STUDY OF A NEW INTERLOCKING STABILISED COMPRESSED EARTH MASONRY BLOCK

Rute Eires
CTAC - Territory, Environment and Construction Centre
University of Minho, Guimarães, Portugal,
E-mail: rute@civil.uminho.pt

Thomas Sturm
ISESE - Institute for Sustainability and Innovation in Structural Engineering
University of Minho, Guimarães, Portugal,
E-mail: tsturm@civil.uminho.pt

Aires Camões
CTAC - Territory, Environment and Construction Centre
University of Minho, Guimarães, Portugal,
E-mail: aires@civil.uminho.pt

Luís F. Ramos
ISESE - Institute for Sustainability and Innovation in Structural Engineering
University of Minho, Guimarães, Portugal,
E-mail: lramos @civil.uminho.pt

Theme 6: Research in Materials and Technology for Conservation and Contemporary Architecture
Keywords: Compressed earth blocks, soil stabilization, interlocking masonry

Abstract

Earth has been a traditional construction material to build houses in Africa. One of the most common earthen masonry techniques is the use of sun dried or kiln fired adobe bricks with mud mortar. Although this technique is cheap and allows the self construction, the bricks vary largely in shape, strength and durability. This has lead historically to weak houses which suffer considerable damage during floods and seismic events. Furthermore, the use of firewood kilns to burn bricks has caused extensive deforestation in several countries of Africa.

A solution which has been proposed in the second half of the last century is the use of stabilised compressed earth blocks (CEBs). These blocks are manufactured by compacting stabilised earth in a manual or hydraulic press. The resulting blocks present higher values of strength and durability, as well as uniform shapes. Since earth is available almost in every location of the world, the CEBs can be produced in-situ. The fact that this blocks are unburned and that the transport can be omitted makes them a cheap material with very low embodied energy. Their use is a cost effective opportunity for locals to have better houses while reducing deforestation.

In this context one developed an ongoing study for the manufacture of CEBs according to different materials available in Malawi. It is envisaged that the constructive solution with the proposed CEBs will enable improvements in durability, in thermal and acoustic comfort and in seismic behaviour of buildings in Malawi, where earth is an abundant material and labour is unskilled.

This paper presents some results of the experimental campaign which has been carried out. For this purpose, soils from Malawi were characterized and tested without stabilization, as well as with cement and/or lime addition.

1. INTRODUCTION

It is estimated that half the world's population is still living in earth buildings (Rael, 1971, Dethier, 1986 and McHenry, 1989, p. vii). Although building with earth is associated with poverty, recent technological advances make this association completely inappropriate. Today, earth buildings can be made in conjunction with contemporary systems and materials, hence minimizing the inherent problems of this ancient building technology.

In countries that lack the technology to produce materials that involve a greater industrialization of production, the use of heavier conventional building systems becomes unsustainable. The amount of waste produced and the increased transportation cost (due to their weight) makes traditional materials expensive and environmentally unsuitable.

With a solution of *compressed earth blocks* (CEBs) proposed within the HiLoTec project, a joint venture between the University of Minho and Mota-Engil SA, a simple masonry solution is being proposed for seismic countries where raw material is abundant and manual labour is unskilled. The intention is to create a masonry system which compromises between mechanical and functional requirements, in terms of economic and construction and in terms of energy savings and durability.

2. BUILDING WITH EARTH

Adobe is one of the oldest building materials on the planet. The adobe blocks began to be used between 10,000 BC to 8000 BC (Houben and Guillaud, 1994, p. 8). In many regions of the globe, earth is the most abundant and cheapest material, and therefore it has been used for centuries.

Several authors (Rael, 1971, Dethier, 1986 and McHenry, 1989, p. vii), estimate that about half the world's population still lives in earth construction. In developing countries, the population living in adobe houses is over 50% (Minke, 2009, p. 7).

As a result of massive historical use of earth as a building material, there are currently at least 18 different techniques of earth construction known. One of the most common techniques is rammed earth. It consists in placing soil in frames of approximately 2m in length, which then is compressed with the help of a rammer in successive layers. Another historically used method is the production of air dried adobe blocks. Unlike rammed earth, adobe for blocks require more water, and sometimes stabilizers such as straw, horsehair, or even cow dung have been used (Basin & Ruskulis, 2008, p. 2 and 3).

In the second half of the twentieth century, the use of CEBs was proposed. These blocks are manufactured by compressing stabilized soil into a mould with a manual or hydraulic press, and subsequently they are air-dried. These blocks have higher values of resistance and durability as well as uniform geometric shapes, thanks to the advantages given by the template used for its production. Since earth is available in almost all parts of the world, these building blocks can be manufactured on the construction site. The fact that these blocks are not burned and that the transportation may be unnecessary makes it an economic and sustainable construction material from an energy point of view.

The demand and use of new constructive solutions based on earth for developing countries has received special attention in recent years. Examples of this are the use of CEBs by NGOs in African countries such as Malawi (the country selected for the case study of the HiLoTec project).

Past experiences show that building with earth can be more economical than other construction materials. Maini states that in Auroville, one cubic meter of finished wall made of stabilized CEBs is generally around 50% cheaper than one of wire cut bricks (Maini, 2005, p. 6). On the other hand, Zingano states that in Malawi 14 cm thick walls made of stabilized CEBs are 23% cheaper than 15 cm thick walls made with cement and sand blocks (Zingano, 2005, p. 8).

3. THE “HiLoTec” PROJECT

The HiLoTec project - *Development of a constructive solution of mixed technology for sustainable self-construction*, an ongoing project at the University of Minho funded by Mota-Engil SA, consists of developing a simple and innovative construction technology for the sustainable construction of small buildings in developing countries with seismic hazard. The country which was chosen for the case study is Malawi.

3.1 The country of Malawi

Malawi is located in southeast Africa and shares borders with Mozambique, Tanzania and Zambia. Its capital is Lilongwe and it extends over an area of 118.484 km^2 which is divided into 28 districts. Lake Niassa, also known as Lake Malawi, occupies most of the territory in the east. Malawi's climate is subtropical, with average temperatures between 17 and 29ºC. The rainy season lasts from November to May. The main natural disasters that have occurred in Malawi are floods, droughts and earthquakes. Malawi has about 15 million inhabitants whose life expectancy is about 50 years.

Malawi was chosen as the country for the case study due to its demographic and socio-economic characteristics as well as for the interest shown by governmental and non-governmental institutions. Interest is focused on experimentation around alternative constructive solutions to burnt bricks.

3.2 The construction in Malawi

The masonry with burnt brick and cement mortar joints has been the most common construction technique in Malawi. Although this technique is simple (allowing self-construction), the bricks vary widely in shape, strength and durability. Consequently, the poor cement mortar joints have a significant thickness, see Figure 1, making them more expensive. Also, since there are no quality controls, the houses built with these materials suffer considerable damage during floods and earthquakes. In addition, the use of wood kilns to burn bricks has caused extensive deforestation in Malawi.

(a) (b) (c)

Fig.1 - Housings in Malawi: a) building aspect, b) size of burned bricks and the mortar joints, c) lack of maintenance after floods (credits: HiLoTec team project, 2010)

As an alternative to burnt bricks, several pilot experiences in the past have been made to implement CEB technology in the country, which are highlighted as follows:

- Habitat for Humanity, an NGO, helped to introduce in the market machines for the CEB manufacture, as HydraForm M5 Blockmaking Machines. These machines use diesel or electricity to produce dense blocks with interlocking, allowing construction without mortar (Habitat for Humanity, 2009);

- There are also in Malawi, small scale CEB manufacturers which use manual presses. These CEBS are more accessible to lower class or rural population, as it has not energy expenditure;
- UN-Habitat and the Department for International Development (DFID) have been promoting the CEB constructive system in several African countries like Kenya, Uganda and Malawi;
- The Faculty of Technology of the Makerere University in Kampala, Uganda, developed during the 90's a manual press for the manufacturing of blocks with "interlocking" to build houses and water tanks (with curved blocks), (UN-HABITAT, 2009, p.4);
- DFID's Construction Unit in Lilongwe used these hand presses to build 1,000 classrooms. Perhaps as a result, the Malawian government has banned the use of burnt brick in some parts of the country (Parliament, 2010);
- The Malawian Ministry of Industry, Science and Technology has proposed in a conference held in 2006 the spread of this construction technology. In the document of the conference is mentioned that the manufacture of presses for CEB by local manufacturers (Genaral Engineering Steel Limited and Encore Products). The intention of this government is to certify the manufacture of these machines in Malawi (Malawi Minister of industry science and technology, 2006);
- Related to this type of construction there is a standard MS 777:2007 - The Malawi Standard Specification for stabilized soil blocks (SSBs), which is based on a standard from Kenya (UN-Habitat – Malawi, 2004).

3.3 The “HiLoTec” project context

The first phase of the project, held between October 2009 and March 2010, aimed to assess local Malawi conditions for the development of the HiLoTec solution and collect the following specific information of the country: geography, climate, terrain, availability of materials, architectural legacies, types of organization of territory, availability of skilled labour, characteristics of local industry, accessibility, media communications, transport, energy resources, know-how, energy resources, needs and expectations of the target population.

Currently, the project is in its second phase, which includes the analysis of soils of Malawi, the study of new stabilized earth mixtures, an architectural study intended to define the needs and conventional building characteristics in Malawi and the study of new constructive systems. This study also includes the adoption of this new solution to the socio-cultural needs and functional requirements. The target market is rural and city families of lower incomes, which seek for better houses. Therefore, the HiLoTec project seeks to develop a building system economically competitive with current systems and more sustainable from the energy point of view. The building of a prototype one story house in Malawi to demonstrate the feasibility of the proposed concept is envisaged.

4. SOIL CHARACTERIZATION

The characterization of soils from Malawi was conducted in two phases. In the first phase soil samples from different locations of Malawi were analyzed, namely Blantyre, Zomba, Lilongwe, Netcheu and Salima. In the second phase the samples collected at the site where the prototype will be build, in Lilongwe city, were further analyzed. These soils are designated by S1, S2, S3, S4 and Smix (a mixture of all soils).

4.1 Selection of tests and methodology to make compressed earth samples

The tests for soil characterization were selected taking into account its ease of implementation, since it is expected that similar tests can be made easily on site for any Malawian (field tests). However, for the project development also more laborious laboratory tests were made, to achieve a better characterization and composition of the new blocks.

The field tests carried out were as follows: visual characterization (colour); texture check (grain size and noise in the handling); odour check (smell of organic matter); stickiness check; consistency test by moulding a sphere and/or a roll; water retention test; adhesion test; cohesion test (mould of a roll, also called "Cigar test"); stiffness test, washing test (ease/difficulty of hand washing); simple sedimentation test (also called "bottle test") and expeditious evaluation of the composition of the clay amount contained in soils ("Emerson test").

The laboratory tests were the following: evaluation of moisture and organic matter content; determination of liquid and plasticity limit in soils with a percentage of fine material higher than 5% and analysis of the clays contained in the soils of the prototype site by X-ray diffraction (XRD).

Also compressed soil specimens from each soil sample were prepared to evaluate the optimum moisture content and the compressive strength of the soil. The compressive strength of the soil is an important indicator of the overall strength of CEB masonry. In the same way, samples with stabilized soil mixtures were prepared.

For the manufacture of the cylindrical samples a metallic mould and a hydraulic press machine with a pressure of 2MPa was used. The intention was to simulate a manual CEB press. The samples had a height of 60mm and a diameter of 50mm. Figure 2 shows the preparation of a sample and a set of produced soil specimens stabilized with 9% of cement.

(a) (b) (c)

Fig.2 - Soil samples (5cm diameter and 6cm height): a) compression in the mould, b) removal of a compressed sample from the mould, c) compressed samples (credits: HiLoTec team project, 2010)

4.2 Results

In general the tested soils had two distinct colours, red, mostly present in the Liliongwe soils, due to the presence of iron oxide in its composition, and brown in the remaining soil.

The field tests show that most of the soils have a good plasticity, sine it is easy to make a sphere or a roll. These rolls have a length between 5 and 11.5cm using the “cigar test”, so the soils were considered suitable for CEB manufacture (Rigassi, 1985, p.39).

The assessment of soil particle size distribution analysis was obtained by simple sedimentation test and dry sieve analysis in laboratory, with soil prepared with mortar and pestle to separate the grains. It was held only a dry mechanical sieving once the amount of clay and silt presented by the soils was poor and it was considered not relevant to find the exact percentage of clay. The results show that the soils of the different regions do not differ significantly in their size distribution. Also the soils of the site where the prototype will be build do not have considerable differences as shown in Figure 3. Although the amount of fine material does not lie within the desirable limits presented by Houben and Guillaud, the soils have a particle size distribution considered sufficiently good for CEB production.

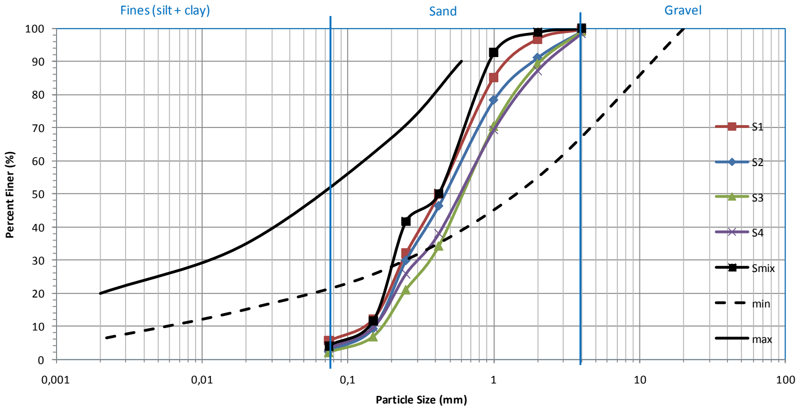
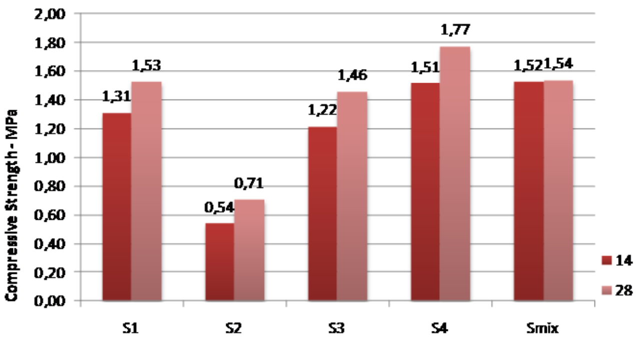


Fig.3 - Soils granulometry and optimal limits of particle size distribution for the manufacture of CEB's (min/max), according to Houben and Guillaud (Houben and Guillaud, 1994, pg. 116) (credits: HiLoTec team project, 2010)

The soils show a higher amount of clay content by using the sedimentation method. An average of 15% clay, 12% silt and 73% sand was verified. This size distribution fits the particle size required for the manufacture of CEB with sandy soil with little clay. However there is not an exact value for the ideal amount of clay and silt, but the percentages reported by several authors are on average between 5 and 25% clay (FAO, 2010).

The tests made with samples of compressed earth showed that to produce the CEBs a water percentage of 10 to 12% mass, depending on the soil, will be necessary. The compressive strength of the soil samples from the site where the prototype will be build after 28 days, without addition of stabilizers, was between 0.71 to 1.7 MPa, as one can observe in Figure 4.

(a)



(b)

Fig.4 - Compressive strength of samples: a) specimen after test, b) compressive strength of soils (credits: HiLoTec team project, 2010)

5. STABILIZED COMPRESSED EARTH

Cylindrical samples of compressed earth stabilized with cement and samples stabilized with cement and lime were produced simultaneously. These specimens were prepared with the same procedure already described.

5.1 Studied mixtures and performed tests

The studied compositions were: soil stabilized with 3, 5, 7 and 9% cement (called C3, C5, C7 and C9); soil stabilized with 5% cement and 2% of lime (called C5L2) and soil stabilized with 5% cement and 4% of lime (called C5L4). The water content differed between 11 and 13.5%. The use of lime in cement stabilized earth mixtures was tested to verify the effect of lime in the mechanical resistances, the water absorption, resistance to rain and in prevention to fungal growth in damp condition.

The performed tests were: the compressive strength in dried samples (in an oven at 40ºC to maintain always the same humidity) and wet samples (after 48 hours of water immersion); capillarity tests by placing the specimens on a sand cover on a permanently wet fabric that permits water to be absorbed by the soil samples during 2 days and immersion tests by placing the specimens in water for 2 days.

5.2 Obtained results

In Figure 5.a) one can observe that the resistances at 90 days of cure increases with the addition of cement. The better resistances were obtained with 9% of cement, with compressive strengths over 3MPa for dried samples and 1MPa for wet samples.

Figure 5.b) shows resistances at 14, 28 and 56 days of cure. It can be observed in this graph that it is not worth to addition lime to the soils when comparing to the results of sample C5. Furthermore the resistance of C5L2 decreased compared with C5 and C5L4 decrease with time in an unexpected way.

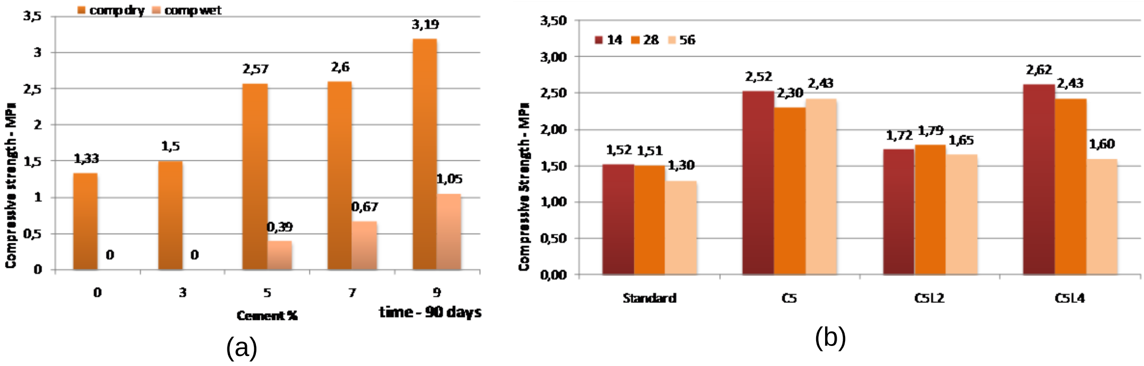


Fig.5 - Compressive strength of the soils: a) stabilized with cement and b) stabilized with cement and cement/lime (credits: HiLoTec team project, 2010)

The results of capillarity tests revealed that only with 5, 7 or 9% of cement content a reduction of the water absorption can be attained when comparing it with the absorption of unstabilized soil. The addition of lime with cement leads to a higher absorption than the soil with 5% of cement content. The water absorption after 48hours of unstabilized soil was around 24%, the one of C3 was 21.5%, the one of C5 was 19% and the one of C7 and C9 were around 18.7%.

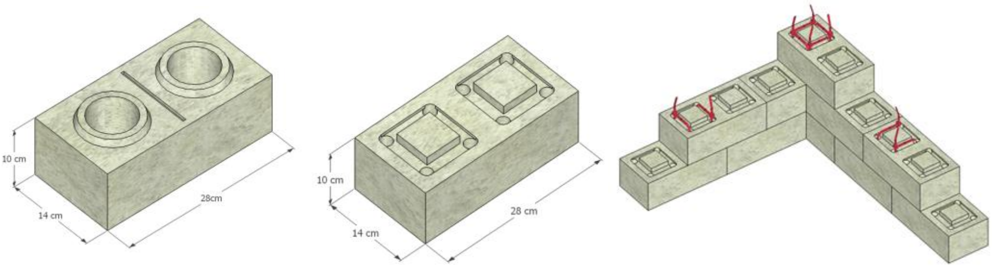
The immersion tests, which were realized only with cement mixtures (C3, C5, C7 and C9) show that 3% of cement is not enough to maintain a block intact; the specimens of C3 broke down after 15 minutes. The water absorption of the other specimens, (C5, C7 and C9) after 48hours was around 18%, without significant differences.

6. THE NEW BLOCKS

The two most dreadful natural hazards to an earth construction are earthquake and floods. Earthquakes create horizontal and vertical base acceleration which induce inertial forces on the whole structure, while floods erode the foundations and the base of walls and weaken the strength of the material.

Guidelines for earth construction in seismic regions proposed by Minke (2001) or the AEI (2005) do encourage the use of hollow CEBs, but only when used with vertical and/or horizontal reinforcements of steel or bamboo and mortar joints. These reinforcements are aimed to resist the tension stresses caused by the bending of the walls, since earthen elements have very low flexural strength. They also advise that the interlocking keys must interlock in both horizontal directions. The idea behind hollow blocks is not only to provide a space for reinforcements, but also to reduce the overall weight of the walls, and thus reducing the inertial forces created by the ground acceleration during earthquakes.

The CEB denominated Sismo-Block-1, has been designed to provide interlocking in both main directions and to be used with vertical steel or bamboo reinforcements. Figure 6.a shows the shape and basic dimensions of the block.



(a) (b) (c)

Fig. 6 - The proposed CEBs: (a) The Sismo-Block-1 block; (b) The Sismo-Block-2 block; (c) Example of a plastic tie reinforced masonry wall.

The disadvantage of vertical reinforcements based on steel or bamboo rods lays in the fact that these have to be placed and anchored to the foundations before building the walls. Later, the holes with reinforcements have to be grouted with mortar. This is not only expensive, but also technically complicated for unskilled labor and in case of self construction.

As an alternative to this technique, a second block has been designed. The Sismo-Block-2, see Figure 6.b, is a new interlocking block which will allow the use of a cheap vertical reinforcement based on plastic straps, also known as cable ties. The idea is to have an interlocking block with holes which allow bonding vertically each course with the following consecutive course of the wall, see Figure 6.c. This way, the vertical reinforcement is built up in a consecutive way, instead from the beginning. The suggested plastic straps that could be used are low insertion and pull through force straps with double lock. Such ties can have maximum tensile strengths of 110 kg.

This novel technique has to be tested yet, but could decrease significantly the construction cost of earth houses in seismic regions, since plastic straps are very cheap compared to steel, there is no need for mortar and it allows to built single leaf external walls, thus sparing material. The plastic straps have also the advantage that they are more durable against weathering than steel or bamboo rods, as long as they are not exposed to direct sunlight.

The Sismo-Block-2 could present an alternative to the previous mentioned classical solutions, and it could be implemented as already shown in Figure 6.c. To evaluate the feasibility of this construction system, extensive mechanical testing on wall prototypes will be done. The test campaign will include compressive, shear and flexural strength tests on single CEBs and small masonry specimens, as well as in-plane and out-of-plane tests of large masonry wall specimens.

7. CONCLUSIONS

The HiLoTec project consists in developing a simple and innovative construction technology, for the construction of sustainable buildings in seismic developing countries. The country chosen for the case study is Malawi. A major premise of the project relates to the conception of a block with "interlocking" with vertical holes, in order to make it lighter and allow the application of structural reinforcement.

Currently, there is an ongoing study of the optimal composition of soils for the manufacture of CEBs with a manual press, according to different materials available in Malawi.

Overall, it is envisaged that the constructive solution with CEBs proposed by the HiLoTec project will enable improvements in durability, in thermal and acoustic comfort and in seismic behaviour of buildings in developing countries, where earth is an abundant material and labour is unskilled.

Bibliography

AEI (2005). *Earthquake resistant buildings with hollow interlocking blocks*. Auroville Earth Institute, UNESCO Chair - Earthern Architecture, Auroville.

Basin & Ruskulis, O., 2008, *Additives to clay organic - Additives derived from natural sources*, this article was prepared. Updated by Otto Ruskulis for Practical Action, www.practicalaction.org acessed in 2010.

FAO Corporate Document Repository, 2010. *Earth as building material*, www.fao.org, Earth as building material, accessed in 2010.

Habitat for Humanity (2009). *Malawi*, www.habitatforhumanity.org.uk, accessed in 2009.

Houben, H. & Guillaud, H. (1994). *Earth Construction, A comprehensive guide*, CRATerre-EAG, Intermediate Tecnology Publications Ltd.

Maini, S. (2005). *Earthen architecture for sustainable habitat and compressed stabilized earth block technology, Programme of the city on heritage lecture on clay architecture and building techniques by compressed earth*, High Commission of Ryadh City Development, The Auroville Earth Institute, Auroville Building Centre, India.

Malawi Minister of industry science and technology, (2006). Held in the Minister of industry science and technology conference room on 18 January, Press briefing by Minister of industry science and technology, www.malawi.gov.mw, accessed in April of 2011.

Minke, G. (2001). *Construction manual for earthquake-resistant houses built of earth.* Eschborn: GATE-BASIN/ GTZ GmbH. Available at:
http://www.asl.unikassel.de/~feb/wissenswertes/manual_engl.pdf

Minke, G. (2009). *Handbuch Lehmbau: Baustoffkunde, Techniken, Lehmarchitektur* (In German: Earth construction Handbook: Material, Technics, Adobe Architecture), Ökobuch Verlag, Staufen bei Freiburg

Parliament (2010).*The role of Interlocking Stabilised Soil Block Technology in addressing Water & Sanitation needs across the developing world*, Memorandum submitted by the ISSB, www.parliament.the-stationery-office.co.uk, October 2006, accessed in April of 2010.

Rael, R. (1971). *Earth Architecture*, Princeton Architectural Press, New York.
Dethier, J. 1986, *Des Architecture de Terre*, In Edition de Centre Pompidou, Paris.

McHenry, P. G. Jr. 1989, *Adobe and Rammed Earth Buildings: Design and Construction*, The University of Arizona Press, Tucson, USA.

Rigassi, V. (1985). *Compressed Earth Blocks: Manual of Production* CRATerre-EAG, Volume I.

UN-Habitat – Malawi (2004). *Urban housing sector profile*, UNON, Nairobi, ISO 14001:2004.

United Nations Human Settlements Programme (UN-HABITAT) 2009, *Interlocking Stabilised Soil Blocks - Appropriate earth technologies in Uganda,* UN-HABITAT.

Zingano, B. (2005), *The problem of fuel wood energy demand in Malawi with reference to the construction industry*, Zingano and Associates, Lilongwe.

Acknowledgments
This work was carried within the HiLoTec project, funded by Mota-Engil, under the protocol between the Department of Civil Engineering of the Minho University and Mota-Engil SA. A special acknowledgement is here directed to Eng. Vânia Silva and Vitor Reis.

Curriculum:
Rute Eires is Architect graduated from University of Minho (UM, 2003). In 2006 completed a master's degree in Materials and Rehabilitation of Construction in the area of Sustainable Materials at the University of Minho. She is currently a PhD student at the Department of Civil Engineering at the University of Minho, and the thesis has the topic of earth construction. She is also invited assistant in the same university.

Thomas Sturm is a structural engineer graduated from the University of Chile in 2008. During two years he worked in the engineering forensic unit at the institute of material research (IDIEM) of Chile. In 2010 he completed his studies in the Advanced Masters in Structural Analysis of Monuments and Historical Constructions (SAHC). He is currently a PhD candidate at the Department of Civil Engineering at the University of Minho.

Aires Camões is assistant professor of building materials at the Department of Civil Engineering of University of Minho, Portugal. His main research interests concerns mineral additions, special concretes, namely high-performance concrete and durability of concrete structures.

Luís F. Ramos is an assistant professor of structures at the Department of Civil Engineering of University of Minho, Portugal. His main research interests concern masonry structures, historical constructions, ND testing and experimental dynamic analysis. Currently, Luís F. Ramos is the coordinator of the HiLoTec Project.