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Towards the development of performance-efficient compressed earth blocks from industrial and agro-industrial by-products

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ABSTRACT

This work addresses the development of compressed earth blocks with high quality using stabilizers and reinforcements of industrial and agroindustrial by-products. A critique of the production of compressed earth blocks using new mixtures, compositions, and characteristics required for adequate performance according to different construction standards is included. Furthermore, the effect of adding stabilizers and reinforcements from industrial and agro-industrial by-products on strength, durability and thermal insulation is evaluated. Fibers improve tensile and crack resistance while stabilizers enhance cohesion of mixtures, originating new compounds with higher compressive strength and lower permeability. Finally, the main prediction tools for engineering design and application of compressed earth blocks in building are discussed. The main findings and research gaps identified provide a baseline for future research projects focused on the transition to a low-carbon future through the production of compressed earth block.

1. Introduction

The construction sector accounts for 38% of global CO_2 emissions, of which 16% represents embodied carbon – CO_2 emissions from material sourcing, manufacturing, and construction activities. The importance of decarbonizing the construction sector through green buildings, bio-based and earth construction is vital. To address the transition to a low-carbon future set by the United Nations Framework Convention on Climate Change, a low-energy earth building element is proposed and assessed in this work. Particularly, compressed earth construction is one of the most important and promising low-impact construction techniques. Compressed earth blocks (CEBs) and bricks are the material of choice in many building types and functions. CEBs have excellent mechanical, physical and thermal properties that can make robust walls and structures with high thermal inertia and resist fire. Therefore, this research aims to provide an overview of CEBs manufactured from industrial and agro-industrial by-products. Particular interest is on the manufacturing of performance efficient compressed earth block, with good reported characteristics validated by testing and reported optimal constituents. The first specific objective is to determine main manufacturing parameters that dominate the stability, performance, quality, and durability of CEBs. The second objective is to determine the main properties required to validate and assessed the development of new CEBs with high quality. The last objective is to clarify the main reported constituents and their effect on CEB performance for optimal

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Nomenclature

Abbreviations

CCR	Calcium carbide residue
CDW	Construction and demolition waste
CEB	Compressed earth block
CFRP	Carbon fiber-reinforced polymer
CSEBs	Compressed stabilized earth blocks
ESP	Eggshell powder
FA	Fly ash
FCB	Fired clay bricks
FEM	Finite element modeling
GBFS	Granulated blast furnace slag
GOS	Ground olive stones
GSB	Geopolymer-stabilized blocks
ICEBs	Interlocking compressed earth blocks
ICSEBs	Interlocking compressed stabilized earth blocks
LOI	Loss on ignition (wt.%)
MS	Manufactured sand
OPC	Ordinary Portland cement
PI	Plasticity index (%)
QD	Quarry dust
SDA	Sawdust ash
RHA	Rice husk ash
SEM	Scanning electron microscope

Notations and units

D	Average fiber diameter (m)
L	Average fiber length (m)
α_f	Fiber/matrix mass ratio (%)
δ	Interphase thickness (m)
ε	Strain (%)
φ	Porosity (%)
ρ	Density (kg/m^3)
σ	Stress (MPa)

mixtures.

The use of soil as a building material for housing has been present since the beginning of society as a civilization. Different communities have constructed buildings based on the materials indigenous to their areas, so it is possible to find various types of these dwellings throughout history. Raw earth is the most widely used building material in the world, particularly in less developed countries. Estimating the current proportion of earthen houses worldwide is not straightforward. In 2012, Jaquin et al. [1] reported that one-third of the global population lived in houses made of earth. In 2015, based on an estimation by the United States Department of Energy [2], Pacheco et al. [3] reported that between 33% and 50% of the world's population lived in dwellings built with earth. In 2019, based on Vega et al. [4], Costa et al. [5] stated that one-third of the world population lives in earthen constructions. Currently, based on UNESCO statistics, Jannat et al. [6] stated that 40% of the world's population lives in earthen houses, while Hasan et al. [7] approximate this value to at least 50% of the population. In developing countries, this percentage increases, concentrated mainly in Africa, Latin America, the Middle East, the Indian subcontinent, Asia, and Southern Europe. Other research indicates that in countries such as Cameroon there are localities with more than 95% of the traditional housing built with earth [8].

Additionally, using earth materials in construction, and mainly compacted earth, is gaining more interest due to the problems derived from construction, such as high energy consumption, and the environmental impact due to the high carbon emissions produced by traditional products [9–11]. The study by Ansah et al. [9] on the life cycle impact of facades with different materials reported that stabilized earth blocks are one of the most sustainable facade construction technologies concerning low embodied GHG emissions. The reduction found with stabilized earth blocks was 39% in cumulative energy demand, 18% in global warming potential and 48% in life cycle cost compared to the conventional concrete block and mortar facade. In this context, Shukla et al. [12] calculated an embodied energy of 720 GJ of 100 m^2 of conventional houses per 100 m^2 of built with unfired brick, concrete and cement. Compared to an adobe house of a similar floor area, a reduction of around 100 tons/year of CO_2 emissions to the environment was found. Similar CO_2 emission reduction results were found by Mateus et al. [13] when investigating rammed earth and compressed earth blocks, indicating that earth is an environmentally friendly building medium compared to conventional construction materials.

The significant global growth rate unquestionably drives sustainable construction and, in this context, compacted earth construction is a great and attractive alternative. Pacheco et al. [14] reported that the current research on sustainable earthen construction had increased ten times over those reported in the 1900s. This increase is mainly due to the unsustainability of conventional construction. In Pacheco et al. [14], it was also noted that progress is being made in regulations associated with earth construction, which shows the genuine interest in using this element in construction and its potential growth in the medium term. An example of the interest in using earth blocks and their use in the medium term is reflected in the research developed by Dorado et al. [15], who rigorously analyzes the feasibility of the implementation and development of construction technology with CEBs in Argentina. However, it also indicates that the current regulatory frameworks in Argentina are inadequate for the development of CEB technology, so more government attention is required.

The current trend of replacing cement with earth in construction is because earth is a renewable, simple, and environmentally friendly resource that contributes to sustainable development and the indoor comfort of the environment. In addition, earth is a natural resource with good insulation characteristics and low cost. Moreover, the increased use of industrial or agricultural waste materials to develop sustainable building materials is also based on the need to generate more ecological and economical alternatives. The development of compressed earth blocks with new additives and stabilizers from industrial or agricultural waste material has been employed and has experienced a significant increase and interest in the scientific community. In this context, the main objective of this work is to study, analyze and evaluate the feasibility of using compressed earth blocks stabilized with different additives with reused materials and wastes for the construction of walls and subsequent manufacture of sustainable, ecological, and economical housing. Therefore, this work provides a comprehensive review of the literature, addressing the characterization and manufacturing methodologies of CEBs, including the main challenges and recent advances obtained from the related research conducted in the last decades worldwide.

Compressed earth blocks (CEB) are obtained from wet soil compressed and compacted manually or mechanically, either statically [16] or dynamically [17], followed by immediate demolding [18]. It is a low-cost alternative [19] with reduced environmental impact since it uses local and natural raw materials [20,21]. In this context, CEB have been extensively studied in the last decade [22–24] and have been established as innovative building materials that constitute a modern or renewed version of molded earth blocks, better known as adobe blocks [25].

Several research teams are focused on understanding and optimizing the strength properties of CEBs subjected to different loading and environmental conditions. Among the most widely used properties and analysis parameters are compressive strength [26–28], flexural strength [29–31], water absorption [32–34], erosion resistance [35–37] and abrasion resistance [33,38]. Other studies also include the evaluation of the deformability of the CEBs [39–41], the thermal performance of the CEBs [42,43], the shrinkage during drying [38], the porosity [30,44], the volume variation [45,46] and even fire resistance [47,48], with emphasis on determining durability [37,49,50] and the increase of the service life [32,38] of the CEBs.

Compressed stabilized earth blocks (CSEBs) are good candidates to replace fired bricks due to the lower amount of energy required for their production, lower cost and lower carbon footprint [51,52]. Compared to cement concrete, CSEBs also require less embodied energy, with some authors indicating that only 1% of the production energy of cement concrete is required [53]. However, stabilization of CEBs and other earth-based construction materials is generally required to increase strength, durability and resistance to erosion and abrasion.

Several research studies have focused on adding stabilizers and reinforcements to improve the performance of blocks. For instance, Atiki et al. [54] incorporated date palm waste aggregates to improve the thermal insulation of CEBs. Elahi et al. [55] incorporated sawdust ash into CEBs to improve compressive strength. Kasinikota & Tripura [33] incorporated crushed brick waste into the blocks to improve abrasion resistance properties. The mentioned studies include a factorial analysis of the percentages of additives or components such as soil, sand, cement, reinforcement and natural stabilizer, providing an analysis of their effects and optimal proportions. To find a sustainable use for other wastes, polyethylene food containers have also been incorporated into the manufacture of the blocks [56], increasing the load resistance by up to 30%. Finally, stabilizing residues of fonio straw and shea butter have also been incorporated to improve the thermo-mechanical performance of CEBs [57].

From the need to generate more ecological and economical alternative constructive elements, this review work investigates the reuse of industrial or agro-industrial waste in the manufacture of sustainable CEBs. The main characteristics necessary to design and produce high quality CEBs in terms of strength, durability and thermal insulation are identified. A critique of the advances in the production of CEBs using new sustainable mixtures and compositions is included, as well as the current achievements and challenges in obtaining a block with adequate performance according to different construction standards. Finally, the main prediction tools for the design and application of CEBs in building walls are discussed and evaluated. The overview, synthesis, and analysis is based on several research studies on the development of compressed earth blocks (CEBs). Over the past 60 years, numerous research studies have been conducted on CEBs, especially on their material properties. However, almost none of those studies have conducted an exhaustive review of the evaluation of the mechanical, chemical, and physical properties of CEBs with agro-industrial by-products. Parameters such as soil types, reinforcements and stabilizers, optimum constituent contents, types of characterization tests, codes and standards are included, examining more than 120 references and covering research in CEBs in most geographical areas of the world.

The main contribution of this study lies in the establishment of a baseline and the updated development of compressed earth blocks with improved strength and durability from stabilizers and reinforcements from agro-industrial waste. The importance of this work is the potential contribution of CEBs to the construction industry, its interesting ecological and economical option for sustainable, and low-carbon construction. Special attention is given to the optimal mixtures to obtain a high performance CEB in terms of strength. Research and climate change policy makers should consider the important practical implications of this work, because while some reports may indicate that CEB units are not applicable in certain areas or countries, other strategies and new manufacturing methods could demonstrate the applicability of this clean technology to the building industry.

This review is structured in four sections. Section 2 presents the research methodology, materials and manufacturing methods of CEBs including the main evaluated properties. The results, analysis and discussion from a comprehensive number of studies focusing on stabilizers and reinforcements of CEBs from different industries are given in Section 3. This section also analyzed the models available for prediction of the load response of CEBs and CEB walls. Finally, Section 4 presents an overall analysis and discussion, as well as the main conclusions, trends, current challenges, and prospects for the future development of performance efficient CEBs research.

2. Material and methods

2.1. Bibliometric analysis of CEB research and the use of industrial and agro-industrial by-products

The development of sustainable materials is currently undergoing a resurgence in order to mitigate global warming caused by the excessive emission of greenhouse gases, such as CO2. In addition, government laws, waste revaluation incentives and the growing interest of users in sustainable and environmentally friendly products make this industry an attractive sector for public and private investment. It is for this reason that this study seeks a viable and sustainable alternative to conventional construction elements such as concrete blocks or fired bricks. The use of compressed earth blocks improved in strength and durability with stabilizers and reinforcements has grown considerably in recent years. Particularly, due to high and increasing agro-industrial waste accumulation, the natural fibers and stabilizers are an interesting ecological and economical option for their sustainable use and the reduction of the carbon emissions from construction sector. In addition, the reuse of other industrial stabilizers also assessed and included in this work.

The bibliographic search of selected scientific reports for this study such as research papers, progress reports, communications and review papers is achieved and performed using different online scientific information services, web search engines or database platforms such as Google Scholar, Web of Science, Scopus and other digital resources available at the Universidad de La Frontera library. From the different databases, the analyzed articles are extracted from publications containing the selected keywords for an effective search: Compressed earth blocks, CEB, Stabilized earth blocks, CEBs, Pressed earth blocks, Compressed earth bricks, Stabilizers, Additives, Natural stabilizers, Stabilizers natural agro-industrial product and natural agro-industrial product. Besides, a specific verification of the results was performed in order to ensure that the works found discussed compressed earth blocks. For this review, an advanced Boolean search by subject and keywords was performed in the Web of Science Core Collection. Among the selected keywords, the following were used: ≪ AK = " compressed earth block” OR AK = "compressed earth blocks” OR TS = "compressed earth block” OR TS = "compressed earth blocks” OR AK = "compressed earth brick” OR AK = "compressed earth bricks” OR TS = "compressed earth brick” OR TS = "compressed earth bricks"≫.

It should be noted that research on CEB mostly consists of evaluating the mechanical performance of CEB, followed by chemical and physical evaluation. Furthermore, a growing trend has been determined in research on stabilizers incorporated into CEBs. In Fig. 1, the reported studies were first classified into two main groups: agro-industrial by-products for reinforcement and stabilizers, and industrial residues for stabilizers.

The evolution of the reported works in scientific journals indexed and included in the core collection of Web of Science (WoS) is presented in Fig. 2. The review and analysis provided in this work is based on and limited to these reported publications. A progressive increase of the growing interest in CEB research from 1997 to July 2022 with respect of publications and citations on this topic is shown in Fig. 2. The percentage distribution of countries publishing on this topic is also given, and France leads this list with a 13.3 of the total publications. This

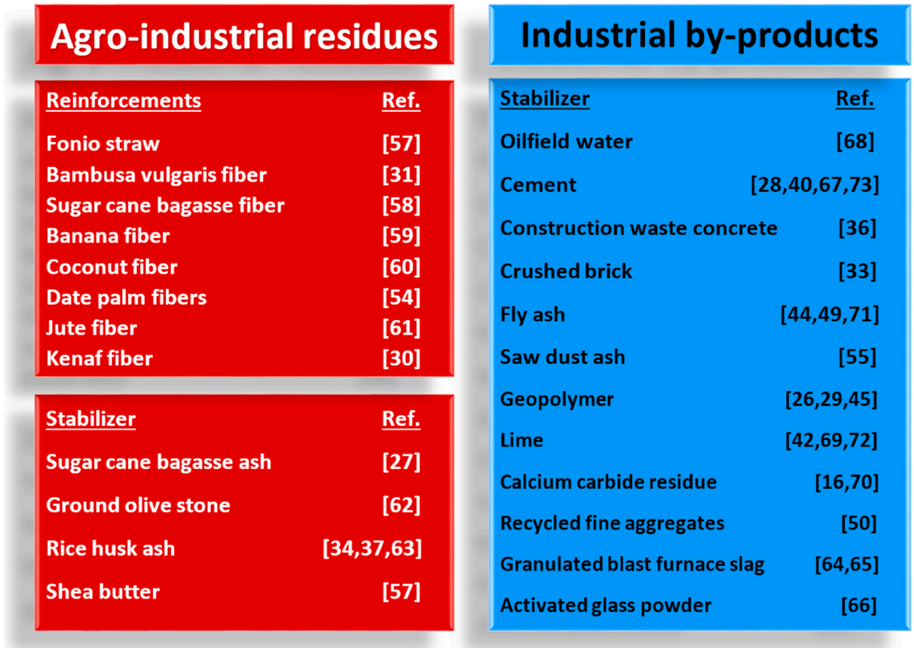

Fig. 1. Stabilizers and reinforcements from agro-industrial and industrial by-products.

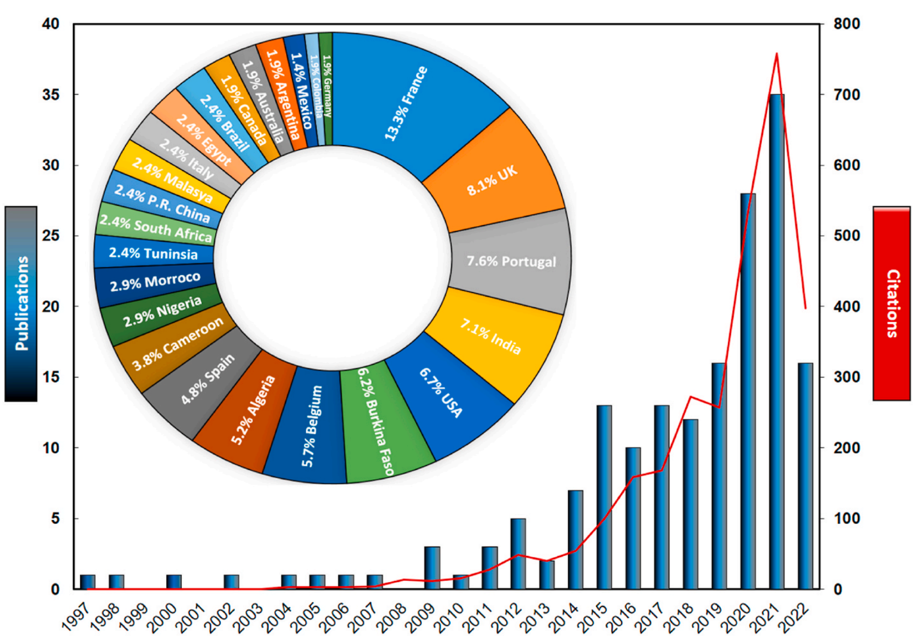

Fig. 2. Publications and citations of articles focused on CEBs from 1997 to July 2022, including proportions by country.

determined growing trend on the study and development of sustainable CEB in the last ten years demonstrates the interest of the global scientific community in improving this construction unit.

2.2. Materials and manufacturing methods of compressed earth block

Compressed earth blocks (CEB) correspond to ecological and innovative construction elements whose manufacturing method is based on the mixing of soil with certain proportions and different particle sizes of its components gravel, silt, sand, clay, and water. After being mixed, compression in a wet state in molds of parallelepiped shape is applied as described in Fig. 3. Several types of CEB shapes can be produced as units for different construction requirements. The most commonly found shapes are standard block and hollow block as shown in Fig. 4. The perforations reduce the weight of the block and are useful for the installation of reinforcements. To improve stacking and joining the masonry units, indentations are also applied to the top and bottom surfaces of the CEBs. It should be noted that different codes such as BIS: 1982; ARSO: 1996; AFNOR: 2001; ICONTEC: 2004; NMAC, 2016; AENOR, 2008; ASTM E2392, 2016; and IS 1725: 2013 suggest a minimum dry compressive strength of 2 MPa for CEBs. Other standards, such as NMX-C-404-ONNCCE: 2012; SLS 1382: 2009, indicate a range higher than 7 MPa, demonstrating a lack of universally accepted standardization [74]. The reader is referred to the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) for more details on different standardizations specific to earth

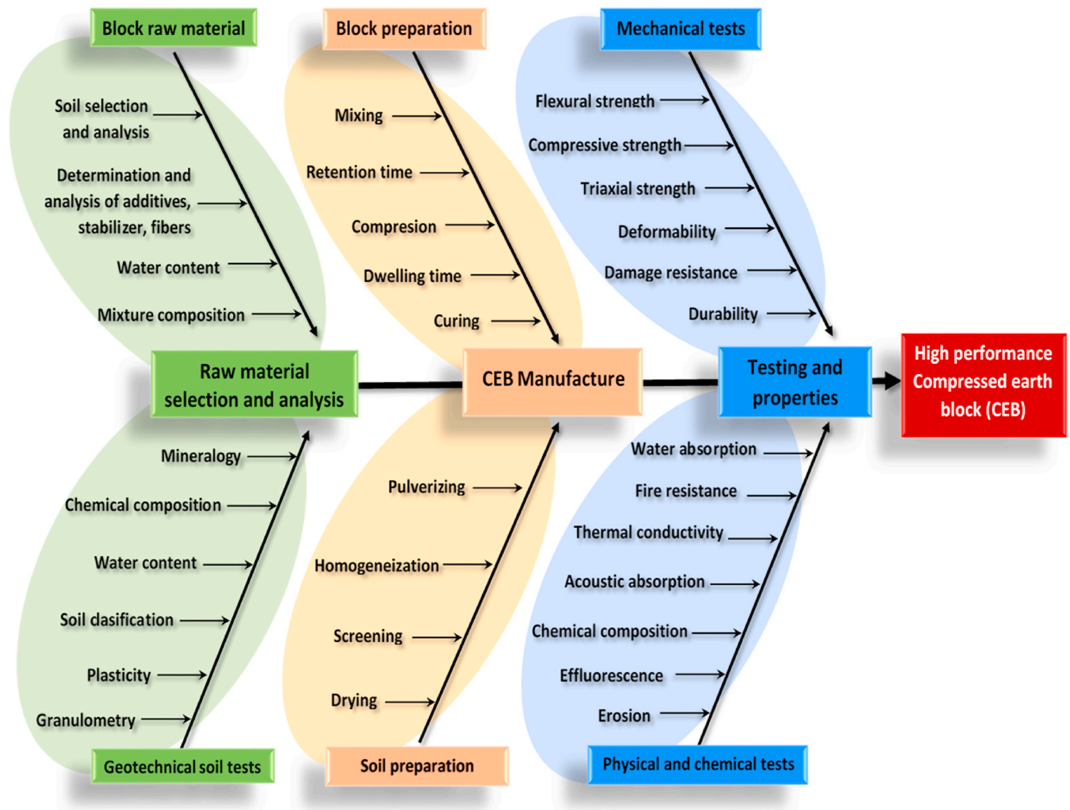

Fig. 3. Flow of processing stages and testing methods for manufacturing CEBs.

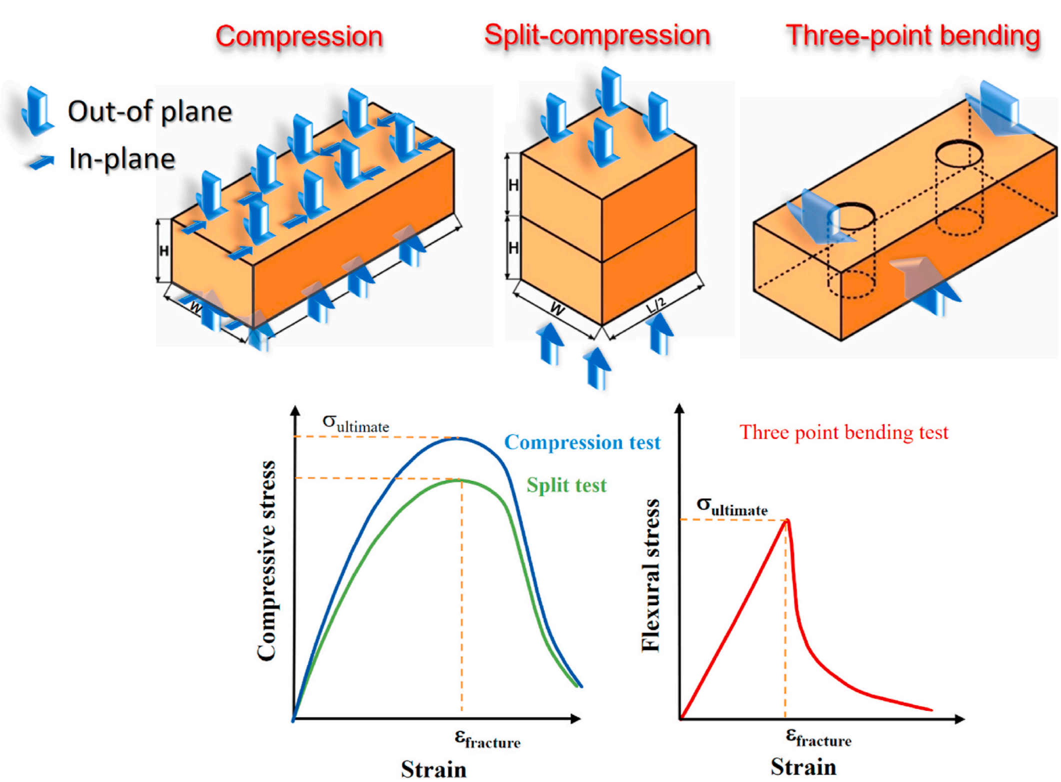

Fig. 4. Experimental tests on CEBs. Compression for infill masonry and three-point bending for hollow CEB are shown.

construction [75].

To design a high-quality CEB wall, it is necessary to analyze and optimize the physical, thermal and mechanical properties of the CEBs based on the requirements of the selected code. Different experimental methods can be applied to select and characterize the index properties of the soil: soil specific gravity, plasticity index, liquid limit, plastic limit, optimum moisture content, maximum dry density [71], particle size distribution, water absorption, and density [33].

Through soil compaction, it has been possible to improve the quality and performance of molded soil blocks [76]. However, new mixtures and compositions continue to be investigated to increase their strength and durability [29,32,77]. Other research have focused on the social, economic and environmental aspects of using CEBs [78]. The effect of CEB geometry and mix design on the flexural and compressive strength of CEBs was the focus of the study by Sitton et al. [79]. Their analysis of water content and cement content on CEBs allows concluding a direct correlation with strength. Based on the latter, an optimization of CEB with a mix design for improved strength is performed, obtaining an optimum mix of 10.9% cement and 11.4% water and with a resulting average compressive strength of 15.15 MPa.

It should be noted that the final characteristics of a durable and good quality CEB depend not only on the type of soil to be used and the stabilizer added in the case of CSEB, but also on the correct execution of all the manufacturing stages. The diagram in Fig. 3 shows the different stages required to achieve a quality CEB. The stages are classified into three main groups: raw material characterization, preparation and manufacture, and block testing. The first stage requires raw material selection and determination of properties through component testing. The second stage, which focuses on block design, requires several processes for soil and block preparation. For the soil: drying, screening, pulverizing, and mixing; and for the blocks: mixing, holding, compressing, and curing is required. In the third stage, the manufactured CEB is evaluated by different testing techniques to validate a high performance CEB.

Soil compaction using a machine increases the pressure and adhesion of the particles, allowing the formation of a quality CEB. Through the compaction pressure, the engineering properties of the earth block are improved, such as the strength, durability, and rigidity of the block compared to adobe or cob [46]. The density and porosity parameters of the block are also improved. The curing of the block is a key process to produce quality CEB; performing adequate curing provides maximum strength and durability. Longer curing time allows for an increase in strength, but the optimum values must be determined. The average curing time for demolded blocks can generally range from about 28 days [60] to 45 days [33]. The maturation (curing) time required to promote soil hardening and achieve adequate resistance properties depends not only on the materials used, but also on the environmental conditions. These can be controlled using several methods, such as a controlled environment (e.g., covering plastics or bags), applying heat from direct sunlight, or allowing outdoor or indoor air drying. CEBs with calcium carbide residue (CCR) or lime require a longer curing time, bordering 40–45 days [70]. During the curing of the block, physicochemical reactions occur between the soil, stabilizers, or aggregates in the mix. Therefore, the curing time varies with the proportions of the materials used to manufacture the CEB. It should be noted that during this period, pozzolanic reactions take place, giving rise to cementitious materials in which the constituent particles are strongly bonded.

2.3. *Performance assessment of CEBs*

Research efforts have been made to identify the main characteristics and properties of CEBs to propose new blends, reinforcements, and stabilizers that improve the engineering properties of CEBs; however, studies using agroindustrial by-products are scarce. The importance of using these by-products, especially organic fibers and stabilizers, is their reuse or recycling for ecological purposes and for improvement of the strength and quality capabilities of CEBs [80]. In addition, the cement industry consumes a significant amount of energy and non-renewable resources, producing high levels of carbon emissions [10,11]. However, replacing or reducing the amount of cement stabilization by using waste ashes from the energy sector derived from the combustion of agricultural and agro-industrial wastes is a big challenge. To achieve a high and efficient performance of CEBs according to different requirements and building environments, it is necessary to always comply with the required standards. In addition, to ensure the use of CEBs in particular construction requirements, the correct identification of mechanical properties of CEBs and their adequate use in computational simulations or full-scale testing are essential to determine the real behavior and safe design of walls and constructions with CEBs.

Table 1 shows a summary of the main properties measured experimentally by different authors to determine the durability and quality of the blocks. Of the authors considered in this table, the most commonly measured and analyzed parameters, from highest to lowest, are compressive strength, water absorption, density, flexural strength, erosion resistance, microstructural analysis, porosity, thermal conductivity, chemical resistance, stress-strain behavior, abrasion resistance, and shrinkage. A lack of studies was found reporting hardness resistance of CEBs to punching loads, resistance to fire, and resistance to impact loads.

Compressive and flexural strength are one of the main properties that define the quality of the CEB. Fig. 4 shows the compression and three-point bending tests, which are the most applied tests methods for evaluating load resistance. The parameters that quantify the performance in these tests are mainly the ultimate compressive strength, flexural strength, and fracture deformation. Some criticism has been raised regarding the stress state in the block during the compression test since the one shown in Fig. 4 produces a triaxial compressive stress with a constrained lateral displacement influenced by friction. In contrast, the stacked and mortar-bonded specimens obtained from split block tested under XP P13 901 provide a more uniaxial compressive state. Designers should consider the type of value reported as it can affect the results when performing building resistance or simulations. The reader is referred to Aubert et al. [81] for additional information regarding the effect of the type of compression sample on the resulting compression properties.

Other tests assessing the effect of environmental conditions on CEB durability include water absorption, water erosion, abrasion, and permeability. Finally, thermal properties are also important to provide comfort and energy efficiency in buildings. The thermal performance is mainly evaluated by heat conduction tests through the transverse or out-of-plane direction of the block, providing mainly thermal conductivity (thermal resistance index), specific heat capacity, and thermal inertia.

3. Results and discussion

In this review, the main novelty and contribution is the establishment of a baseline for future research projects focused on improving the performance characteristics of compressed earth blocks incorporating local, natural and reusable materials, with particular focused on agro-industrial by products. The stabilizers and reinforcements applied in compressed earth blocks are analyzed and compared. The results and approaches previously published by the scientific community indicate that these aggregates have been reported to substantially improve the properties of CEBs in wet and dry condition. Most of the articles analyzed in this review indicate that CEBs without stabilization present lower durability than CSEBs. Over the past ten years, various research groups have conducted extensive literature reviews on the challenges of using CEBs in construction, their properties, and the incorporation of natural materials. However, in this review a comprehensive analysis is performed focusing on the optimal reported mixtures for performance-efficient CEB from industrial and agroindustrial by products in terms of strength. The following sections cover the studies on blocks produced with reused materials from construction, and other industrial wastes. Finally, it concludes on advances in the manufacture of CEBs using agro-industrial by-products.

Among the most found stabilizers are lime, cement, pozzolans, and other materials such as residues or ashes from the combustion of agro-industrial wastes. Stabilizers are materials with an amorphous

Table 1
Mechanical, chemical, and physical properties of CEBs for performance assessment.

Aggregate type	Comp. strength	Flexural tensile strength	Erosion resistance	Abrasion resistance	Chemical resistance	Density	Porosity	Water absorption	Thermal conductivity	Shrinkage	Stress-strain behavior	Micro-structural analysis	Reference
Jute fiber	✔	✔	–	–	–	✔	–	–	–	✔	–	–	[61]
Coconut fiber	✔	✔	–	–	✔	✔	–	✔	–	–	✔	–	[60]
Kenaf fibers	✔	✔	–	–	–	–	✔	–	✔	–	–	✔	[30]
Rice husk ash	✔	–	✔	✔	–	✔	✔	✔	–	–	–	–	[37]
Rice husk ash	✔	–	✔	–	✔	✔	–	✔	–	–	–	–	[63]
Sugar cane bagasse ash	✔	✔	–	–	–	✔	–	✔	–	–	–	✔	[58]
Hydraulic and hydrated lime	✔	–	✔	–	–	–	–	✔	✔	–	–	–	[42]
Geopolymer	✔	✔	✔	–	–	✔	✔	–	✔	–	–	–	[45]
Fly ash (FA)	✔	✔	–	–	–	✔	✔	✔	–	–	✔	✔	[44]
Crushed brick waste	✔	✔	–	✔	✔	–	–	✔	–	✔	–	✔	[33]
OPC cement and sand	✔	–	–	–	–	✔	–	✔	–	–	✔	✔	[82]
Cement	–	–	–	–	✔	–	–	–	–	–	–	✔	[64]
Recycled fine aggregates (RA), cement and lime	✔	✔	✔	–	–	✔	✔	✔	✔	–	–	–	[50]

siliceous or siliceous and aluminous content that react with calcium hydroxide in the presence of water to form cementitious hydration products (calcium silicate hydrates and calcium silicate aluminate hydrates). The result is a union or cohesion of the particles of the mixed materials by chemical reactions, originating new compounds with higher mechanical resistance and lower permeability. The stabilizing capacity of the stabilizer depends on the chemical and mineralogical composition, the type and proportion of its active phases, the specific surface of the particle, the lime/stabilizer ratio, the water content, the curing time and the temperature [83]. Furthermore, fibers are used to reinforce the CEB, i.e., to improve the mechanical characteristics of the block, such as tensile strength and reduction of shrinkage cracks. Finally, this review classifies these materials into "stabilizers or binders" and "fiber reinforcement."

Stabilizers are different materials, from organic to industrial products, which are added during the CEB manufacturing process and allow maintaining the cohesion of the mixed materials. Depending on particular conditions or characteristics, specific stabilizers are used, which depend largely on the type of soil used to manufacture the block. Due to its nature, soil is a material that can be easily separated by low mechanical forces, such as contact with water, and requires stabilizers that allow its permanent cohesion. As Barbero-Barrera et al. [72] indicate, stabilizers largely solve the susceptibility of soil exposed to water. For instance, clayey soil requires lime as a stabilizer [42] rather than cement, which is more suitable for sandy soils. Alginate stabilization for clay-based construction materials can provide mechanical characteristics similar to those stabilized with cement and lime soil, as reported by Galán-Marín et al. [84]. In the case of using cement for a fine-grained soil type, Islam et al. [82] recommend the content of 50%–60% coarse sand with ≥6% cement.

According to the scientific articles reviewed on compressed earth blocks, most use cement as a stabilizer. This is because cement is a material that provides good performance and effectiveness and is easily available. However, it is an expensive material and is not environmentally friendly. To address this issue, many studies have used a low percentage of cement and included other natural or recyclable materials such as rice ask hush, jute fiber, and coconut fiber to replace it and to obtain better performance in terms of strength and durability [37,60,61], while other research have completely replaced the use of cement, incorporating other materials such as calcium carbide residue and glass waste activated with NaOH solution [66,85]. For instance, the compressed stabilized earth blocks (CSEBs) reported in the study by Nshimiyimana et al. [37] showed a low capillary absorption coefficient and excellent durability indicators such as erosion resistance to standard water pressures (50 kPa) and high pressures (500 kPa), with a surface abrasion coefficient higher than 7 cm^2/g recommended for masonry facing construction.

The growing interest in improving stabilization in earth construction has led to the use of different techniques through various earth construction methods. The novel method developed by Sravan & Nagaraj [86] used an enzyme to stabilize soil properties after being incorporated into their mixture. In the study by Sravan & Nagaraj [87], the optimum enzyme dosage for effective stabilization was determined based on the unconfined compressive strength of the soil, which increased with the addition of the enzyme. The research results [86] indicate that blocks prepared with the enzyme significantly improve the compressive strength and durability of compressed soil blocks.

Many studies have reported that the progressive increase in the proportion of stabilizers does not guarantee the best mechanical and thermal performance of the blocks. Therefore, it is necessary to find the optimal percentage of stabilizers to obtain the best block characteristics, considering that a higher proportion of stabilizers can lead to higher production costs [45,49,88]. For example, Omar Sore et al. [45] investigated CEB stabilized with 5%, 10%, 15%, and 20% geopolymer, finding that increasing stabilizer contents improves the mechanical performance of CEBs with an increase in compressive strength of at least

4 MPa for 10% or 15%. Regarding thermal performance, it was reported that increasing the stabilizer fraction improves the diffusivity and thermal conductivity up to a level of 15%, delivering a lower performance of 20%. Islam et al. [49] and Elahi et al. [44], using fly ash (FA) and cement to stabilize CEBs, conclude that the addition of FA increases the mechanical strength up to a certain value of FA (optimum) and beyond that optimum value the strength decreases. Using SEM analysis of the block for a 15% FA and 7% cement, Islam et al. [44] demonstrate that a compact matrix in CEBs is obtained where most of the voids are filled with FA, soil particles, C–S–H, or C-A-H gels, where C–S–H and C-A-H are mainly responsible for providing strength because of the hydration reaction. This well-coordinated connection observed for the 15% FA justifies the optimum content found for high strength and durability of the blocks. Other values of optimum FA content were obtained for different cement content with similar SEM observations. Kasinikota & Tripura [24] fabricated hollow interlocking compressed stabilized earth blocks (ICSEBs) with 4%, 6%, 8%, and 10% cement, recommending a cement content ≥6% for the production of durable ICSEB with high mechanical performance (compressive strength, flexural, and splitting tensile strength). Ammari et al. [88] reported that compressive strength increases with cement rate. Nevertheless, for each soil material, there is a specific rate of increase in strength up to a certain dosage for stabilization, and this increase is non-linear with the cement rate. This phenomenon is explained by the combined effect of the granular texture and mineralogical composition of each earth material. The addition of cement intensified the bonds between the sandy-gravelly skeleton. However, this occurs when the clay matrix is primarily stabilized by its mineralogical constituents, such as calcite and quartz. Based on these studies, it is concluded that it is necessary to determine an optimum value of the stabilizer content that satisfies the construction requirements according to the codes and the criterion of low production cost. The effectiveness of the stabilizers depends not only on the percentage chosen for its use but also on the dry weight of the soil, its texture, its structure, and its chemical compounds, such as sulfates, oxides, and hydroxides, etc. For example, CEB stabilized with geopolymer or cement [26,33] can generate efflorescence when sulfate attacks. For the CEB stabilized with rice husk hush [63], this phenomenon should be considered because, in an environment where acid rain occurs, the CEB must be resistant to acids to avoid the formation of salts and thus the formation of cracks. It is important to note that the soil acts as a system in which the coarse material provides support and consistency, and the fine material acts as a binder that provides cohesion to the CEBs. However, due to its heterogeneous nature, the soil must be mixed with certain proportions of stabilizer. In addition, reinforcing materials such as fibers can generate CEBs that are even more suitable for construction. For example, the use of coconut fibers and cement stabilization in CEB by Thanushan et al. [60] was shown to provide improved block durability and reduce degradation problems against alkaline attacks, acid attacks, freeze-thaw cycles and moisture drying.

3.1. The optimal mixtures and the effect of stabilizers on strength

Powder by-products. The effect of different proportions of ground olive stones (GOS) was incorporated in CEBs by Djadouf et al. [62] to analyze their mechanical and thermal behavior. The maximum compressive strength is achieved with 15% of the GOS. This percentage improves the mechanical properties of the studied CEBs by 19.66% and decreases the thermal conductivity by 37.63%. Poorveekan et al. [34] produce CEBs stabilized with an alkali-activated eggshell powder (ESP) binder. The optimum mixtures of the constituents obtained considering water absorption capacity and mechanical strength for block production are 10:90 and 20:80 eggshell powder and rice husk ash, respectively.

The use of cement and palm water as additives in compressed earth blocks has been studied by Mohan et al. [89]. Their results indicate that the compressive strength of the block increases with the additives, in the proportion of 5% cement and 50% palm water in the mixture, with a maximum compressive strength of 3.2 N/mm^2.

Ashes from natural wastes. Ash stabilizers from the combustion of agro-industrial waste have been the subject of interest by different research studies owing to their favorable mechanical characteristics and low thermal conductivity. The three reports integrated into this section mainly focus on identifying the optimal percentage to fabricate CEBs. For example, Hwang et al. [90] investigated the development of compressed stabilized earth blocks (CSEBs) with three different percentages of cement, lime, and wood ash with 5%, 10%, and 15%, respectively, as soil replacement. The effectiveness of the improvements of CSEB properties was found with lime and wood ash by mixed with cement at a ratio of 2.5%, 5%, and 7.5%, respectively. The optimum ratios obtained for improved compressive strength, density and water absorption rate among the studies values are 5% lime to 5% cement and 5% wood ash to 5% cement.

In Elahi et al. [55] the effectiveness of 0–10% sawdust ash (SDA) content and 4%, 6%, 8%, and 10% cement contents in CSEB were investigated, determining that the compressive strength of the blocks increases with values between 21% and 147% compared to non-stabilized earth blocks. The optimum amount of SDA in relation to cement was found to be 4% SDA for 4% cement, 6% SDA for 6–8% cement and 8% SDA for 10% cement.

Finally, the work of Yatawara & Athukorala [63] used rice husk ash (RHA) to manufacture CEBs and analyze their mechanical and physical behavior. A replacement of 7.5% clay soil with RHA improves compressive strength by 25.7% compared to CEBs without RHA. In addition, the RHA in CEBs produces acceptable erosion resistance, decreases dry and apparent densities and reduces water absorption.

Geopolymers. This inorganic material is produced through geosynthesis from silica-alumina gels in an alkaline environment. These binders allow improving CEB properties; obtaining blocks with strengths twice higher than CEB produced with Portland cement. The main advantage of using geopolymers is the more environmentally friendly condition of stabilizer than ordinary Portland cement. Moreover, geopolymers use less energy and have a lower environmental impact during production, emitting less CO_2 than cement production. However, problems of efflorescence or leaching of salts during the manufacture of the blocks have been encountered [26].

Idriss et al. [29] also investigated chemical stabilization with alkali-activated alkali-bonded geopolymer binders based on calcined clay. By using an activation solution of a 2:1 volumetric mixture of SiO_2/Na_2O ratio 3.1, LOI = 60 wt% (commercial sodium silicate) and 8 M sodium hydroxide obtained by diluting commercial soda (17 M and 99.9% purity), a significant increase in compressive and flexural strength of up to approximately three times was obtained. The authors recommend using a 15%–20% stabilizer for environments with extreme weather environments. Poorveekan et al. [34] also developed stabilized earth geopolymer blocks using rice husk ash (RHA) binder, alkali-activated eggshell powder (ESP) and caustic soda to analyze their influence and compare compressed earth blocks with cement and adobe blocks. The geopolymer blocks achieved the mechanical strength limits of the Sri Lankan standard recommended for non-load-bearing masonry units. A comparison of the compressive strength values of the geopolymer blocks with the compressive strength values of the cement-stabilized earth blocks showed that the geopolymer blocks had lower values. It should also be noted that the cost parameters, energy requirements, and CO_2 emissions can be reduced by using geopolymers to produce the blocks. The feasibility of using geopolymer stabilizers in the fabrication of compressed earth blocks (CEBs) was also the objective of the study conducted by Omar Sore et al. [45]. A geopolymer synthesized by mixing metakaolin and sodium hydroxide solution with 5, 10, 15, and 20% geopolymer as a stabilizer in CEBs was compared with CEBs containing 8% Portland cement and CEBs without stabilizer. The results showed that the geopolymerization of the CEBs significantly improves the mechanical performance and thermal properties of CEBs. However, the thermal conductivity value remains very close to that of the blocks without a stabilizer. A 15% geopolymer content improves the quality of CEBs, particularly for their stability in water, ensuring a good cohesion of particles, whereas CEBs without stabilizers show poor cohesion. The compressive strength with the geopolymer stabilizer added to the CEB achieved at least 4 MPa [45].

Larbi et al. [66] analyzed the production of compressed earth blocks from two sediments from Oran and Sidi Lakhdar, composed of a glass powder additive and a NaOH solution to identify the optimal mixture for the production of CEB. The objective of using this glass powder additive and a NaOH solution is to contribute to the sustainability of the construction industry, particularly since the use of these two compounds would divert the material from landfills, allowing it to be recycled. Their results conclude that adding a 4% glass solution to the mixture provides maximum compressive strength. In addition, a high compressive strength with less porosity was obtained by adding less percentage of activated glass powder with NaOH solution.

Palanisamy & Kumar [91] manufactured geopolymer soil bricks reinforced with coconut fiber waste, and using different proportions of soil, fly ash (FA), granulated blast furnace slag (GBFS), quarry dust (QD), coconut fiber waste, and alkaline solution. The alkaline liquid investigated combined Na_2SiO_3 and NaOH (97%–98% purity), with a variation of molar ratios of 6 M, 8 M, and 10 M sodium hydroxide solution. The results indicated an improvement in the compressive strength of the geopolymer-stabilized blocks (GSB) in the range of 1.3 MPa for 6 M to 6.9 MPa for 10 M. In addition, an optimum fiber reinforced GSB of FA: GBFS:Soil:QD content ratio of 0.5:0.5:1.75:0.25, 10 M and a coconut fiber content of 1% was found. Finally, the CEB obtained were proposed to construct load-bearing structures.

Over the past ten years, various research groups have conducted extensive literature reviews on the challenges of using CEBs in construction, their properties, and the incorporation of natural materials. However, in this review a comprehensive analysis is performed focusing on the optimal reported mixtures for performance-efficient CEB from industrial and agroindustrial by products in terms of strength. The following sections cover the studies on blocks produced with recycled materials from construction, industrial production, and other industrial wastes. Finally, it concludes on advances in the production of CEBs using agro-industrial by-products. Compared to existing literature, for instance Turco et al. [92] and other reviews on CEBs, this study provide a comprehensive and updated roadmap for manufacturing good quality CEBs. It also, critically analyzes the techniques used for the characterization of compressive strength, one of the most important quality indicator parameters. Reviews the different stabilizers and reinforcements used in CEBs for optimum mixtures, analyzing the performance delivered to the blocks in terms of strength, and determines other variables that should be considered to define the quality of the blocks, along with the analysis techniques that should be included to demonstrate the significance of the results. A clear classification is proposed in terms of industrial and agro-industrial stabilizers and reinforcements. In addition, provides the evaluation of the state of the art of prediction methods for the design of building engineering with CEB.

3.2. Compressed earth blocks with fiber reinforcement

Several types of fibers, natural or synthetic, differ in their mechanical properties and behavior. Reinforcement such as coconut, palm, polypropylene, banana, kenaf, and jute fibers has been reported [93]. Among the studies analyzed, it was found that adding fibers increases the tensile strength of CEBs. Other studies have reported that an optimal proportion of fibers allows decreasing the porosity, thermal conductivity, and increasing the flexural strength. In contrast, an opposite effect can be observed when a non-optimal percentage range of fiber proportion is used.

Natural fibers are a renewable resource that have been used for thousands of years in the manufacture of materials. However, their properties and characteristics can vary significantly depending on the environmental conditions [94]. Therefore, appropriate manufacturing processes and control methods are required to ensure high quality CEB. To determine an optimal fiber ratio, parameters such as length, weight, porosity, and concentration that influence block strength should be considered [30,31]. Among the natural fibers reported for the fabrication of CEBs are sugarcane bagasse fibers [58], sisal fibers [95], jute fiber [61], date palm fiber [54,96,97], banana fiber [59], bamboo fibers [31], coconut fibers [60] and cassava husks [80]. In the review by Laborel-Préneron et al. [98], different studies are analyzed to determine the optimal size and percentage of natural fiber to avoid crack formation after CEBs are fabricated. The finding was that the absorbent character of the fiber affects the differential volume changes of the fiber and the soil matrix, resulting in desiccation cracks. Therefore, each type of natural aggregate and composite block should be specially analyzed to determine the optimum values of fiber percentage and fiber size. Subramanian et al. [99] highlight that natural fibers are a good alternative to conventional materials used in CEB. This is due to the ability of fibers to increase resistance to unidirectional loads, increase water absorption capacity and improve thermal stability. The natural fibers reviewed in their study were banana, coconut, sisal, palm, and cassava.

The effect of incorporating kenaf fibers (different contents and lengths) on water accessible porosity, flexural and compressive strength, and thermal conductivity was investigated by Poullain et al. [30]. Porosity was found to decrease with fiber length and increase with fiber concentration. The combined effect of porosity reduction caused by fiber addition influenced the optimum fiber length for flexural and compressive strength. The decrease in porosity with the addition of fibers also decreases the thermal conductivity.

Abessolo et al. [31] also demonstrated the suitability of using fibers, in particular compressed earth blocks reinforced with *Bambusa vulgaris* fibers, increased by 43.6 % the compressive strength of the blocks with an optimum fiber content of 0.5 % by weight and with a length of 4 cm, as for the flexural strength also increases with increasing fiber content and length. The highest flexural strength value is obtained with the block containing 1.0 wt% fiber content.

Table 2 summarizes the main constituents and properties of the soil used for the elaboration of CEBs with fibers and ashes by different research studies. It also includes block sizes and optimal mass fractions.

Kumar & Barbato [58] studied compressed earth blocks, with 0%, 0.5% and 1.0% by weight of sugarcane bagasse fibers (SCBF) and 0%, 6%, and 12% by weight of ordinary Portland cement type II, conclude that CSEBs with 0.5% and 1.0% by weight of SCBF and 12% by weight of cement content provided the best strength and durability. Sisal fiber reinforcement was investigated by Labiad et al. [95]. By characterizing the physical and mechanical properties of CSEBs with different fiber and cement contents, an optimum ratio for maximum strength was found. First, the tensile strength increases as the fiber content in the mix increases, but after the optimum proportion, increasing the fiber content also increases the porosity of the block and reduces the strength even to lower values than unreinforced blocks. Other results obtained by Thanushan et al. [60] related to the post-peak strength and performance of cementitious compressed earth blocks with coconut fiber concluded that coconut fibers fail to improve the initial compressive or flexural strength of the blocks. However, fibers can improve the residual strength, ductility, toughness, and energy absorption of CEBs. In addition, through alkaline and acid attack tests, the durability of the investigated CEB was reduced by adding fiber. A mixture of pulverized clay, sand and water and jute fiber for the elaboration of CEB was investigated by Zardari et al. [61] using compressive and tensile strength tests. The effect of drying time on crack development was also incorporated into their study. Their research concluded that the addition of jute fiber reduces compressive strength, deflection, drying time, shrinkage, and cracking.

Concerning the increase in block deformation capacity or ductility, Donkor & Obonyo [39] included commercially available polypropylene fibers in the performance assessment of CEBs. The fiber length was 54

Table 2
CEBs produced with natural stabilizers are reported in the literature. Include soil properties, mass fractions investigated, and optimum percentage contents of constituents.

Soil							Aggregate type				CEB optimum content	CEB size (cuboid) [mm^3]	Ref.
Liquid limit [%]	Plastic limit [%]	Plasticity index (PI) [%]	Clay [wt.%]	Silt [wt.%]	Sand [wt.%]	Gravel [wt.%]	Fiber		Ash				
							Type	[wt.%]	Type	[wt.%]			
33	17	–	–	–	–	–	Jute fiber	0.5, 1, 1.5, 2			70% clay, 30% well sand and 0.5% jute fiber.	–	[61]
16	–	1.07	45.8	45.8	50.2		Coconut fiber	0, 0.2, 0.4, 0.6			–	400 × 100 × 100 150 × 150 × 150	[60]
28	14	14	14.8	23.5	61.7	0	Kenaf fibers	0.5, 1, 1.5			–	40 × 40 × 160	[30]
35.47	22.94	12.53	31.12	58.03	9.85	<1	Sugar cane bagasse fiber	0, 0.5, 1.0			0.5%–1.0% by weight of sugar cane bagasse fiber in the block with 12% by weight of cement	290 × 150 × 75	[58]
50	–	20	20	–	–	–			Rice husk ash	–	18:2 to 16:4% of CCR: RHA	–	[37]
–	–	–	27.8	33.9	38.3	38.3			Rice husk ash	0, 5, 7.5, 10, 15, 20	7.5% RHA in replacement of clay soil	300 × 150 × 100	[63]
–	–	–	–	–	–	–			Sugar cane bagasse ash	0, 4, 6, 8, 10	8% by weight of sugar cane bagasse ash in the block with 5% by weight of cement	305 × 143 × 105	[27]

mm and an equivalent diameter of 0.82 mm. Their study determined that the incorporation of these polypropylene fibers improves the ductility and deformability of the block. The optimal range found was between 0.4% and 0.6% of polypropylene fibers, while outside those values, the strength could decrease depending on the fiber weight fraction. Finally, it is noted that the fiber length is a parameter that must be considered, determining its optimum value so that the compressive strength and density of the CEBs are not reduced. A block suitable for construction must have an optimum strength value and low porosity. In addition, the strength and mechanical property values should be indicated with the corresponding moisture content of the CEB. As proved by Nshimiyimana et al. [70], these properties are highly sensitive to the moisture content of the earth block during testing.

3.3. Reusing industrial and agro-industrial by-products

3.3.1. Recycled construction materials

Several authors have incorporated different recovered construction products in recent years. For example, Bogas et al. [50] incorporated recycled fine aggregates from construction debris in CEB stabilized with 8% cement, CEB stabilized with 4% cement and 4% lime and non-stabilized CEB. Valenzuela et al. [100] incorporated ground recycled concrete, soil and water in CEBs with weight proportions of 1:4:1, obtaining 130% higher compressive strength than conventional earth bricks. Other research has incorporated crushed brick waste into CEBs, significantly improving CEB performance, especially under wetting/drying cycles and sulfate attacks. In Kasinikota & Tripura [33], the obtained dry and wet compressive strength increases by 11% and 12 % by adding 20% crushed brick waste.

The use of alkaline activation and waste materials to manufacture compressed earth blocks and to evaluate the life cycle of construction waste on the associated environmental impact has been the focus of several research groups [9,28,73]. According to the analysis, baked blocks present the highest source of embodied CO_2 per square meter of wall compared to cement-stabilized CEBs, alkali-activated CEBs, cement-stabilized rammed earth, and alkali-activated rammed earth. However, it is also noted that stabilization (cement, alkali activator/precursor and heating/firing) contributes more to the global warming potential (GWP).

Regarding the wear of CSEB with cement, Bezerra & Azeredo [64] performed external sulfate attack exposure using cyclic processes of capillary absorption time variation and sodium sulfate concentration variation. The physical attack of sulfates mostly affected the damage of CSEBs with precipitation of thenardite and mirabilite in the micropores and pressure generation. In addition, moderate chemical sulfate attacks by ettringite precipitation reactions was identified. The sulfate concentration and capillary adsorption directly influenced the wear of CSEBs.

The influence of particle size and percentage replacement of crushed brick waste on the compressive strength and structural anisotropy of CEBs has also been analyzed [33]. The results demonstrate that crushed brick waste particle size affects the strength of the blocks and that 20% replacement of crushed brick in CEBs with a particle size less than 4.75 mm provides the highest strength.

The addition of processed granulated blast furnace slag (GBFS) instead of construction and demolition waste (CDW) and manufactured sand (MS) has been shown to produce the highest strengths in rammed earth and CEBs, irrespective of the type of binder. It is observed that the thermal conductivity of the samples with GBFS is lower than that of the other two aggregates [28,40,73]. The use of GBFS has also been a subject of study [65]. Its use along with cement to manufacture CSEB was done by substituting an optimum percentage of GBFS with different added percentages of cement to produce the blocks. Compression and water absorption tests as per Indian Standard (IS) specifications on CSEB with lithomargic clayey soil and CSEB with lateritic soil were performed. The determined optimum GBFS substitution percentages were 25% and 20% for lithomargic clayey soil and lateritic soil, respectively. The results obtained for water absorption were lower than 15% for all samples within the established limits. CSEBs prepared with 25% GBFS, 10% cement, and 75% lithomargic clay or with 80% lateritic soil incorporating 20% GBFS and 6% cement can be used in masonry for the construction of load-bearing walls. The obtained cement percentages were recommended as sufficient to manufacture CSEBs with better dry compressive strength and lower energy consumption.

Malkanthi et al. [36] considered the reduction of clay and silt content because the high content of these components leads to a reduction in compressive strength. To preparing industrial-scale CSEB, 10% clay and silt content with 8% cement is suitable. A modified soil from soil type 1 (38% fine aggregates: clay and silt) and crushed construction waste was prepared to investigating the variation of the fine aggregates content (5%, 10%, 15%, and 20%) as well as the cement content (10%, 8%, and 6%) for each percentage of fine aggregates. Cement type or grade was not specified. The maximum particle size for the construction waste selected was 12 mm to reduce fine aggregates while controlling the larger particles amount based on the particle packing optimization method. Construction waste and sand were used to control content of larger particles, but the specific percentages of crushed construction waste were not reported. The dry compressive strength, dry density, and water absorption were determined to grade the blocks according to SLS code 1382. As expected, compressive strength was found to increase with both a reduction in the percentage of fine aggregates and the increase of cement content. The most appropriate fine aggregates content was set at 10%, as a 5% content requires more sand and construction waste, being less economical. The industrial block was prepared and tested with 8% cement and 10% fines, with resulting properties complying with Grade 1 of the SLS code 1382. Eight percent of cement was chosen since it is the proportion most used by the industry to produce cement blocks, as reported by the authors. Finally, crushed construction waste for CSEB was found to contribute to the management of environmental pollution due to construction waste and the scarcity issue of construction materials.

3.3.2. *Industrial waste*

The main industrial products used as constituents of CEBs listed in Table 3 are cement, lime, geopolymers, fly ash, crushed bricks. The interest in investigating the possible use of lime is also due to other considerations. Lime requires much less energy than cement to manufacture and slowly returns to its original limestone state through carbonation processes. Lime is permeable to water vapor, absorbing it and releasing it quickly, making it possible to control the moisture of walls and floors [48]. In some proportion, lime can have antibacterial and antiseptic properties, increase the pH, and negatively affect microorganisms. According to BS EN 13501–1, lime is classified as a completely non-combustible material (A1). Barbero-Barrera et al. [72] used two types of lime, NHL 2 and NHL 3.5, for the stabilization of CEB at four dosages ranging from 3% to 12% lime. These components produced an increase of the mechanical strength (flexural and compressive) and modulus of elasticity. In addition, the water absorption coefficient decreased with NHL 2 but increased with NHL 3.5 and the pore size and volume increased with NHL 2 and decreased with NHL 3.5.

Calcium carbide residue (CCR) was investigated by different authors [16,85]. CCR to stabilize CEBs containing 0–20 wt% was proposed by Nshimiyimana et al. [16]. In addition, Nshimiyimana et al. [70] specifically investigated the effect of production and curing parameters on CEB mechanical performance, such as curing temperature on the reactivity of the earth materials with CCR and molding and curing conditions concerning the compressive strength of CEB. Their results highlight that temperature influences the reactivity of kaolinite and quartz-rich earth materials and that the compressive strength of stabilized CEBs increases with higher curing temperature for the investigated range between 20 °C and 40 °C.

For CSEBs with low proportions of clay and silt, Malkanthi et al. [69] suggest the combination of cement and lime. This is based on the analysis conducted with different combinations of lime and cement-lime stabilizers to produce CSEBs. For CSEBs containing only lime as a stabilizer, the optimum lime content of 10% was determined. Then, other compositions were investigated by replacing the 10% lime with cement-lime mixtures with cement fractions of 3%, 5%, and 7%. The results determined that a combination of 7% cement and 3% lime stabilizer achieved a compressive strength of 4.1 N/mm^2. In addition, the blocks stabilized with 10% lime with a resulting compressive strength (dry) of 1.7 N/mm^2 were recommended for load-bearing walls of single-story buildings according to the Sri Lankan Standard (SLS 855: Part 1: 1989), which minimum requirement of compressive strength is 1.2 N/mm^2. However, for other standards, such as ASTM C90, the strength obtained for the developed CSEB is considerably lower than the minimum requirement of 13.8 N/mm^2. The Mexican standard NMX-C-404 defines 12 MPa as the minimum compressive strength of solid block units. The French standard (AFNOR - XP P13-901) specific to

Table 3
CEBs produced with non-natural stabilizing industrial products reported in the literature. Soils properties, investigated mass fraction and optimum percentage contents of constituents are included.

Liquid limit [%]	Plastic limit [%]	Plasticity index (PI) [%]	Clay [wt. %]	Silt [wt. %]	Sand [wt. %]	Gravel [wt.%]	Type of stabilizer	Mass fraction [wt. %]	optimum content [wt. %]	CEB size (cuboid) mm^3	Ref.
29	18	11	19.4	17.6	47	15.9	hydraulic and hydrated lime	6% of hydraulic lime and 1% of hydrated lime	–	300 × 150 × 70	[42]
50.5	22.6	27.9	5.36	10.05	48.41	36.18	Geopolymer	5, 10, 15, 20	10%–15% geopolymer	140 × 140 × 95; and 295 × 140 × 95	[45]
48	34	14	28		72	0	Fly ash (FA) and cement (OPC)	FA: 0, 10, 20, 30; OPC: 4, 6, 8, 10; OPC: 4, 6, 8, 10	10% FA for 4 and 6% OPC; 20% FA for 8% OPC; 30% FA for 10% OPC	90 × 90 × 90	[44]
50.48	27.12	23.36	30.14	67.21	2.65	0	Crushed brick waste	6, 12, 18, 20, 24, 40, 60, 80, 100	20% crushed brick waste	290 × 140 × 100	[33]
40	22	18	41	47	12	0	OPC cement and sand	OPC-type I: 0, 4, 5, 6, 7, 8, 9; sand: 20, 30, 40, 50, 60, 70	Coarse sand 50%–60% and OPC ≥6%.	240 × 115 × 90	[82]
28.64	18.62	10.02	0.78	16.78	77.29	5.15	Cement	12%	–	250 × 125 × 75	[64]
18	15	3	35.4		61.2	3.4	Recycled fine aggregates (RA), cement and lime	15% RA, 8% cement, 4% cement and 4% lime	–	145 × 140 × 90	[50]

CSEB sets a minimum of 2 MPa.

The compressive strength and mass of CSEBs with cement and lime after exposure to sulfate attack were also investigated [28]. The CSEBs subjected to chemical curing with sulfates and water were determined, showing that the action of sulfates on CSEBs depends mainly on the nature of the base soil and the type of treatment and the level of compaction. Chaibeddra & Kharchi [28] conclude that sulfates are detrimental to fine soil with added lime and that coarse soil with cement for block stabilization resists sulfate attack better than fine soil with lime. The subsequent expansion in the block was found related to the formation of sulfate reaction products (ettringite and gypsum). This expansion is restricted when the density of the block is higher and exerts a lower pressure in the more porous blocks.

Another study has included different by-products, such as coal combustion, specifically coal ash, to make blocks mixed with clayey soil stabilized with Portland cement and lime [48]. Fly ash (FA) was the subject of study and incorporated into CEBs obtaining different results. For example, Islam et al. [49] investigated the suitability of compressed stabilized earth blocks (CSEB) stabilized with cement and fly ash (FA). The 15% FA was the optimum content for a cement ratio of 5%–7%, allowing the manufacture of CSEBs with strength ≥5 MPa. Their study highlights that FA allows reducing the water absorption capacity, which varies between 10.2 % and 18.7 % depending on the mix composition. In addition, a typical house built with CSEB and fired clay bricks (FCB) were compared through an economic cost analysis, resulting that CSEB stabilized with cement and FA reduces the cost between 24% and 39%. Elahi et al. [44] developed compressed stabilized earth blocks (CSEB) with fly ash (FA) and cement. The study analyzes the effect of the cement-FA ratio on compressive strength, density, porosity, and curing age. Values of 6–10 % cement and 20–30 % FA for CSEBs provided the optimum content for strength and durability. The dry compressive strength values found ranged from 2.25 to 6.0 MPa. In addition, increasing the cement effectively increases the maximum deformation of the blocks and failure strain; the water absorption of the blocks decreases with increasing cement, and the porosity decreases as the FA content increases. Concerning curing time, from seven to twenty-eight days, an increase in the compressive strength of CSEBs was observed. Elahi et al. [71] also reported a study of compressed stabilized earth blocks (CSEBs) with fly ash (FA). The study indicate that the addition of FA is effective in reducing the cement content. In addition, for maximum compressive strength, flexural strength, and splitting tensile strength, the optimum amount of FA combined with ordinary Portland cement (OPC) type I was 10% (for 3% OPC), 20% (for 5% and 7% OPC), and 30% (for 10% OPC). In addition, the performed life cycle analysis indicated that CSEBs are better than traditional fired bricks (FCB) regarding energy consumption and global warming potential. However, constructions with CSEB were 21.2% more expensive than those with FCB. Finally, the reuse of oilfield produced water to produce interlocking stabilized compressed earth blocks is highlighted [68]. The physical, thermal, mechanical and toxicity properties of CEBs of two types of soils were analyzed. The Nimr soil showed higher compressive strength and lower thermal conductivity than Marmoul soil at twenty-eight days of curing.

3.3.3. *Agro-industrial by-products*

The importance of an integrated approach to the agroindustrial sector with construction and materials is based on the growing demand for food production and its consequence of a significant increase in the generation of agroindustrial waste [101,102]. According to Oliveira et al. [102], over 30% of the food produced is wasted, creating an opportunity for re-valuation. To address this problem and improve the sustainability of production and consumption, biocircular strategies are proposed, such as the implementation of a Life Cycle Assessment and Emergy accounting Applied Framework (LEAF). This integrated approach aims to reduce environmental impacts, make use of food waste and promote more efficient and sustainable production in the agro-industrial sector.

Trends of new opportunities for advancing sustainable production are identified and discussed by Freitas et al. [101]. The development of efficient technologies is required to promote sustainability, with an emphasis on respect for the environment and moderate costs, including parameters that facilitate the increase of scale for industrial production, and the valorization of agro-industrial waste for the development of new products. This last point is relevant, as it highlights the importance of the growing trend for sustainable and environmental awareness at the macro level, considering agro-industrial waste as an opportunity rather than a problem.

Other sustainable applications identified by Shaheen et al. [103] as opportunities for the sustainable use of rice biowaste biochar and rice compost are highlighted as opportunities in the agri-environmental and construction sectors. Specifically, direct applications in the management of contaminated soils and water, to improve soil quality and water management. In the context of construction, the advances with regard to the manufacture of energy efficient materials from waste have been developed. For example, biochar from waste derived from rice husks was effectively used to improve the mechanical strength of concrete due to its pozzolanic properties and high content of silica fumes, which makes it an effective filler material for use as a partial replacement for sand or cement. On the other hand, the study indicates that the processing of these materials involves considerable costs in terms of economy and energy, but nevertheless, the net benefits outweigh the costs.

In the context of the study and elaboration of compressed earth blocks with different natural and agro-industrial waste as constituent materials with focus on increasing the strength and durability properties have been of constant interest in recent years. Several natural and agroindustrial waste have been incorporated in CEBs and the resistance behavior has been primarily assessed. Fig. 5 summarizes the effect of different stabilizers and reinforcement on the compressive and tensile (flexural) resistance of CEBs. Ground olive stones (GOS) in proportions of 15% weight produces a CEB with 7.7 MPa of compressive strength [62]. The use of GOS stabilizer, an agro-industrial waste incorporated in CEB, is identified as the most significant for improving the compressive strength of CEBs, followed by RHA. Note that RHA produces a higher strength than the industrial saw dust ash. The effect of other industrial wastes on compressive strength of CEB are near 6 MPa.

The resistance response and quality of CEB are not only depending on the reinforcement and stabilizer components. Different factors dominate the performance and durability of the block. Manufacturing pressure,

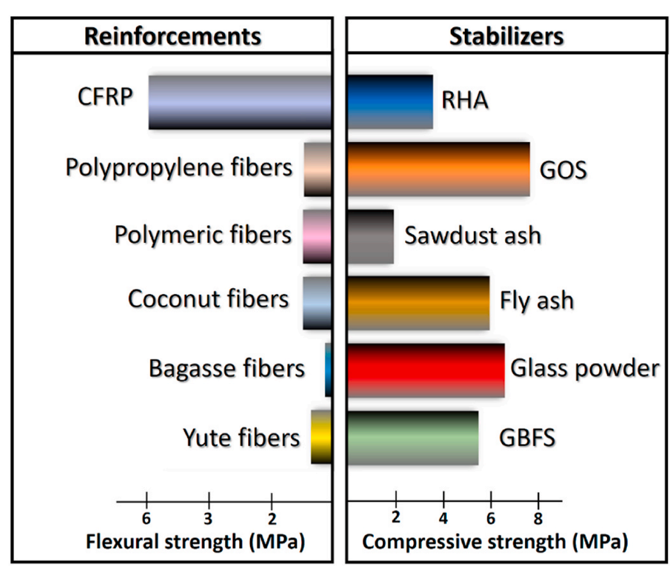

Fig. 5. Strength of CEBs incorporating different industrial and agro-industrial by-products.

curing time, humidity, percentage and dimensions of reinforcements, percentage and dimensions of stabilizers, amount of water and soil type. For instance, Sassu et al. [104] considered interlocking compressed stabilized earth blocks (ICSEBs) with three different mixtures, an unstabilized control block with soil-lime and soil-straw. Tensile strength and ductility were improved by the addition of fibers without significantly affecting compressive strength. The addition of lime resulted in an increase in strength and caused the block to exhibit a brittle behavior.

The stabilization of soil mixed with lime and seawater to analyze the influence of seawater on soil swelling reaction was investigated by Singh et al. [27]. The dry and wet compressive strength increased by adding sugar cane bagasse ash and wheat straw additives. The increase in wet compressive strength is explained by the binding of the soil material with the additives. Soil used is classified as coarse grain according to ASTM, with 32.8% soil passing the number 200 sieve and 93.7% passing the number 4 sieve. The increase of strength is caused by the pozzolanic behavior of sugar cane bagasse ash with water, and the addition of straw as fiber reinforcement material. Lavie Arsène et al. [38] have used three different types of aggregates: limestone, sandstone, and porphyry to evaluate the drying shrinkage, compressive strength, water absorption, and abrasion resistance of CEBs. The addition of aggregates improved the strength and service life of CEBs. Water absorption was reduced because aggregates are less sensitive to water than clay. Increasing the amount of aggregates also reduced the drying shrinkage of the blocks.

It is worth mentioning that to improve the performance of CEBs, compaction pressure has an important role. Mansour et al. [105], for instance, focused on increasing the thermal (thermal conductivity and thermal effusivity) and mechanical (compressive strength and modulus of elasticity) resistance of local pure CEBs manufactured using soil from the region of Sidi Amor (Tunisia). The compaction pressure reported was 0.39–3.16 MPa. This compaction pressure considerably affected the bulk density and the porosity of the CEB with variations from 1610 to 2194 kgm^{-3} and 41.6%–21.7%, respectively. For the same pressure range, the thermal conductivity increased between 0.618 and 1.483$Wm^{-1}K^{-1}$ and thermal effusivity from 657.5 to 1282.5 $Jm^{-2}K^{-1}s^{-1/2}$. The optimized bulk density obtained was 1750 kg m^{-3}, which reduced the thermal conductivity twice (to 0.75 Wm^{-1} K^{-1}) and provided a sufficient target compressive strength of 1 MPa.

Scanning electron microscopy was performed on CEBs by Sravan and Nagaraj to analyze the potential of using an enzyme as a stabilizer in the mixture of soil, cement, and lime [86]. According to their results, the changes in the macro-level properties of the blocks prepared with the enzyme are verified by the changes induced in the microstructure of the blocks.

Finally, it is noted that the reported research on agroindustrial, recycled and industrial waste based compositions of CEBs lacks statistical analysis such as one-way ANOVA or T-student to highlight or demonstrate the significance of the results. In addition, a lack of optimizations of the experimental campaign to reduce the specific proportions of stabilizers or reinforcements investigated is identified. These strategies can significantly reduce the number of experiments and, at the same time, enlarge the investigated mix ratios to obtain verified overall optimal mixtures. Efficient design of experiments to determine optimal constituent fractions and appropriate constituent ranges, as well as significant differences between control blocks, should be included in future research.

3.4. Applications and prediction modeling of CEBs

The design of reinforced CEB is generally affected by the associated porosity of the material. To determine the optimal fiber length, the model of Poullain is analyzed. The finite element method, considered as the most widely used prediction technique in engineering design, is also included. It allows to predict the response of CEB walls and units subjected to different force and environmental loads, in particular, the method calculates the load-carrying capacity, deformations, and thermal insulation performance.

3.4.1. Porosity prediction model

In fiber-reinforced compressed earth blocks, the overall porosity is dependent on the concentration and length of fibers [30]. This was determined based on the assumption of a porous interface between the fibers and the compressed earth matrix, but with a porosity greater than in the matrix, due to the decompaction of the material at the interface. The proposed model of Equation (1) for total porosity prediction of the CEB is a function of the concentration, diameter and length of the fibers.

$$\varphi_T = \varphi_i + \frac{\rho_m}{\rho_f}\alpha_f \frac{\left((\varphi_f - \varphi_i) + \varphi_i\left(1+\frac{2\delta}{D}\right)^2\left(1+\frac{2\delta}{L}\right)\right)}{1+\frac{\rho_m}{\rho_f}\alpha_f\left(1+\frac{2\delta}{D}\right)^2\left(1+\frac{2\delta}{L}\right)} \tag{1}$$

The subscripts *T*, *i*, *m* and *f* correspond to total, interface, matrix and fiber. In addition, $\varphi, \rho, \alpha_f, \delta, D, L$ correspond to porosity, density, percentage of fiber mass with respect to matrix mass, interphase thickness, average diameter, and fiber length, respectively. Fig. 6 shows the evolution of the total porosity of the blocks as a function of a given configuration for two cases: with the interface between the fiber and the matrix and without the interface. The model proposed by Poullain et al. [30] considers that the interface between the fiber and the earth matrix affects the total porosity of the CEB. The fiber length influences this porosity. However, when a linear model is used, no effect is observed. The model fits well with the experimental tests and can be used to determine the representative parameters of the mixture: interface thickness and interface porosity. The interface model must be fitted to the experimental data obtained for each fiber concentration. However, the model depends on the measurement of the diameter of the fibers, which is difficult to determine and time-consuming. In addition, the mechanical properties of CEBs are strongly influenced by the fibers, which are the combined effect of the decrease in porosity caused by the addition of fibers and the reinforcement of the material caused by the tensile strength of the fibers. The results of kenaf-reinforced CEB with three proportions (0.5%, 1%, and 1.5%) show an optimum fiber length that exceeds the limit of interest of fibers addition. For shorter lengths than the optimum value, the increased porosity of the material dictates the mechanical behavior, leading to a degradation of the mechanical properties in both bending and compression. However, it is necessary to evaluate the model and the findings in other CEBs reinforced with different types and nature of fibers.

3.4.2. Load and damage response predictions

Finite element modeling (FEM) have been used to calculate stress concentration factors around the holes of CEBs designed for vertical reinforcement [79]. Using this numerical tool, the flexural and compressive strengths of various CEBs with fourteen different mix designs produced experimentally with the same soil type were simulated. The results allowed demonstrating that CEBs can exceed the minimum strengths required for concrete masonry units. Goutsaya & Ntamack [40] used a numerical simulation method based on the nonlinear behavior law that couples isotropic elastic damage. A simple compression test of CEBs, and CSEBs with 4% and 8% cement was performed. The maximum stress and Young's modulus of the CEBs stabilized with 8% cement were higher than those obtained for the 4% stabilized and non-stabilized CEBs. The proposed model was very accurate compared to the experimental results, considering a good fit of the damage coefficient parameter. Finally, the study shows that it is possible to use the proposed model to predict the mechanical behavior of CEB and CSEB.

According the experimental and finite element analysis of Cottrell et al. [41], the geometry of compressed earth blocks significantly influences compressive and flexural strength. Their study investigated the nonlinear elastoplastic behavior by determining the compressive and flexural strength of solid CEBs with and without assembly grooves

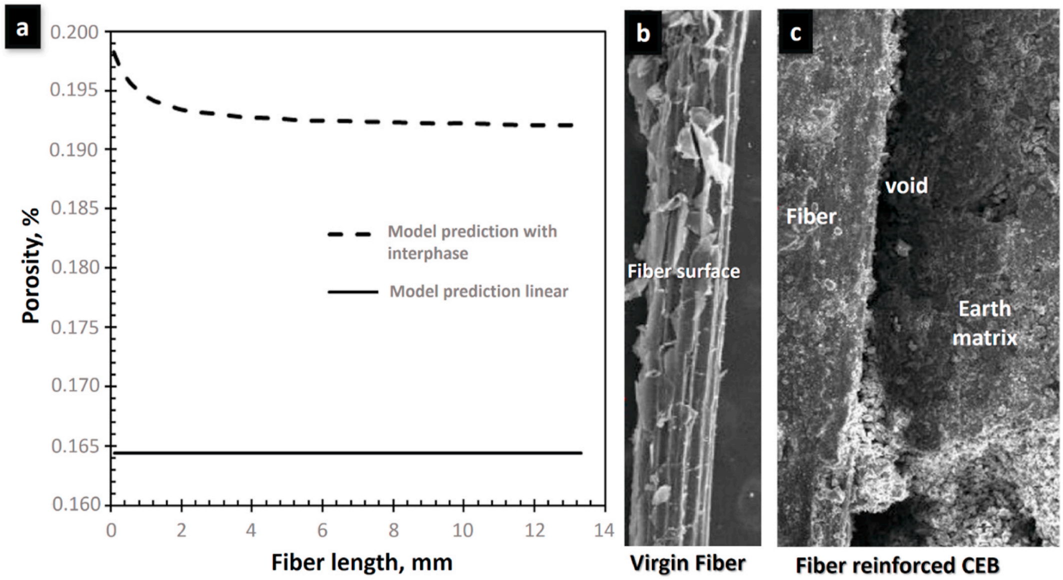

Fig. 6. (a) Prediction of porosity as a function of Kenaf fiber length considering a model with the interface and linear model (without interface) adapted from Ref. [30]. (b) Sugar cane fiber and (c) fiber-induced porosity of the soil matrix [58].

corresponding to 3.74 and 6.73 MPa and between 0.63 and 1.31 MPa, respectively. Furthermore, statistical analysis indicates that the solid block demonstrates significantly higher stress and strain values and significant partial differences between a solid block with grooves and a hollow block. The hollow block achieved higher mean stress and strain values than the slotted block, as determined by the 3-point compression and bending test.

It is worth noting that for predicting the behavior of loaded CEBs using the finite element method, the Solid65-3D element implemented in ANSYS Workbench 19.1 software has been shown to provide correct prediction results [41]. The element, generally used for modeling concrete, contains three degrees of freedom of linear motion (x, y, z) at each of its eight nodes, representing the plastic behavior of the material, the crushing stress, and the occurrence of cracks. To calibrate the model in

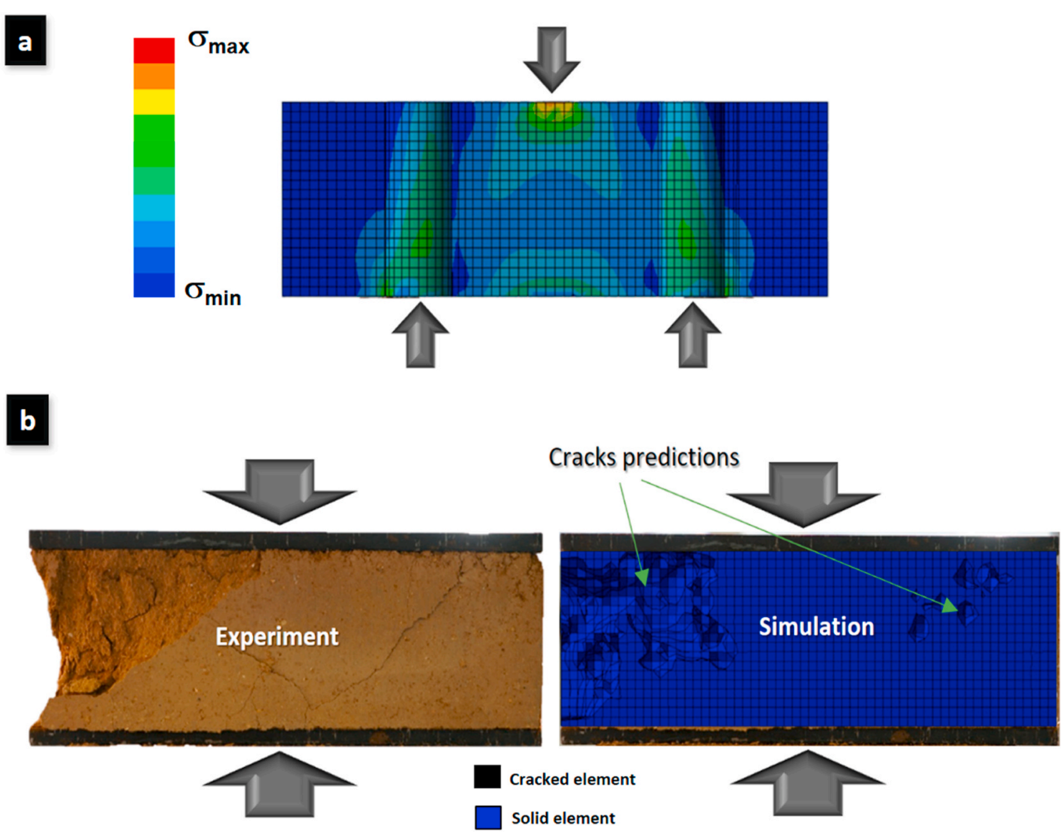

Fig. 7. Finite element prediction of loaded CEBs adapted from Cottrell et al. [41]. (a) Stress distribution during a three-point bending test. (b) Cracks correlation between experiment and simulation of a compression test.

the element, it is necessary to introduce the experimental curve of uniaxial compression vs. uniaxial strain relationship discretized in points until the appearance of cracks and fracture of the block. The simulation results shown in Fig. 7a with the finite element model are the stress distribution, and in Fig. 7b a damage model predicts the cracks formation. Deformation and displacement fields obtained with this computational tool are also results of interest for the engineering design of CEBs.

3.4.3. CEB wall performance under thermal, environmental and out-of-plane loadings

The lack of an established or standardized test methodology for earth-based building materials has already been highlighted. In addition, considering that the strength and durability of blocks are generally indicated for compression and tensile based on the three-point bending test, a brief section of studies focused on out-of-plane loads in composite walls of CEBs: force, thermal, and environmental loading conditions is addressed.

The compressive strength, thermal conductivity, thermal capacity, and water vapor permeability of CSEBs produced by eight brick factories in Senegal were evaluated [106]. The determining compressive strength of the CSEBs produced by these factories was found insufficient for the application of load-bearing walls according to the African standard ARS 674. The average thermal conductivity obtained was 0.75 W m-1 K-1 and an average specific heat of 1040 J kg-1 K-1, with a coefficient of variation of 8% and 7%, respectively. These values are indicators that the CSEB may have good thermal inertia. In addition, the water vapor permeability values obtained for bricks from four factories show low water vapor resistance and good interior moisture regulation capacity.

The optimal thermal performance of a CEB building with three different external wall layer designs and two ventilation scenarios was determined by Hema et al. [43]. The daytime overheating was reduced by using a layer of CEB on the inside and insulation on the outside of the building made with CEB. In contrast, walls with a CEB layer on the outside and an insulation layer on the inside are more suitable for spaces occupied only at night. Malbila et al. [107] also reported the thermal performance of walls designed with CEBs for Ouagadougou City. Their simulation results obtained with EnergyPlus™ software show that the number of hours of thermal discomfort and the energy required for air conditioning were reduced by about 10 % and 94 %, respectively, compared to cement walls.

The durability of prisms and walls constructed with CEBs and evaluated experimentally by performing wetting and drying cycles of the walls has also been reported [67]. Two types of mortar were utilized to bond the CEBs, cement and an earth-based mortar. The water content in the earth-based mortar that provides the best bond and compressive strength was 30%. Moreover, the cement mortar for the construction of prisms and walls was 80% and 60% stronger than its their counterparts constructed from CEBs using earth-based mortars.

Laursen et al. [108] investigated the load-bearing behavior of walls by applying structural analysis of 5 interlocking CEB walls designed according to practices used in Indonesia and Thailand. The obtained behavior and failure of the walls were dominated by bending (out-of--plane loads). However, the particulars type of blocks, wall geometry, and construction method could provide different results and for other block types and wall designs, the validation should be determined by specific structural tests such as Masonry Standards Joint Committee 2013 [109]. In addition, Saad et al. [110] also investigated out-of-plane loads to evaluate the effect of using carbon fiber-reinforced polymer (CFRP) laminates in the production of CEBs on wall performance. The three half-scale walls experimentally tested using quasi-static loads in the out-of-plane direction showed that a higher percentage of stabilizers improves the walls performance of CEBs in the out-of-plane direction, increasing stiffness, strength, displacements, and dissipated energy response. However, when comparing the results obtained with walls made with concrete units or blocks, a lower resistance capacity was still obtained.

The finite element method is a useful tool with high potential for the design and prediction of thermal, strength and durability capacities of CEBs. However, according to the analyzed studies, there is a lack of computational analysis of CEBs and CEBs under application loads. Furthermore, it is necessary to consider appropriate models that allow the correct prediction of the behavior of CEB units and CEB wall.

Based on this review and analysis of the performance of CEBs produced from different proportions of constituents, mixtures and techniques, further research is needed to develop high performance CEBs from industrial and agro-industrial by-products. The new findings should include the source of error in the experimental results reported by various research studies, as optimal experimental design and statistical analysis are generally not applied to determine the optimal mixtures and significance of the results. Finally, this low-energy earth building element is novel and supports the transition to a low-carbon future established by the United Nations Framework Convention on Climate Change. To tackle climate change, policy makers should carefully consider these findings, because while some reports may indicate that these earthen building units are not applicable in certain areas or countries, other manufacturing strategies and methods not discovered or reported in scientific papers may demonstrate that this CEB technology is fully feasible and applicable to the construction industry.

4. Conclusions

The main reported advances and challenges in the development and manufacturing of high quality compressed earth blocks (CEBs), stabilized and reinforced with industrial and agro-industrial by products is discussed and analyzed. This work is the baseline for future research projects focused on improving the performance characteristics of compressed earth blocks with local, natural and reusable materials. Recent trends and significant advances achieved are also synthesized, providing research gaps and the need for future research based on the global challenge of carbon emissions reduction. From this review, the following general conclusions related to the engineering design of CEB are summarized:

- Manufacturing a compressed earth block with good characteristics requires testing and evaluating its constituents and manufacturing parameters. Among the factors that dominate the stability, performance, quality, and durability of the block are the manufacturing pressure, curing time, humidity, percentage and dimensions of additives or reinforcements, percentage of stabilizers, amount of water, and soil type.
- The fibers are incorporated to reinforce the CEB, improving mechanical characteristics such as tensile strength and crack resistance.
- Stabilizers in CEBs enhance the cohesion of the particles of the mixed materials by chemical reactions, originating new compounds with higher mechanical resistance and lower permeability. Among the most commonly used stabilizers are lime and cement. There is a trend to search for new efficient pozzolans of industrial origin and agro-industrial waste to mitigate the carbon footprint.
- Non-stabilized CEBs generally exhibit lower durability and strength than ash-stabilized or fiber-reinforced CEBs.

Among the articles reviewed, limited to those in the Web of Science database over the last decade, there is a lack of studies reporting on the hardness resistance of CEBs to punching loads, resistance to fire, and resistance to impact loads. The evaluation of walls subjected to out-of-plane loads that simulate the wind or seismic loads (cyclic loads) has not been widely addressed. Concerning hygiene, it is recommended to include studies that determine the fungicidal effect and the bacterial characterization of CEBs. The quantification of the carbon footprint in the production of the blocks or walls and their comparison with other construction methods, such as fired bricks, is also highly suggested.

The reported studies should also include statistical analysis such as one-way ANOVA or T-student to highlight or demonstrate the significance of the results. Particularly, an efficient design of experiments to determine optimal constituent fractions and adequate constituent ranges, as well as significant differences between control blocks is also lacking.

Among the tools and calculation methods for the application of CEBs, the finite element method is highlighted as a useful tool with a high potential for engineering design and prediction of the thermal, strength, and durability capacities of CEBs. However, studies indicate that it is necessary to consider adequate models that allow the correct prediction of the behavior of the investigated CEB units and CEB walls.

The sustainability trend of substituting cement and lime with agricultural and industrial by-products such as calcium carbide waste, sawdust ash, cassava, rice husks, or polyethylene food packaging is highlighted. For an important contribution to the development of sustainable and environmentally friendly construction, it is necessary to propose and investigate new stabilizers or natural additives and their appropriate incorporation into CEBs.

Finally, to tackle climate change, policy makers should carefully consider this review, because while some reports may indicate that CEBs units are not applicable in certain areas or countries, other manufacturing strategies and methods not discovered or reported in scientific papers may demonstrate that this technology is fully feasible and applicable to the construction industry.

Author contributions

Conceptualization, M.V. and V.T.; Methodology, M.V., V.T., G.C.; Formal analysis, M.V.; Investigation, M.V.; Resources, V.T.; Data curation, M.V.; Writing – original draft preparation, M.V., V.T.; writing-review and editing, G.C., J.P.C., C.M., A.O., G.P., A.S., S.A.; Visualization, M. V.; Supervision, G. C., V. T.; Project administration, M.V., V.T., G.C.; Funding acquisition, M. V. All authors have read and agreed to the published version of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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