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Compressed Stabilized Earthen Blocks and Their Use in Low-Cost Social Housing

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Abstract: Earthen techniques have been historically used in construction of housing in Africa, Asia and Latin America. In the past two decades the interest in earthen material has grown considerably, leading to the development of sustainable materials such as compressed earth blocks (CEB), compressed stabilized earth blocks (CSEB) and interlocking stabilized soil blocks (ISSB). Scientific publications from various countries and context have examined the physical aspects of these earthen building materials, but so far, the results are not well connected to housing practices for and by low-income households with their self-organizing skills. This research sought to close this gap by documenting the housing projects where earth blocks are applied in participatory social housing. The study provides an overview of relevant practical examples from the three world regions (Africa, Asia and Latin America), with their cultural and climatic differences, and an analysis of similarities and possibilities. Based on the lessons learned from these examples, recommendations are made on further research on sustainable building materials within social housing practices, which can benefit the scientific community. We propose to set up a worldwide database of housing projects where earthen techniques have been applied responsibly. We conclude and recommend that more high-quality pilot projects with CSEB and ISSB are needed to get a broader picture on the potential of these materials for social housing, and the necessary support for local communities wishing to be involved in these sustainable housing practices.

Keywords: CEB; CSEB; ISSB; low-cost housing; social housing; earthen construction

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1. Introduction

Worldwide, there is a huge housing shortage, which is illustrated by projections from international institutions such as United Nations (UN). The UN has estimated that three billion people will need access to adequate housing by the year 2030. The global housing challenge demands a massive housing production for households with low incomes, and more specifically for those being in severe need of a decent house, including the homeless [1]. Estimations of the World Bank Group show that across the sample of 64 emerging economies, there is a current housing deficit of 268 million housing units affecting 1.26 billion people. Moreover, about 55 percent of the world's population that currently resides in urban settlements is expected to increase significantly by 2030, adding an estimated 1.6 billion people to urban areas [2].

The above data reinforces the urgency and extent of housing challenge, especially related to households with low incomes, who are increasingly confronted with scarcity of land to build a home together with sharply rising land and real estate prices. In addition, future housing construction must be sustainable and therefore, eco-friendly, resilient and circular, which is lacking in contemporary housing construction and low-cost housing practices. Acioly [3] has mentioned that "housing is multi-dimensional, multi-disciplinary and multi-institutional, and has a range of economic, political, social, legal and technological attributes that influence policy options and the behaviour of providers and consumers in the market". This means that among other things the following issues must be addressed in affordable housing projects: stakeholder arrangements, building skills- and knowledge development, affordable housing design, sustainable building materials and construction techniques.

While there are different routes to create affordable housing, sustainable construction materials offer interesting possibilities for cost reduction, as construction materials constitute a major portion of the total cost of a house. The interest in sustainable and environmental friendly building materials for housing is rising globally especially due to growing concern on harmful environmental impact of conventional building materials such as concrete and fired bricks. As alternatives to these materials, earthen construction materials are seen as promising [4].

Several non-governmental organisations (NGOs) are involved globally in building low-cost housing with earth. Despite the rising interest and research on the improvement of properties of earthen materials and on low-cost social housing, there is a lack of scientific literature that provide information on low-cost social housing with earth [5–8]. Therefore, this article discusses the use of earthen materials for low-cost housing, including other infrastructure such as schools and community centres. Due to diversity of earthen techniques used in building structures, this article is restricted to the use of earth block techniques for walls, namely compressed earth blocks (CEB), compressed stabilized earth blocks (CSEB), interlocking stabilized soil blocks (ISSB) and adobe building blocks. These techniques will be discussed throughout the article with a specific attention to its use in Africa, Asia and Latin America. The article attempts to bridge the gap between the technological development of earthen blocks and their implementation in low-cost housing projects. As well as the focus on the materials, the authors also focus on the application of these materials in social housing programs and projects in several countries that are spread over three continents.

The first research question explored in this research is whether it is possible to compile and draw conclusions from the practical applications of CEB/CSEB/ISSB in social housing. The second research question is if the scaling up of housing production with CEB/CSEB/ISSB is possible, how can that be realised, and where could it be realised the best?

Although earthen technologies with CEB/CSEB/ISSB are present in each of the three continents, its application in social housing projects is not very widespread. Therefore, we have also provided recommendations on improving housing production with CEB/CSEB/ISSB. We also evaluated if the research practice is in line with the need to intensify social housing production globally, including the use of sustainable earthen techniques, as envisioned in the Millennium Development Goals.

The authors have been able to visit some projects/practices themselves, including in India, Thailand, Uganda and El Salvador, where local actors, including homeowners and villagers, were questioned. Where possible, research institutions were visited, such as Auroville Earth Institute in India and FUNDASAL's research department for building materials in El Salvador. The authors have also been in contact with research institutions in the Netherlands such as TU Delft, TNO, LEVS Architects and Oskam vf., which are actors involved in research and development of sustainable building materials, especially for application in Africa.

The structure of this article is as follows. Section 2 focuses on the necessary shift from mainstream to more sustainable building materials, the latter being earthen materials and its corresponding new construction techniques. Thereafter, Sections 3–5 present the case studies concerning earthen building blocks used for walling in low-cost social housing projects in Africa (3), Asia (4) and Latin America (5), respectively. In Section 6 the research on earthen blocks in low-cost housing is being evaluated. Section 7 discusses the development of earthen blocks for low-cost housing with emphasis on eco-friendly stabilizers for future low-cost housing projects.

2. From Mainstream to Sustainable Building Materials

2.1. Current Mainstream Building Materials for Housing

Popular building materials used in low-cost housing such as fired bricks and concrete blocks can provide a good construction, but are expensive, energy-intensive and often based on industrial production [6,9,10]. A brief overview of common building materials for exterior walls of low-cost housing construction is provided below.

Fired clay bricks (see Figure 1a)

Figure 1. Mainstream building materials for walls used for low-cost housing: (**a**) fired brick wall in Uganda; (**b**) wall of hollow terracotta bricks in Brazil; (**c**) hollow concrete blocks for housing in Nicaragua; (**d**) wall of adobe blocks in El Salvador. Sources: Bredenoord.

Production of traditional fired bricks made out of clay have negative effects on the climate. Firing produces smoke and smog—if conducted in or near the cities- and causes extreme carbon dioxide emissions [11]. If fired with wood, it causes deforestation. The bricks' quality is not always constant and this leads to low quality bricks and inefficiency in the use of raw materials and mortar. Good quality bricks can be durable and are often used, also for stacked construction.

Terracotta bricks (see Figure 1b)

Hollow terracotta bricks are used for housing construction, mainly in cities. The quality of the bricks is optimal given the limited amount of clay used, but these are not seen as sustainable. Terracotta bricks are often used in between frames of concrete. Plastering of exterior walls is mostly desirable.

Concrete building blocks (see Figure 1c)

The use of hollow concrete blocks is mainstream in many countries. The structural quality is mostly acceptable, but they are regarded as unsustainable due to high quantity of cement used in making them. Plastering of the walls is desirable.

Earthen materials (see Figure 1d)

Earthen materials such as adobe and cob are often used for housing mainly in rural areas of Latin America, India and Africa. Earthen materials are mostly inexpensive, readily available and require minimal processing before use. Due to their low or no carbon dioxide emission, they are considered sustainable. Nowadays, modern earthen construction technique such as compressed stabilized earth block is also used in housing projects.

This overview shows the mainstream building blocks and bricks for housing. More examples of such materials can be found in construction practice. The materials can be compared on the basis of relevant properties, such as strength and durability, weight, thermal insulation, sound insulation, energy efficiency, water resistance, mortar consumption, etc. This research focuses on the use of CEB/CSEB as substitutes for mainstream building materials (see an overview in Figure 1). The use of adobe building blocks is traditional in many countries, but the use of adobe for walls has often been problematic in case of earthquakes and floods (see also Section 3). However, adobe building blocks can be applied responsibly if their properties are improved to the level of the properties of CSEB.

2.2. Development of Earthen Materials and Techniques

Earth or mud is an abundant resource on our planet that has been used as a construction material for over 10,000 years [12]. Building walls with earth is common in Asia, Africa, the Middle East and Latin America, North America and in some European countries. It is estimated that 8–10% of the world population currently live in earthen houses [13]. This proportion is about 20–25% for low- and middle-income countries.

Earth or soil is widely available resource which is a mix of solid aggregates (or particles) such as clay, silt, sand and gravels. The distinction between these aggregates is their size as represented in Figure 2. The clays are the smallest of the aggregates and act as binder. Soils often also contain water, salts and other organic minerals. The earthen material or elements such as wall is formed by mixing soil with desired amount of water thoroughly and giving shape to this mixture. The process of shaping the wet earth is also referred to as construction techniques. Some of the most common traditional earthen construction techniques are wattle and daub, adobe, rammed earth and cob.

Figure 2. Composition of earth or soil based on ISO14688-2019, a guideline that specifies rules for identification and classification of soil. The aggregates of soils are represented with their size ranges as suggested in ISO14688-2019 [14]. Source: Kulshreshtha.

One of the earliest earthen walls were constructed with woven reeds and branches covered with mud (referred to as wattle and daub technique) around 8500 BC, but blocks such as adobe (handmade unfired bricks) soon became popular (around 8400 BC). The rammed earth technique which includes thick monolithic wall constructed with rammed layers of soil is reported to be used since 1320 BC [15]. Whereas cob construction, in which a thick monolithic wall raised from the foundation, is known to have existed from 1400 AD [16]. While most of these earthen construction techniques (especially adobe, wattle and daub, and cob) are seen in rural areas, they have been used successively used in mass housing in ancient settlements such as Taos Pueblo in Mexico (1000 AD), Fujian in China (between 15th and 20th century) and Shibam in Yemen (18th century) [17,18].

The selection of soil and preparation of appropriate mixture is important for construction of high-quality earthen buildings. However, soil available locally may not always be suitable for construction. Therefore, soil is often modified by (i) adding extra clay or sand, (ii) compaction or (iii) adding a binder such as Portland cement or hydraulic lime. A binder (also commonly referred as stabilizer) is usually added to the soil to achieve a higher compressive strength and water resistance.

In addition to aforementioned traditional earthen construction techniques, modern earthen construction techniques have been invented in past decades which produce a higher quality of earthen material. A major leap in quality was made possible by the introduction of hand presses and mechanized presses to make compressed earth blocks (CEB), which is a widespread modern earthen technique in which soil is compacted with a manual or a hydraulic press. Due to compaction process, these blocks are denser, stronger and dimensionally more uniform than adobe. These blocks are often stabilized with a mineral binder such as cement or hydraulic lime and referred to as compressed stabilised earthen block (CSEB). One other form of CSEB is known as an interlocking stabilised soil block (ISSB). The distinction between CSEB and ISSB is not always clear, but the appearance of the walls hardly differs. ISSB is an interlocking building block, which has the potential of bricklaying without joints/mortar. Asian forms of ISSB usually have cavities, through which the walls can be reinforced or strengthened internally, by means of reinforcement iron and grout. Solid rectangular building blocks do not have cavities and walls often need to be reinforced externally which is usually achieved with frames of reinforced concrete beams and columns. In general, CSEB/ISSB are stabilized with 5–12% cement or hydraulic lime.

One of the first compressed block making machine, for example, the Cinva Ram press was developed in 1952 by Raul Ramirez in Colombia. The blocks made with it were stronger and more water resistant than adobe. Since the 1960s, many projects have been executed with earthen techniques to improve homes and other buildings. New presses were further developed in India by the Auroville Earth Institute (AVEI) and the Indian Institute of Science of Bangalore (IISc) for CEB and CSEB. The development of ISSB in Thailand has gone through several stages and that has led to high-quality earthen building blocks that can be strengthened internally (through cavities) [19]. In Thailand and Sri Lanka, CSEB or ISSB have been developed according to their own standards, as have been in New Zealand, Australia and the US. In France, CRAterre-ENSAG promotes earth techniques and is a centre of expertise of the UNESCO chair 'Earthen Architecture, Constructive Cultures and Sustainable development' [20]. They have developed educational material that supports construction with earth.

The search for 'affordable and sustainable building materials for housing' received a new impulse from UN-Habitat in the first decade of this century. Several pilot projects have used earthen technologies such as CSEB and ISSB. Earthen technologies were promoted for housing for low-income households due to their environmental, social and economic benefits. Moreover, UN-habitat has recommended the use of local soil for producing compressed blocks [4]. They have also indicated that the low-cost houses should be preferably built by local families, communities and small local enterprises. Knowledge transfer on CSEB to local communities and small businesses is essential. Such viewpoints and ambition are also shared by European Union and NGOs such as Habitat for Humanity. The Compressed Stabilized Earth Block (CSEB) production for low-cost housing is also supported in Sri Lanka [20]. Another example is the support for Compressed Earth Bricks and community enterprises is a project developed by the Nepalese NGO Community Impact Nepal, which is supported by UN-Habitat [8].

Environmentally friendly building materials and building technologies can thus be made more accessible to the urban poor, while meeting building standards and lowering the impact of the environment and the climate. Compared to fired building blocks and concrete blocks, CEB/CSEB and ISSB offer great advantages. Earthen materials improve indoor air quality and thermal comfort [21]. They consume minimal energy for material production and reduce operational energy use [22,23]. The transportation costs are also reduced due to local resource utilisation [24]. While the cost of earthen building depends on factors such as location, availability of material and labour, the economic advantage of building with earth are widely acknowledged. Earthen houses are claimed to be up to 35% cheaper than concrete construction [25]. In a study in India, Cement stabilized CSEBs were reported to be 15% cheaper than fired bricks [26]. The environmental footprint of earthen building is also known to be significantly lower than conventional building materials. Fernandes et al. [27] reported that the environmental footprint of CSEB was around half to that of fired bricks and concrete blocks. Venkatarama Reddy and Kumar [28] found that the embodied energy of stabilized earthen material was up to 25% lower than the fired bricks.

The CSEB/ISSB are already used for walls for housing, schools, sanitary facilities and kitchens. The CEB, CSEB and ISSB can be bricked within reinforced concrete frames with columns and beams. Thus, the blocks themselves do not have to be load bearing. The shapes of the interlocking blocks can differ greatly. This building technology allows multy-story buildings (at least two to three floors) to be built as the openings in the blocks are being used for structural reinforcement of buildings. Reinforcement iron is used with grout, which together creates internal columns and beams within the walls. These reinforcements are also not visible. Some of the examples of CSEB and ISSB is shown in Figure 3.

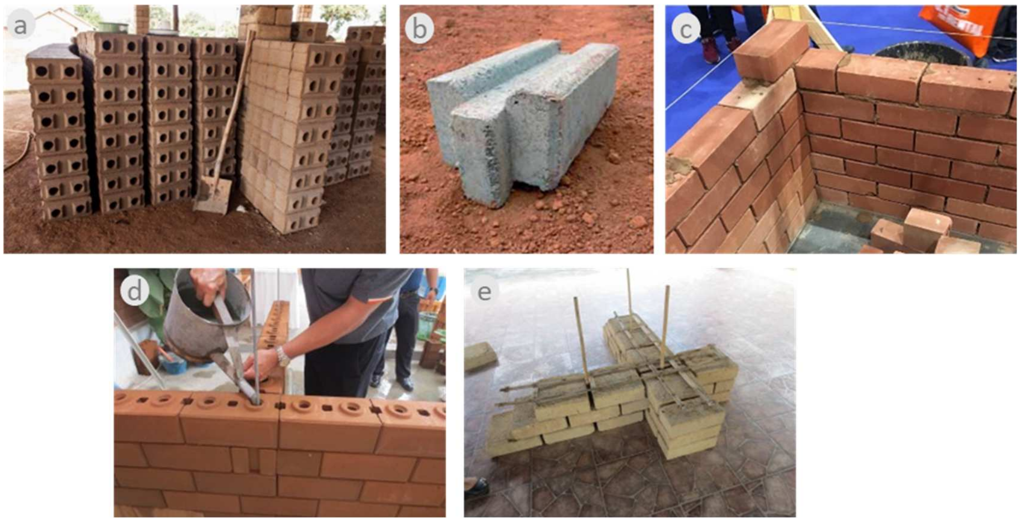

Figure 3. A collection of various compressed stabilized earth block (CSEB) and interlocking stabilized soil block (ISSB). (**a**) ISSB in Uganda (model 'Tanzania'); (**b**) interlocking Hydraform ISSB Uganda; (**c**) rectangular loam bricks for Mali; (**d**) Interlocking blocks Thailand; (**e**) adobe blocks for walls El Salvador. Source: Bredenoord.

Since around 2000 international attention for CEB-CSEB/ISSB technologies has risen throughout the world. Rocha [29] described CEB/CSEB as a material with sustainable properties, low environmental impact, great eco-design capacity and possibility to build houses with two and three floors. The three-story residential building of Auroville in India is an example of such multi-storey building.

Salami [30] shows the potentials of the CEB technology in relation to self-help housing, that is seen as a solution to the affordable housing crisis in sub-Saharan Africa. Salami states that CSEB technology might represent an evolution of the adobe (mud) bricks towards adequate load-bearing capacity, suitability, durability and easy maintenance of housing. As such, CEB could serve as an alternative to conventional building materials in the provision of low-cost housing combined with poverty alleviation through self-help. This indeed is relevant because most families in developing countries are self-builders. The training on CEB technologies could empower local families that want to create low-cost houses. Four factors that are connected to the assimilation of CEB technology into self-help housing practices worldwide are: (1) security of tenure; (2) affordability; (3) capacity of individuals, households and resident groups; and (4) sustainability in social organization. There are several aid organizations that offer the CEB building technology to groups of residents and local communities, all in the context of poverty alleviation. Several examples of these type of project are described in this article.

The aforementioned discussion indicate that the production of the building blocks must be conducted professionally to ensure high quality. In the self-construction of houses with these blocks by families, the residents can be involved because bricklaying is relatively simple so that they can cooperate under the responsibility of professional masons. In several countries there are already factories that produce and sell CEB and CSEB on the market. Examples of projects from CEB, CSEB and ISSB from various countries are discussed in the following section.

3. Earthen Building Blocks in Africa

3.1. Humid Tropical Climate in Central Africa: Earthen Bricks in Uganda

In Uganda, UN-Habitat was involved in several housing projects realized with CSEB, such as schools, health centres, toilet blocks and housing [31]. Nambatya [7] studied Interlocking Stabilized Soil Blocks (ISSB) technology in Uganda, where cement was added to soil and compressed. Nambatya stated that ISSB is an environmentally friendly alternative and technically superior to fired bricks. ISSBs are more cost-effective per square meter with up to 40% cost savings accruing from dry stacking and less mortar for plastering and rendering. ISSB block presses are widely available in Uganda, with Makiga and Hydraform as local suppliers. Hydraform realized various affordable housing projects in Uganda with the help of NGOs, social enterprises and commercial enterprises [32]. HYT Uganda has built affordable housing for child-headed families (without parents), community centres and water tanks, among other things [33]. Both Hydraform and HYT use the interlocking stabilized soil block (ISSB) in Uganda, as shown in Figure 4.

Figure 4. Earth bricks used in Uganda: (**a**) storage of CSEB in Jinja ('Tanzania' Brick); (**b**) house built with ISSB of Hydraform; (**c**) house under construction with Hydraform ISSB. Source: (**a**) Bredenoord, (**b**) Hydraform Uganda, (**c**) HYT Uganda.

The National Slum Dwellers Federation of Uganda, together with the NGO Actogether and SDI (Slum Dwellers International) realized a community facility and training centre in the city of Jinja, that was built for the production of climate-friendly building materials, including CSEB and ISSB. There, the local youth are trained in the construction trade so that they can obtain regular incomes, among other things by selling their materials, and helping families in building their own homes with CSEB [34]. A housing project for Jinja's countryside has delivered 450 sustainable low-cost homes. The homes are built for grandmothers who lived in poor, dusty and leaky homes, often without sanitation and electricity. These grandmothers have care over their grandchildren because their parents have died. These homes were made possible with the help of donations [35]. In this case the bricks were pressed in a mobile hydraulic press of Oskam. The CSEBs made of ordinary non-organic soil, sand, a low percentage of cement and water. Depending on the mixture, the blocks were stored and dried in a shed for some days, before it was used for wall masonry [36]. These blocks are shown in Figure 5.

Another example in Uganda is the work of the social enterprise Smart Havens Africa (SHA) that addresses social inclusion by working with women in house construction. Herewith, employment was created for many women. SHA completed several projects with the use of ISSB which is seen as environmentally friendly and cost effective. One of their projects is ISSB Housing Scheme, which uses a pay-as-you-go model, allows clients to be able to save and buy these ISSB blocks at their own pace. SHA has completed several housing projects with the use of ISSB, which is seen as low-cost and environmental-friendly building material for housing [37].

Figure 5. Earth blocks in Uganda: (**a**) rectangular earthen building block, (**b**) storage of CSEB, (**c**) houses built with CSEB. Sources: Oskam and Grannies2Grannies.

3.2. Dry Climate in West Africa: Mali, Senegal and Burkina Faso

In West-African countries the climate is dry and landscape circumstances differ very much from the tropical region of Central Africa. In Mali, an example of earthen building blocks can be found in a project of 300 houses in Bamako, commissioned by the Ministry of Urban Development and Housing (Figure 6). Building blocks are produced with a mobile installation that manufactures hydraulically compressed earthen blocks (called HCEB). The building blocks are rectangular earthen bricks that are built with mortar of only 0.5 cm. In these blocks, cement was not used, which is feasible in the dry climate. However, for the load-bearing walls, a small percentage of lime was be used as a stabilizer. The Dutch enterprise Oskam-vf. supplied the technology and the machines for this and other projects in Africa. Its partners LEVS Architects from Amsterdam and TNO are conducting research on cementless compressed earthen building blocks. Research on local resources in Senegal has shown that local and cheap (waste) resources are available to make a 100% locally cementless compressed earth block [38]. Other construction projects carried out with the same building blocks are a practical training college in Sangha, Mali, a community centre in Wadouba and two schools in different villages, all in Mali [39]. A description of modern building with earth in Africa is given by [40].

Figure 6. Social housing project in Bamako, Mali. Source: LEVS Architects.

Other examples in West Africa originates from the work of architect Francis Kéré from Burkina Faso, who designed and built a series of schools with similar compressed earthen building blocks, which were rectangular in shape. The architect also designed the Centre for Earth Architecture in Mopti, Mali, with 7% cement added to the CSEB for greater stability [41]. Despite these good examples, there is a great reluctance in Burkina Faso among families to use CEB as a building material [42,43]. This is the result of a negative image about local building materials among the population, such as CEB. This is still too often seen as a building material of the poor, and the qualities of CSEB are often questioned—something that can only be changed by good education and well-executed demonstration projects [44].

4. Earthen Building Blocks in Asia

4.1. CSEB in Various Climatic Zones of India

India has a variety of bio-climatic zones: cold and cloudy, hot and dry, warm and humid, and composite. Traditional building techniques such as cob, wattle and daub and adobe are used in rural areas. Modern earthen techniques such as CSEB is gaining popularity. Organizations such as Infrastructure Development Finance Company (IDFC)-Rural Development Network, have recommended that the government of India promote earth construction [45]. The greatest potential for the application of modern earth technologies are in the rural areas due to the availability of raw materials, low incomes and poor housing. The poor rural areas require housing production for millions of families who are in need of good quality housing.

Several organizations in India are active in building with earth, especially using CSEB in their project. Several institutes and organizations are advocating ecological construction with CEB in India. Some of these organizations such as Auroville Earth Institute (Auroville), Hunnershala (Bhuj), Mrinmayee (Bangalore) and Development Alternatives (Delhi) have carried out projects with CSEB in India and their work is briefly discussed below.

Auroville Earth Institute (AVEI) is a centre of expertise in earthen material and technology that organizes courses and training regarding the production and application of CSEB. It has also developed (in partnership) the Auram press, which is capable of producing CSEB with up to 7.5 MPa compressive strength, allowing the construction of multi-storey buildings, arches, vaults and domes. The variability of size and shape gives CSEB versatility in appearance and applicability. The Auram press 3000 has been sold to many countries on all continents around the world. Over the years, the AVEI expertise centre has realized several buildings with CSEB, including three- and four-storey residential apartment buildings [46]. An apartment building complex of 13 units on 4 floors and a collective kitchen was realized with the Vikas Community in Auroville, an international township in Tamil Nadu, near the city of Pondicherry. The project was a finalist for the World Habitat Award in 2001 [47]. Earth was used in all parts of the building. The areas where the soil was extracted were planned first and the excavated soil was used in construction. In the building project appropriate design and self-build methods have both been used. For the buildings, compressed stabilized earth blocks (CSEB) were used together with ferrocement elements and other appropriate building technologies. The foundation was made with stabilized rammed earth (5% cement stabilization) and the walls with CSEB (5% cement stabilization). Lime-stabilized earth plasters were used on selected walls. Several cost-effective houses were also built in or near the Auroville complex [46]. Several private companies in India market ISSB as 'Solid Rectangular Compressed Stabilized Earth Block', with the dimensions $30 \times 15 \times 9$ cm.

Hunnershala is one of the organizations that has worked in construction of earthen houses for low-income households. It is known for its role in rehabilitation of houses in Gujarat after the catastrophic earthquake in 2001 and other post-disaster rehabilitation construction. In partnership with Mrinmayee, it has been active in production and application of CSEB in post-disaster housing [48]. Mrinmayee has developed an earthen press named 'Mardini', which produces CSEB (with cement/lime) of $30.5 \times 14.3 \times 10$ cm. In fact, their efforts have resulted in construction of over 20,000 CSEB houses in past three decades [6].

Delhi based Development Alternative is an organization that has developed their earthen technology to suit the needs of low-income communities [49]. It has developed the TARA Balram press which is capable of producing CSEB of various sizes (such as $23 \times 11.5 \times 7.5$ cm). The blocks produced by it uses 4–8% cement giving compressive strength of 3.5–7 MPa [50].

Academic institutes such as the Indian Institute of Science (IISc) in Bangalore are active in research and development of earthen construction and have produced several scientific outputs related to it. The engineers trained in the Application of Science and Technology for Rural Areas centre (ASTRA) at IISc have contributed significantly to the dissemination of the CSEB technique. The availability of the CSEB-making press at reduced rates and its increase usage in contemporary construction has made it cost-effective and desirable. In fact, it was reported that more than 600,000 blocks have been produced (with a hydraulic press) and sold in just 2 years by an entrepreneur in Tirthahally village, Karnataka [6].

In the state of Kerala (south India), over 15 Nirmithi Kendra (Building centres) are spread across the state that train workers in low-cost construction techniques, producing and selling low-cost building materials, employment generation, housing guidance and counselling [51]. Inspired by their success, the Housing and Urban Development Corporation of India (HUDCO) reported the establishment of more than 500 building centres in the country and claimed to impart training to over 300,000 artisans on cost effective, environmental and energy efficient building techniques [52]. One of the main challenge involved in wide spread application of earth in India is its low social acceptance.

In 2001, a massive earthquake devastated huge areas of the district of Kutch in the state of Gujarat. Rehabilitation was planned by the government and NGOs realized its aid programs for housing reconstruction. For example, the Catholic Relief Services assisted on several rehabilitation programs and built 2698 houses of various types in 39 villages (Figure 7). They produced about 8 million hollow interlocking blocks for earthquake resistance and trained/employed more than 2000 people. The technology with hollow interlocking blocks (called CSEB then) was developed by Auroville Earth Institute and approved by the Gujarat State Government. The average wet compressive strength achieved with local soil and 8–9% cement was around 50 KG/cm^2 (5 MPa) [42].

Figure 7. (**a**) Contemporary CSEB used in Gujarat; (**b**) wall with CSEB built for housing in Gujarat (2002). Sources: (**a**) Indiamart.com; (**b**) Catholic relief services.

After the catastrophic cyclone in Odisa state in east India in 1999, organization including centre of sustainable solutions used ISSB for construction of 1450 housing units. To ensure standard quality of blocks, a central production unit was established in between villages and block was produced using local soil [53].

4.2. ISSB in Southeast Asia

4.2.1. ISSB in Thailand

Since the mid-1980s, interlocking stabilized soil blocks (ISSB) developed in Thailand have benefited households, local communities, and small and medium enterprises. The ISSB are made of local raw materials which are mixed and compressed by using hand presses. It performs enough compressive strength of the building blocks which can be used for house construction: outer walls, inner walls, both with load bearing capacity. The construction process using ISSBs and the developed building technology result normally in rapid and cost-effective construction. The government stimulates the establishment of new businesses and the creation of jobs in the rural communities. The use of ISSBs in the construction of homes, sanitary facilities and water tanks is seen as a sustainable 'green' building technology. The involvement of local households and communities is a social sustainability goal, that is reached by the promotion of the use of ISSBs and the transference of knowledge and equipment to local communities and small businesses. The ISSB building blocks are most conveniently used for low-rise in one or two storeyed houses. Many other buildings such as schools, community centres, hotels, industrial buildings and private housing can be realized with the ISSB. Having one's own home is vital for many families in Thailand. The modest housing type is model Style a 1, with 45 m^2 floor space. The houses built with the first generation ISSBs—already a period of around 35 years—still have a good quality [54,55]. Some of the housing solution with ISSB in Thailand is shown in Figure 8.

Figure 8. Housing solution with ISSB in Thailand: (**a**) ISSB of TISTR Thailand; (**b**,**c**) wall building with ISSB; (**d**) model house built with ISSB. Sources: (**a**–**c**) Bredenoord, (**d**) TISTR Thailand.

4.2.2. ISSB for Housing in Cambodia

Kongngy Hav is a social entrepreneur from Phnom Penh, Cambodia, and he has developed 'My Dream Home', a concept designed to provide affordable quality green housing to those who cannot afford to buy traditional housing in Cambodia (Figure 9). It utilizes an interlocking brick system, designed to provide sturdy construction that can be put together by people without building skills. Through the initiative, an average small two-storied home can be built for between USD 4000 and USD 6000, including design and technical assistance on the construction site. According to the entrepreneur, a dwelling would take two low-skilled people just a couple of months to build. Furthermore, it is claimed that these houses are 20–40 per cent cheaper than traditional housing, less labour intensive and better for the environment, with consideration about location, safety and access to utilities and clean water. The ISSB blocks are ecological and uses minimal cement. They are also aesthetically appealing when used in modern building [56].

Figure 9. Housing solutions with ISSB in Cambodia: (**a**): row houses in two floors built with ISSB; (**b**) individual house built with ISSB, by My Dream Home, Cambodia. Source: Kongngy Hav.

4.2.3. ISSB for Housing in Nepal

In Nepal, Community Enterprises were set up by Community Impact Nepal (CIN), a Nepalese non-profit social purpose organization, to produce sustainable building materials and organize housing reconstruction. In the areas affected by natural disasters, a project has been launched that enables families and small entrepreneurs to build or rebuild earthquake-resistant, environmentally friendly homes, at low cost. Several small companies have emerged to produce building blocks in the form of CSEB or ISSB from local raw materials using manually operated press. Central Nepal was hit by two earthquakes in 2015, where more than 9000 people were killed and 800,000 dwellings were destroyed. There, more than 3500 homes were built in the remote rural areas, while 200 micro-businesses were established, creating 2200 jobs. Roughly half of all masons trained in the construction of CSEB homes are from deprived groups and almost a third are women [57]. Many other houses with CSEB interlocking bricks were (re)built by Build-up-Nepal Engineering, together with empowering rural entrepreneurs and communities to build safe, affordable homes and resilient incomes. ISSB stabilized with cement (10%) were used to build earthquake resistant structures [5]. Example for the use of CSEB in Nepal is shown in Figure 10.

Figure 10. CSEB in Nepal; (**a**) compression press and ISSB, (**b**) curing of ISSB, (**c**) construction with ISSB. Sources: Community Impact Nepal.

5. Earthen Building Blocks in Latin America

5.1. CSEB in Mexico

In Mexico, the social enterprise 'Échale' focuses on social housing [58]. This socially oriented company claims to have realized 250,000 housing solutions (of which 30,000 are new homes) in 28 Mexican states, while creating 450,000 (temporary) jobs in the construction industry and providing one million financial services for low- and middle-income families. Échale focuses on sustainable community development and the self-construction of homes, through their own housing model. Everyone in the communities is trained in how to make the environmentally friendly earthen building blocks, and in building their own home and communal neighbourhood facilities and infrastructure. The most important standardized building material for walls is the 'Ecoblock', which was developed from 1997–2000. This is a compressed stabilized earth block (CSEB); an earthen block that is stabilized with approximately 5–10% cement (or lime) and compressed under high pressure. 'Echale Financiera' provides appropriate financial resources, consisting of credit for (1) the construction of a new home, (2) for a step-by-step self-build home, (3) loans for home improvements and (4) credits for sustainable and ecological technologies, e.g., solar collectors and sanitation. The Echale housing model has shown in practice that sustainable housing with maximum resident participation has led to a very significant housing production. The price of the houses that were built in self-construction was around USD 10.000 [59]. The financing structure is threefold: (1) savings of the families, (2) state subsidies and (3) loans or mortgages. Echale Financiera acts as an intermediary when applying for grants and loans. Housing project in Mexico by Echale is shown in Figure 11.

Figure 11. CSEB and housing in Mexico; (**a**) used CSEB, (**b**) built house, (**c**) realised Echale neighbourhood. Source: Echale.

5.2. Adobe Building Blocks in El Salvador

El Salvador is a country where 60% of the homes in the rural areas have a traditional adobe architecture. However, many earthquakes occur in the country and that has often led to destroyed homes. During the 2001 earthquake, 1160 people were killed, 166,529 homes were destroyed and 110,065 homes were damaged. The NGO Fundasal developed a construction method with reinforced adobe immediately afterwards. In Ciudad Barrios, 38 houses were built with fortified adobe in six different communities (Figure 12). Walls of adobe are reinforced with internal reinforcement with steel bars, and bamboo bars in vertical and horizontal directions. The finishing of the walls with stucco or plaster is important to fill in the cracks, crevices and cavities. This helps to protect the population against insects. The plaster is also necessary to protect the walls from the rain (outside) and humidity (inside) [60].

Figure 12. Adobe housing in El Salvador; (**a**) storage adobe blocks, (**b**) model earthquake resistant house, (**c**) built earthquake resistant house. Sources: (**a**) and (**b**) Bredenoord; (**c**) Fundasal.

6. Results: The Use of Earthen Blocks in Low-Cost Housing

Based on the described housing programs and information collected, it is found that the housing programs discussed in previous section are exemplary projects that still require follow-up on a larger scale. However, these housing projects do provide insight into technical and social aspects, which can facilitate building with earth and bridge affordable housing shortage. One of such technical aspect is availability of variety of compression press. Based on the discussion on use of CEB, CSEB and ISSB in several countries, the information on the CSEB produced by manufacturer is summarised in Table 1.

While each housing project discussed in previous section is unique to its socio-economical and geographical situation, several insights can be drawn. These insights are compiled here.

Table 1. Comparison of CSEB/ISSB in the described housing projects.

Country	Manufacturer	Block Form	Dimensions in cm	Stabilizer	Compressive Strength
Uganda	Hydraform, HYT, SHA	CSEB/ISSB, massive	27.5 × 15 × 15	Cement 10%	n.a.
Mali Burkina Faso	Oskam LEVS architects NGOs	CEB/HSEB rectangular, massive	29.5 × 14 × 9	Lime 5%	4–6 MPa. 6–18 MPa (lime stabilized
South India	Auroville Earth Institute	CSEB, various forms	Half CSEB 240 (24 × 11.5 × 9)	Cement or Lime	n.a.
North India	Gujarat State NGO	CSEB/ISSB various forms	30 × 15 × 9 Earthblocks.in	Cement 6–8%	5 MPa
North India	TARA, Delhi	CSEB various forms	23 × 11.5 × 7.5	Cement 4–8%	3.5–7 MPa
South India	Mrinmayee, Bangalore	CSEB various forms	30.5 × 14.3 × 10	Cement/lime	n.a
Thailand	TISTR research, entrepreneurs	ISSB model TISTR	12.5 × 25 × 10	Cement	5–7 MPa
Cambodia	Kongngy Hav, entrepreneur	ISSB model TISTR	12.5 × 25 × 10	Cement	5–7 MPa
Nepal	Build-up-Nepal, new entrepreneurs	CSEB/ISSB model TISTR	12.5 × 25 × 10	Cement 10%	5–7 MPa
Mexico	Echale (entrepr) NGOs	CSEB massive rectangular		Cement 5–10%	n.a.
El Salvador	Fundasal NGOs	adobe rectangular	40 × 40 × 10	Cement 3%	n.a.

- Suitability of CSEB/ISSB for Low-Cost Residential Construction

In most housing projects, the use of CSEB and ISSB is shown to be suitable for low-cost housing construction where residents can be engaged for parts of the implementation. CSEB stabilised with cement or lime is shown to be sufficiently strong and durable.

- Transfer of Building Knowledge to Local Communities

Local residents are often involved in the production of earthen blocks and construction of houses. Moreover, the labour involved in the construction process is also sourced locally, often limited to the household, the extended family or members of the local community [10,14], thus saving on labour costs. The local people are often trained by organisations and these training program imparts knowledge to the local communities. However, strict supervision of the block production and the construction of houses is required to ensure high quality. In areas where self-construction is adopted, this will have to be well organized and complemented with sufficient information and training.

- Development of Small-Scale Entrepreneurship

The rise in entrepreneurs involved in construction of low-cost housing with earth is positive for the widespread dissemination of earthen buildings. In some countries, the development of small-scale entrepreneurship is stimulated by the government or by aid organizations. This not only empowers local community but provide them with opportunities for economic growth. The production of CSEB/ISSB within small social enterprises is often feasible and thus, should be promoted.

- Support by Government and International Organisations

A successful housing project with earth is often supported by local and national government and international organisation. The support from government and organisations though housing finance and training provide for better opportunities for local people. Moreover, this support is essential for wide scale application of earth within a short duration of time. For example, UN-Habitat recommended replacing poor quality fired bricks by unfired earthen bricks which are seen as eco-friendly and give a good indoor climate in Uganda [31] and Darfur region [4]. Hence, its adoption in these areas have increased.

- Technical Aspects of Building with Earth

Selection of appropriate soil and stabiliser is the first step for any earthen construction project. The selection of soil and preparation of appropriate mixture is important for construction of high quality earthen buildings. Therefore, this must be conducted by a professional. For mass housing project, a large amount of soil will be required which need to be extracted through mining. This would require adequate spatial and logistical planning and a permit system. The addition of a stabiliser depends on the quality of soil and required compressive strength. The compressive strength requirement depends on the height of the building. In most cases, houses of only one story were realized with exception of those by Kongngy Hav (two storeys), Cambodia and Build-up-Nepal (two storeys).

- Disaster-Resistant Houses

Some housing projects discussed in the previous section are initiated after the loss and damage to the houses due to disaster. Disaster resistant structure is required, particularly a strong and stable structure that can resist earthquakes and heavy flooding.

- Absolute Housing Production

The largest housing production is achieved by Echale in Mexico. This is possible due to the further developed integral system, including the housing financing that is supported by the Mexican government. Such an advanced system does not yet exist in other countries. That is why projects are occasionally financed by the government (Mali) or by the input of aid organizations. The small-scale construction companies have had a major influence, in Thailand and Uganda this is strongly stimulated by the governments.

7. Discussions: Development of Earthen Blocks for Low-Cost Housing

While there are widespread housing projects with use of CEB, CSEB and ISSB, their adoption is still slow. In particular, the use of CEB is challenging due to low social image of earth and its link to poverty. Moreover, issues with erosion due to rain, termite attack, low structural strength and frequent maintenance discourage people for choosing CEBs [6]. These limitations in CEB are often solved with the use of binders such as cement and lime, as has been demonstrated in all the aforementioned projects. However, the use of cement in earthen construction is debated as it increases the environmental footprint of the building, increase the costs, and impacts re-usability negatively. Hence, many experts are interested in binders or stabilizers that can be locally sourced and emit no, or only low, carbon dioxide during the processing. While the search for an alternative binder can improve housing construction with earthen blocks, the design of the house, up-scalability of technology and other practical concerns prevent its widespread use. These challenges are briefly addressed below to provide various development routes for earthen blocks.

7.1. Search for Eco-Friendly Stabilizers

Researchers and professionals globally are searching for eco-friendly alternatives to cement and hydraulic that are preferably natural or of biological origin or extracted from waste, making the blocks 100% circular (re-usable). In recent decade, much attention is given to biological stabilizers. Biological stabilizers of animal and plant origin, such as plant juices containing oil and latex derived from sisal, agave, bananas and Euphorbia have been used in traditional earthen construction, often in combination of hydraulic lime [61]. Stabilizers derived from animals (cow-dung, casein, chitosan), plants (starch, guar gum, cactus mucilage, lignin, tannin, linseed), seaweeds (alginate, agar, carrageen) and microbes (xanthan gum, gellan gum) have been investigated thoroughly by the researchers more recently [62]. Studies on biological stabilizers have shown promising improvements in strength and water resistance with xanthan gum, gellan gum and agar gum. Stabilizers such as cow-dung, which has been traditionally used in earthen construction, show a significant improve in water resistance, while its effect on compressive strength is insignificant [63]. An example of wall made with cow-dung stabilized blocks is shown in Figure 13. Other traditional stabilizers such as tannins and casein have also shown their potential in improving the water resistance of earthen materials. Starch is one of the stabilizers that has a potential to improve water resistance and strength by heating it at elevated temperature. However, it should be noted that the improvement noted through biological stabilizers are less compared to cement or lime stabilized earthen blocks. Their application is also limited by the high cost of these stabilizers. However, stabilizers that can be extracted from waste such as cow-dung, starch and casein can be cost effective and enhance performance to a desired level.

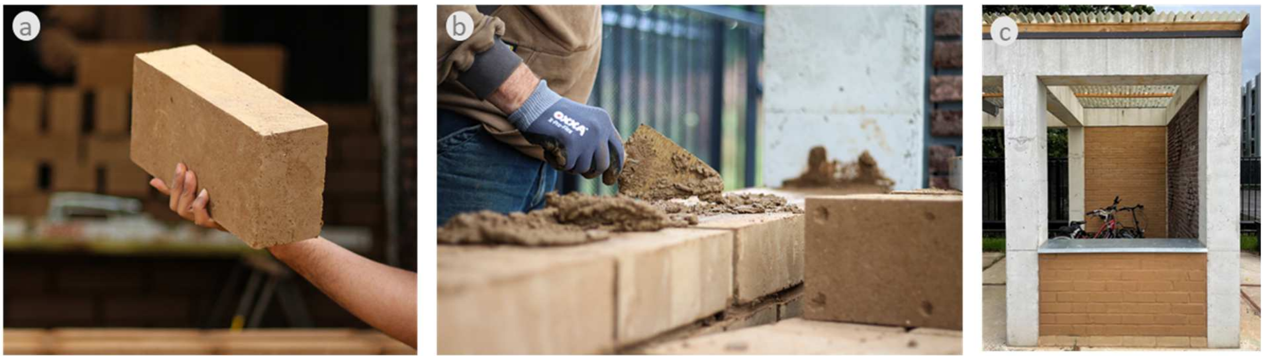

Figure 13. Cow-dung stabilised CEB wall constructed at TU Delft, Netherlands provide evidence of its water resistance characteristics in the rainy weather of Netherlands. (**a**) Cow-dung stabilised CEB block, (**b**) Cow-dung stabilised earthen mortar, (**c**) Cow-dung stabilised CEB wall. Source: Kulshreshtha.

Waste products from food production have also been investigated for use as a raw material in sustainable building materials, such as rice husk, and rice husk ash combined with hydraulic lime as stabilizer in CSEB [64,65]. Research is also conducted on feasibility of using industrial waste such as iron mine waste [66]. Research is also conducted on geopolymer based stabilizer which uses industrial or agricultural waste and combination of 'activators' that provide strength and water resistance similar to cement and lime stabilized earthen blocks [67,68]. TNO in Netherlands have also developed a binder based on geopolymer technique which is being used in earthen construction in Senegal. The search for new stabilizers as an alternative to cement in earth blocks is a major challenge and can lead to finding bio-stabilizers that might completely replace cement in CSEB and ISSB for certain applications.

7.2. Protective Elements in Building and Housing Image

A poorly designed unstabilized earthen dwelling is not durable, but a well-designed earthen structure could survive for centuries. An CEB house made designed with appropriate architectural details, such as a long overhang and pitched roof, could prevent erosion due to rain and improve lifespan [69,70]. Hence, the design of roof and the foundation, famously known as the principle of 'good hat and strong boot' is equally important as providing high quality CEBs. However, modern architectural aspirations (with exposed walls) and lack of confidence in CEB had led to increases in the use of CSEB/ISSB. The protective elements are important when using CSEB or ISSB.

The widespread use of the earth blocks is limited due to association of earth with poverty. This association is based on poorly designed earthen houses that are widespread. Poorly designed structures are often built by low-income households, without having access to technical assistance, housing financing and practical tools. However, a well-designed structure is often built by architects, engineers and entrepreneurs experienced in earthen construction. Hence, involvement of people with technical expertise is crucial to produce durable houses. The presence of large numbers of earthen houses of good performance in multiple locations and contexts can lead to wider acceptance of earth. Entrepreneurs also play a key role in dissemination of earth block technology. If the government can support entrepreneurial initiatives, it can lead to wider dissemination of modern earthen construction techniques.

8. Conclusions

The first research question was whether it would be possible to bring together important and sufficient applications of CEB/CSEB/ISSB to social housing projects. The authors have presented several interesting examples that could inspire further dissemination of CSEB technologies for low-cost social housing. In the projects documented in this research, the involved aid organisations and social entrepreneurs were already using sustainability goals that are related to the UN Development Goals. It is expected that globally there are many more examples and they should be documented and made accessible for research.

Limitations such as the low image of the existing CEB and adobe and overall low quality of structures discourages the use of earthen block in more social housing projects. Scaling up housing can only be successful if more high quality pilot projects are realized with CSEB or ISSB materials. The training of construction workers and the households involved who carry out a lot of work themselves will be crucial.

In regard to the second research question, the authors are of the opinion that scaling up housing production with CSEB is more feasible in rural areas and smaller cities than in large cities. The availability and proximity of raw materials for CSEB in rural areas is often better and local communities know the soil types in their area while the costs are usually (still) low. Local communities could be involved in mining the raw materials, producing the building blocks, and building the dwellings themselves. Training of local construction groups and small-scale construction companies is necessary, on the one hand because there is new technology that needs to be implemented, and on the other hand because (new) knowledge of organizational aspects of construction is required.

One of the challenges in earthen construction is the limited local or regional availability of raw materials, such as sand, clay, loam, lime and the like. In several countries there is already a major shortage of sand for housing and urban development. Another restraint is that local communities, including land-owners, must be involved in the search for raw materials, which will cost time. Especially with large-scale housing projects, considerable extraction of raw materials is required. This aspect will have to be further investigated, and considered in pilot projects.

In addition to the examples that the authors have found, many comparable housing projects have been set up in other countries with the application of sustainable building materials and construction methods. There are many aid organizations that have given impetus for this. However, in many cases the aid organizations and public institutions concerned have not systematically documented their pilot projects. The authors think this is necessary and here lies a clear task for government institutions and umbrella organizations of NGOs to do that research. It requires international cooperation too, which could help other projects globally.

There are countries where the application of sustainable building materials such as CSEB/ISSB is not on the agenda. In many countries housing construction is often with building blocks made of concrete, or other building materials are being used in which cement is incorporated. Due to the requirements for earthquake-resistant homes, cement and concrete must be used in building elements such as in foundations, columns and beams for frameworks, and also in bearing walls. The use of concrete ensures that the houses are earthquake-resistant, and therefore are durable. However, concrete is no longer seen worldwide as sustainable, as a result of carbon dioxide emissions in the production of cement, and because it is not circular. Moreover, the high cost of cement is a constraint for many households. The application of CSEB/ISSB could bring alternative solutions to local communities, but adequate communication on the possibilities of production and responsible application must be seen as crucial for successful implementation. To make earthen constructions sustainable, there is a need for eco-friendly stabilizers for the earthen building blocks, that can be extracted locally and can provide good strength and water resistant properties.

The authors give a short overview of the possible and desired future research, including the provision of protective elements in building and the betterments of the housing itself. Some of these are:

- Setting up a worldwide database of applications of earthen building blocks in low-cost social housing.
- Creating a more extensive application of earthen building materials for social housing through implementation of pilot projects in multiple countries.
- Promoting good architecture quality of earthen houses, and their maintenance, to gain a widespread acceptance.
- Setting up international exchange of knowledge on the search for bio-stabilizers for CSEB/ISSB.

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