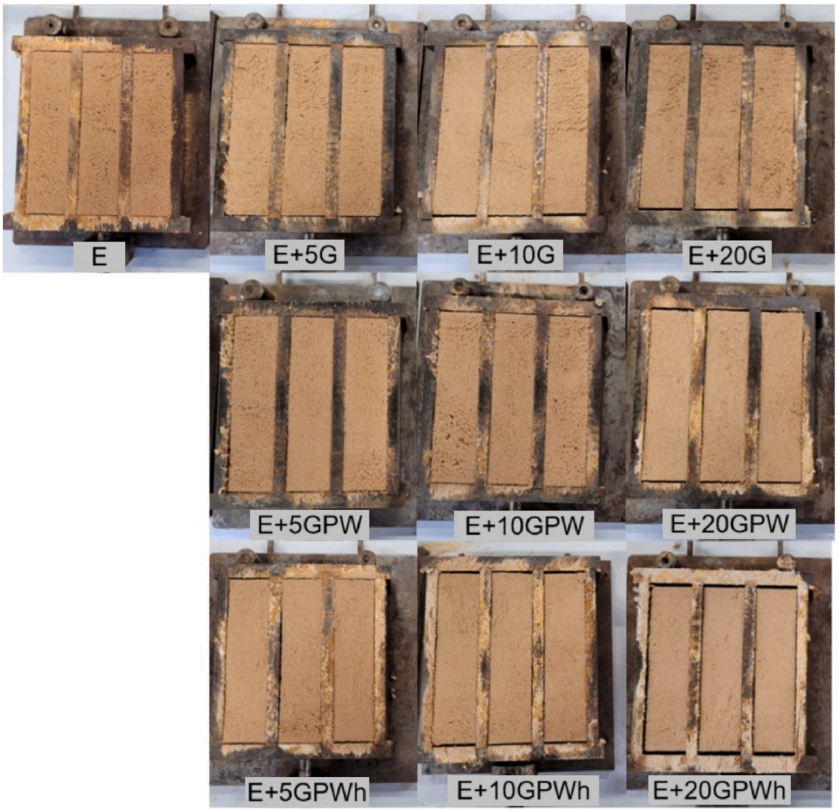

Fig. 7. Observation of the specimens' shrinkage in the moulds, showing the shrinkage increase with gypsum-based binder contents.

Comparing the dry bulk density and thermal conductivity of the plasters, there is no clear relationship between them, and the expected trend is not observed: an increase in thermal conductivity with an increase in the dry bulk density, and vice-versa. Only the plasters with addition of 5 % G and 10 % GPWh followed the expected trend of direct proportionality between dry bulk density and thermal conductivity. However, it is necessary to consider that there is no significant change in the dry bulk density of the plasters (remains approximately 1.7 kg/dm^3) that could influence the thermal conductivity of the plasters. The changes observed in the thermal conductivity of plasters may be related to their porosity and the dimension of the existing pores, since dry bulk density was determined in prismatic specimens (with mechanical compaction) and the thermal conductivity was determined in cylindrical specimens (with manual compaction). However, this characteristic has not been determined for confirmation. Furthermore, the possible different moisture content inside the specimens may have an influence on the results obtained, since the tests were carried out under ambient conditions.

3.5. Dynamic modulus of elasticity, flexural and compressive strength

The dynamic modulus of elasticity and flexural and compressive strengths of mortars are presented in Fig. 10. The addition of 5 % of hemihydrate (G) and of 5 %, 10 % and 20 % of plasterboard waste (gypsum GPW or hemihydrate GPWh) promoted an increase in the dynamic modulus of elasticity of the mortars compared to the reference one. The same occurred for the flexural and compressive strengths, except for the E+10GPWh mortar that presents lower compressive strength than the reference earth mortar (E).

Analysing the influence of the addition of each type of gypsum-based material on the flexural strength of earth mortars, it is possible to conclude that the addition of 5 % of unheated (gypsum) or heated (hemihydrate) gypsum plasterboard waste (E+5GPW and E+5GPWh) promotes a slight increase compared to the reference mortar (E). Compared to the mortar with 5 % of raw hemihydrate (E+5G), the results are similar, which demonstrates good behaviour of gypsum-based waste (GPW and GPWh) compared to the raw material (G). Therefore, unheated (GPW) and heated (GPWh) gypsum plasterboard waste does not significantly influence the flexural strength of the earth mortars, whatever the percentage of addition. In this way, the type of gypsum (hemihydrate – GPWh – or hydrate – GPW) does not influence the flexural strength of the earth mortars. This is a good indicator, demonstrating that, to obtain similar characteristics, there is no need to heat treat the gypsum waste, thus reducing the energy consumed.

In the case of compressive strength, the results follow this trend for mortars with the addition of 5 % of raw or wastes gypsum-based (hemihydrate – G and GPWh – or gypsum – GPW) binders: they increase compressive strength, compared to the E mortar, but the results are similar between them. However, it appears that the behaviour of mortars with the addition of unheated (GPW) and heated

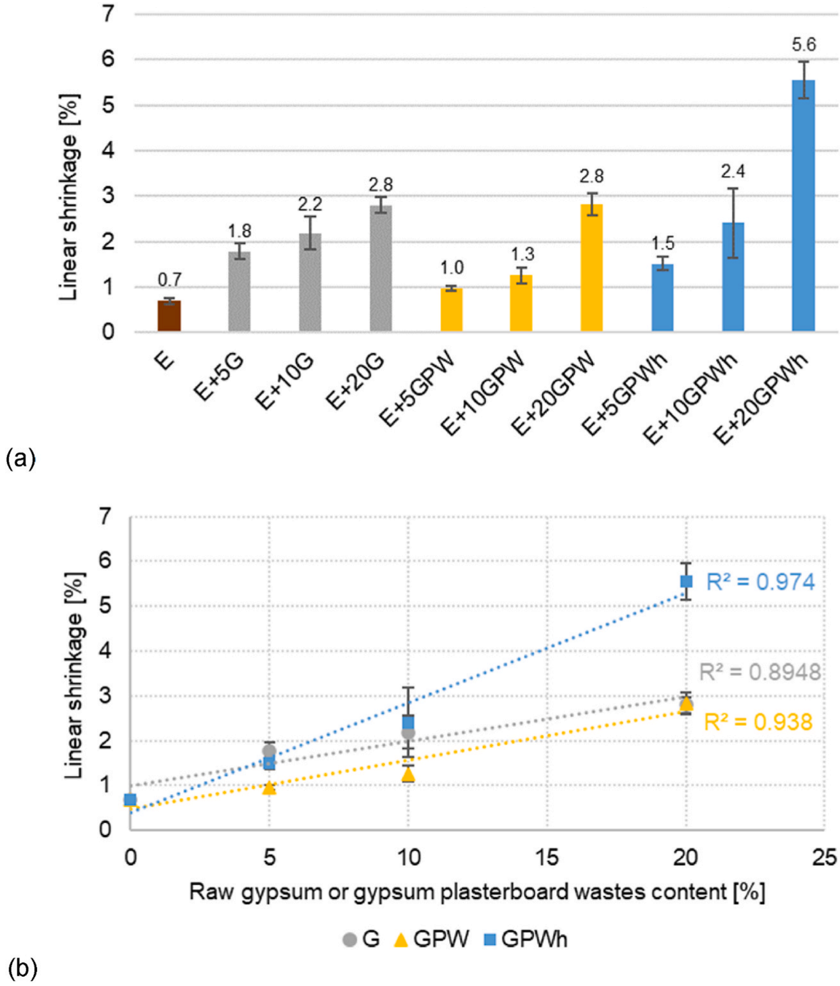

Fig. 8. Linear shrinkage of mortars: average and standard deviation (a) and relationship between the gypsum type (G and GPWh – hemihydrate, GPW – gypsum) and content, and linear shrinkage of mortars (b).

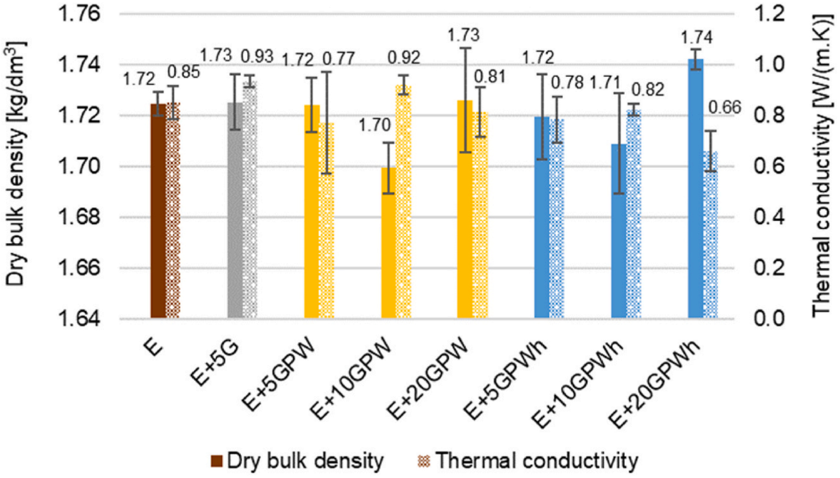

Fig. 9. Dry bulk density and thermal conductivity of mortars: average and standard deviation.

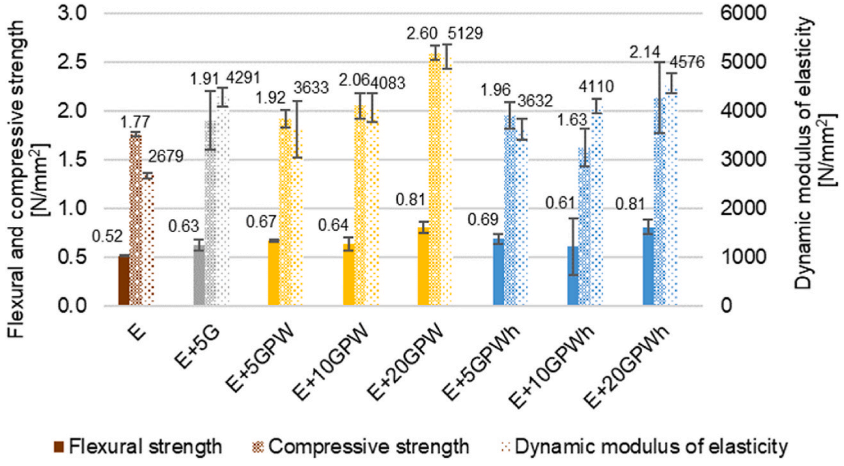

Fig. 10. Dynamic modulus of elasticity and flexural and compressive strengths of mortars: average and standard deviation.

(GPWh) gypsum-based plasterboard waste is not maintained. The compressive strength increases with increasing percentage of GPW addition, while in the case of GPWh addition this does not occur as the addition of 10 % of GPWh decreases the compressive strength compared to the addition of 5 % of GPWh. The E+10GPW mortar has a higher compressive strength (2.06 N/mm^2, more 16.4 %)

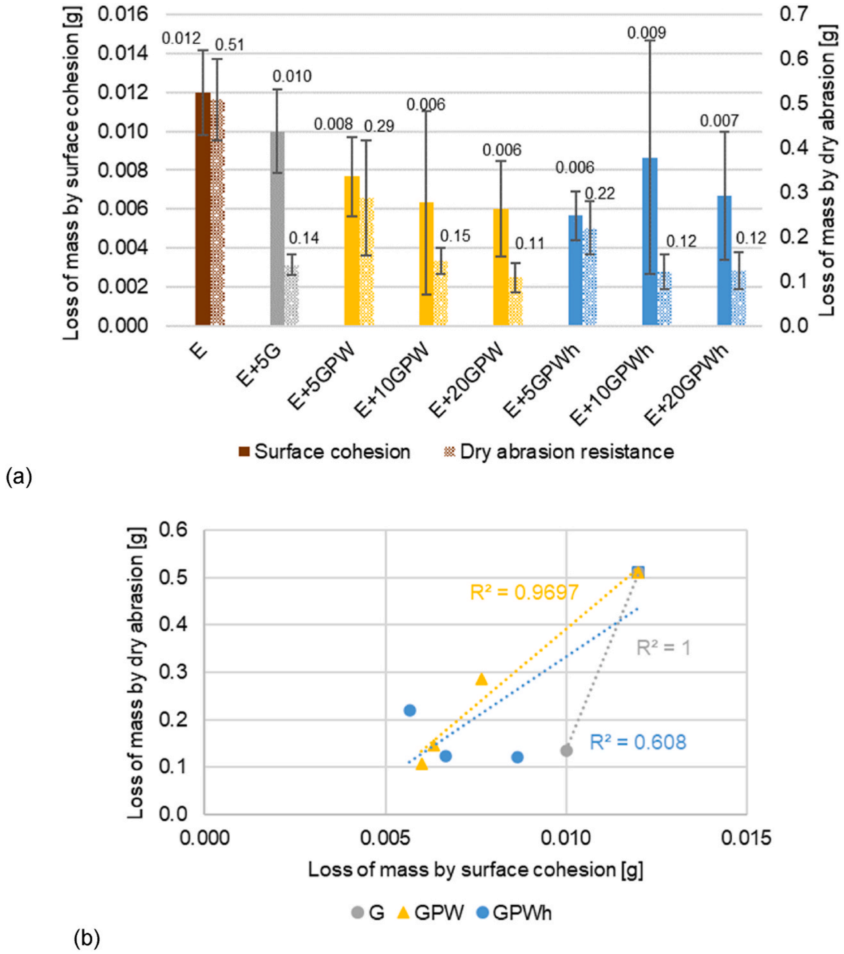

Fig. 11. Loss of mass by surface cohesion and by dry abrasion of plasters: average and standard deviation (a) and relationship between loss of mass by dry abrasion and by surface cohesion (b).

compared to the reference mortar (1.77 N/mm^2), while the E+10GPWh mortar has a lower strength (1.63 N/mm^2, less 7.8 %). This decrease on the strength of the mortar with 10 % of GPWh compared to the addition of 5 % was already seen in the flexural strength (although less significant). Finally, mortars with addition of 10 % and 20 % of GPWh present lower compressive strength than mortars with the same percentages of GPW addition: the E+20GPW mortar has a much higher compressive strength (2.60 N/mm^2, more 47.1 %) than the reference mortar, and higher when compared to the E+20GPWh mortar (2.14 N/mm^2, more 21.1 %). This may demonstrate that the heat treatment of gypsum-based waste, and consequently the higher water content to maintain workability, may not significantly influence the flexural strength of the mortars but influences its compressive strength. The high water content in mortars with the addition of 10 % and 20 % of GPWh could have led to the existence of more pores or larger pores in these mortars, or in the tested area of the specimens, promoting this lower compressive strength of the mortars. A weak bond between the hemihydrate (GPWh) and the type of clay used, associated with the water content used, could also justify this lower compressive strength compared with mortars with addition of gypsum (GPW).

When Pedreño-Rojas et al. [29] investigated the influence of the heating process (at 150 °C at 3 h) on the use of recycled gypsum in plasters, researchers confirmed that recycled gypsum plasterboard waste without any heating process (with water/gypsum ratio of 1.0–1.3) can substitute 100 % of commercial gypsum (hemihydrate, with water/gypsum ratio of 0.55), even improving its mechanical strength characteristics relative to commercial gypsum. In the present study, this can be confirmed with the specimen produced with 20 % unheated recycled gypsum plasterboard waste (E+20GPW), resulting in the mortar with the highest compressive strength and

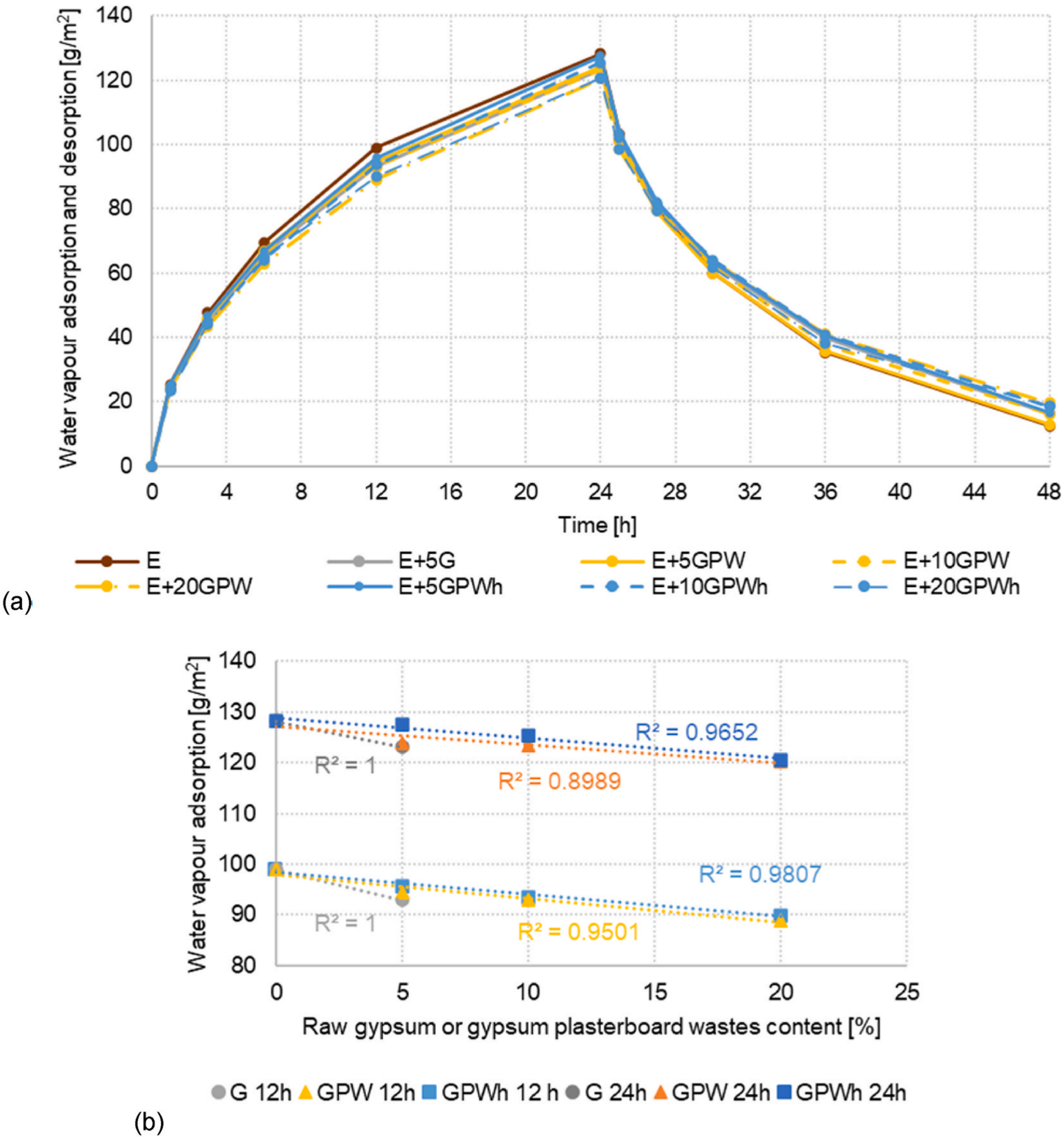

Fig. 12. Water vapour adsorption and desorption of plasters (a) and relationship between the gypsum type (G and GPWh – hemihydrate, GPW – gypsum) and content, and water vapour adsorption of plasters, after 12 h and 24 h (b).

amongst the highest in flexural strength and dynamic modulus of elasticity.

3.6. Surface cohesion and dry abrasion resistance

The surface cohesion and dry abrasion resistance of earth plastering mortars is presented in Fig. 11a. As for surface cohesion, the higher the mass loss verified, the lower the surface cohesion of the plasters. It is possible to conclude that, as expected, the addition of hemihydrate (G) and plasterboard waste (gypsum – GPW – and hemihydrate – GPWh) promote a reduction in the loss of mass by surface cohesion of the plasters compared to the reference plaster (E), that is, these additions improve the surface cohesion of the plasters. However, there was no significant change (considering the associated standard deviations) in the surface cohesion of the plasters, especially in plasters with the addition of G, GPW and GPWh. There is no clear relationship between the percentage of addition and surface cohesion.

Analysing the loss of mass by dry abrasion of the plasters, it is possible to conclude that the addition of gypsum-based binders (hemihydrate – G and GPWh – or gypsum – GPW) promoted a decrease of loss of mass by dry abrasion, which means an improvement in dry abrasion resistance.

Dry abrasion resistance, as well as the surface cohesion of plasters, are important properties in the life cycle of plasters. There is a relationship between the loss of mass by dry abrasion and by surface cohesion (Fig. 11b). The results obtained demonstrate that the addition of gypsum-based binders improves these characteristics. There is good behaviour in the plasters with gypsum plasterboard waste (GPW and GPWh), with no significant differences between the unheated and heated product, which demonstrates good performance of unheated gypsum plasterboard waste.

3.7. Water vapour adsorption and desorption

The water vapour adsorption and desorption curves of plastering mortars are presented in Fig. 12a. It is possible to conclude that the addition of gypsum-based binders (G, GPW and GPWh) promotes a slight decrease in the water vapour adsorption capacity of the plasters compared to the reference one, verifying a relationship between the increase of binder content and the decrease in water vapour adsorption capacity (Fig. 12b). This small decrease of water vapour adsorption capacity of earth plasters with these additions (less than 10 g/m^2) is a good indicator, not negatively affecting their good hygroscopic capacity.

Analysing the addition of different gypsum-based materials (G, GPW and GPWh) and the same percentage of addition (5 %), the addition of raw hemihydrate (G) causes the greatest loss of water vapour adsorption capacity (93.0 g/m^2 for 12 h and 123.1 g/m^2 – less 3.9 % – for 24h for E+5G, compared to E) comparing with plasters with unheated (GPW – gypsum) and heated (GPWh – hemihydrate) gypsum plasterboard waste (94.4 g/m^2 for 12 h and 124.0 g/m^2 for 24h for E+5GPW, and 95.8 g/m^2 for 12 h and 127.5 g/m^2 for 24h for E+5GPWh). The earth plasters with additions of 5 % of gypsum plasterboard waste (GPW and GPWh) present similar adsorption capacity and a slightly lower variation of that capacity compared with the reference one. After 12 h, the E, E+5GPW and E+5GPWh plasters present adsorption of 98.9 g/m^2, 94.4 g/m^2 and 95.8 g/m^2, respectively, and, after 24h, 128.2 g/m^2, 124.0 g/m^2 (less 3.3 %) and 127.5 g/m^2 (less 0.5 %), respectively. Earth plasters with three different percentages of addition (5 %, 10 % and 20 %) of unheated (gypsum) and heated (hemihydrate) gypsum-based plasterboard waste present similar water vapour adsorption capacity, although the plasters with 20 % of GPW and GPWh present the lowest adsorption capacity compared to the reference (120.4 g/m^2 and 120.6 g/m^2, less 6 % compared to E, after 24 h, for E+20GPW and E+20GPWh, respectively). Therefore, it is possible to conclude that the heat treatment of the gypsum waste, and, consequently, the type of gypsum (hemihydrate – GPW – and gypsum – GPWh) does not influence the adsorption (and desorption) capacity of the plasters, which is a positive indicator.

In the desorption phase, it is possible to observe in Fig. 12a that all the plasters present hysteresis, i.e., none of them released all the water vapour that they adsorbed. The E plaster (reference) is the one with the lowest amount of desorbed water vapour (12.5 g/m^2) after 24 h. However, the E+5GPW plaster showed a very similar amount of desorbed water vapour (12.8 g/m^2) for the same test period.

Finally, it is possible to observe that, after 24 h, all the plasters, with or without the addition of raw or wastes gypsum-based (hemihydrate – G and GPWh – or gypsum – GPW) binders, show a still increasing trend of the water vapour adsorption curve and not a tendency towards stabilization. The same happens in the desorption phase. For this reason, it is predicted that, if the test is continued for a longer time, the water vapour adsorption and desorption results could show higher hygroscopic capacity to capture and release moisture.

3.8. Resistance to contact with liquid water

As expected, the gypsum-based binders' additions (hemihydrate – G and GPWh – and gypsum – GPW) improves the resistance to contact with liquid water of the plasters compared to the reference plaster without additions (degraded in less than 1 min): after 18 min of contact with water, all samples of all plasters had degraded, except for plasters with addition of 10 % and 20 % of GPWh (E+10GPWh and E+20GPWh), which remained without degradation until the water in the *Petri* dish was completely evaporated.

4. Conclusions

Currently, it is very important to rethink the way construction and rehabilitation are carried out to increase their sustainability. In this sense, it is increasingly important to use environmentally friendly building materials, such as earth. On the other hand, it is important to think about the end of life of some of the building materials currently used. In that regard, the present study evaluates the influence of using grinded gypsum-based plasterboard waste as 5 %, 10 % and 20 % (vol. of total of solids – clayish earth and sand) additions on earth mortars formulations, and of using the same waste but after being thermally treated (heated) for 1 h at 150 °C. The corresponding mortars were compared with the same additions of raw hemihydrate and with a reference earth mortar (without additions). With the results obtained, it can be concluded that:

- Increasing of the hemihydrate or gypsum content (raw, gypsum waste from plasterboards just crushed or after submitted to additional thermal treatment) requires an increase in water content to maintain the workability of the earth-based mortars.
- The fast-setting time of the mortars with 10 % and 20 % additions of raw hemihydrate leads to the production of a mortar that quickly loses its workability and, consequently, the specimens are produced with big voids; experimentally, that does not allow to perform a good characterization, and, *in situ*, that would not allow a good applicability. In future works, the influence of a setting retardant should be evaluated in these mortars. This is not as pronounced in mortars with gypsum-based plasterboard waste, which is very positive.
- The addition of hemihydrate (G and GPWh) and gypsum (GPW) increases the linear shrinkage of mortars, which may be related to the increase in water content. The addition of 5 % of gypsum-based plasterboard waste (E+5GPW and E+5GPWh) has less impact on the linear shrinkage of earth-based mortars compared to the ones with the same percentage of raw hemihydrate addition, despite having the same water content. The addition of 20 % of heated (hemihydrate) gypsum plasterboard waste has the highest impact of all analysed mortars and this can be due to the highest water content of this mortar.
- The addition of hemihydrate or gypsum (raw or waste) does not influence the dry bulk density of the mortars.
- There is also no relationship between the added hemihydrate or gypsum (raw or waste) content and the thermal conductivity of the mortars. The raw hemihydrate, and both the unheated (gypsum) and heated (hemihydrate) gypsum from plasterboard waste, do not have a significant influence on the thermal conductivity of the earth-based mortars. However, earth mortars with 20 % of GPW and GPWh have less thermal conductivity compared with mortars with 10 % of the same gypsum-based materials. It is important to refer that, as thermal resistance is obtained by the quotient of the plaster thickness by its thermal conductivity and considering the low thickness of common plasters (1–2 cm), the variation obtained in the thermal conductivity is not significant for a wall's thermal resistance.
- In general, the flexural strength of the earth mortars increases with the addition of hemihydrate or gypsum (raw or waste). The type of gypsum (hemihydrate or gypsum) does not influence the flexural strength of the earth mortars. As for compressive strength, an increase is verified with the increase of the added hemihydrate or gypsum (raw or waste) content. However, there is a loss of compressive strength with the addition of 10 % heated (hemihydrate) gypsum-based plasterboard waste.
- The surface cohesion and dry abrasion resistance of earth plasters improve with the addition of gypsum-based binders. These additions also improve the resistance of plasters to contact with liquid water, which is a good indicator.
- Comparing all earth-based plasters, the addition of gypsum-based materials (raw or waste) reduced a maximum of approximately 8 g/m^2 of adsorbed water vapour, after 24 h. Therefore, concerning the adsorption capacity, no significant influence of the additions of raw hemihydrate (G), unheated (GPW, gypsum) and heated (GPWh, hemihydrate) gypsum plasterboard waste is verified, i.e., the type of gypsum does not influence the adsorption capacity when these mortars are used for plastering. In this way, these additions will not influence the good hygroscopic performance of the earth-based plasters and, consequently, the passive moisture buffering performance when they are applied in buildings.

The results shows that it is possible to improve the mechanical performance, and shows signs of improvement when contact with water, of earth-based plasters with the addition of gypsum-based waste from plasterboards (hemihydrate or gypsum), without a significant drawback on the hygroscopic capacity, both for adsorption and desorption. It seems that this waste can be just crushed, after removing the paper, and used to stabilise earth mortars, with no advantage for being thermally treated. This is important to ensure, by an eco-efficient addition, a good performance when applying these mortars to plaster indoor walls and ceilings, both for durability and acting as moisture buffers. Finally, the gypsum-based binders' additions analysed show signs of improvement when in contact with water. These results justify performing complementary characterization to fully understand the effect of adding gypsum waste from plasterboards on the formulation of earth-based plasters, namely when in contact with water. In future works, it is recommended to further evaluate the effect of these additions on the durability of earth-based plasters, namely resistance to weathering and biological growth over time, as well as the influence on the microstructure and to quantify the plasters life cycle analysis.

CRediT authorship contribution statement

Tânia Santos: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Nienke Wulani Luijten:** Writing – review & editing, Writing – original draft, Investigation. **António Santos Silva:** Writing – review & editing, Validation, Methodology. **José Dinis Silvestre:** Writing – review & editing, Supervision. **Paulina Faria:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

Nothing to declare.

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Data availability

Data will be made available on request.

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