MASTER

Gypsum stabilised earth
research on the properties of cast Gypsum-stabilised earth and its suitability for low cost housing construction in developing countries

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Robbert Vroomen
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Cover illustration: A GsE block with the ingredients: Soil, gypsum, water, retarder and plastifier (from back to front).
Gypsum stabilised Earth

Research on the Properties of cast Gypsum-stabilised Earth and its Suitability for Low Cost Housing Construction in Developing Countries.

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Abstract

Research has been carried out into the optimal mix-conditions and material properties of gypsum stabilized earth and its suitability for application in low cost housing construction in developing countries. Main inspiration was found in the work of chemical engineer Lowenhaupt (USA). He has proposed the addition of gypsum to earth to render it castable. He developed a method (Cast Earth) in which walls are cast at full height, similar to large scale concrete casting.

In modern low cost housing construction in developing countries, the hollow concrete block market has a near complete monopoly. Main reasons are the legal obstacles for and the inferior image of alternative building methods. When the enormous amount of energy that is needed to produce cement (around 4.8 MJ/kg) is considered, and the release of CO₂-gas (around 1.2 kg/kg cement), a strong motivation can be found to search for alternatives.

The application of gypsum with earth through which the consistency of the mix can be reduced to such a level that it can be poured, is one of the alternatives that has not yet been studied extensively earlier. As the material can be applied with modern construction methods, it is expected to be highly appreciated by the main stakeholders: the future owners of low cost housing. A great advantage of gypsum over cement is that it can be produced locally by small scale enterprises and it demands a low amount of energy in production as it can be calcined at approx. 125°C in stead of 1100°C.

Based on the advantages summed up above it is assumed that this method potentially offers an improvement over cement based products, such as hollow concrete blocks.

The following research questions were defined:

- What are the mix-conditions and material properties of GsE?,
- What are suitable construction techniques? and,
- Is GsE suitable for application in low cost housing construction in developing countries?

The study consists of literature study, laboratory research of the material characteristics of the soil-gypsum mix, the development of a successful retarder, examples of appropriate building technology, and an assessment of it’s suitability for low income housing-construction in developing countries compared to alternative methods.

The sub-conclusions are that a mix of plain aggregate (soil) and 24% gypsum can have a compressive strength of 5 N/mm² after 28 days. Gelatine was found as an effective retarder, among other substances. Contrary to cement, the first studies show no negative effects of silt and clay-particles on the effectiveness of gypsum. Main disadvantage of this method is that with increased moisture content, the compressive strength drops to about 2 N/mm².

The main conclusion is that due to the high amount of gypsum required, the low wet compressive strength, and the additional technical measures required, the method will most probably be not competitive to Hollow Concrete Blocks. Next to that it is concluded that the complexity of the casting-method is too high for Self-help construction in Developing Countries. If more research is done however, especially in the field of moisture resistance and wet compressive strength, GsE could be successful.
Samenvatting

Er is onderzoek gedaan naar de optimale mix omstandigheden voor, en materiaal eigenschappen van, gips gestabiliseerde aarde. Daarnaast is bekeken of het materiaal geschikt zou zijn voor de bouw van wanden voor goedkope woningbouw in ontwikkelende landen.

De studie borduurt voort op het werk van chemisch ingenieur Lowenhaupt (USA). Hij heeft het voorstel gedaan gips toe te voegen aan aarde om het zo stortbaar te maken. Hij heeft een methode ontwikkeld (Cast Earth) waarmee wanden in een keer gestort kunnen worden. vergelijkbaar met de gietbouw methode die gebruikelijk is bij betonconstructies.

In ontwikkelende landen zijn de traditionele bouwmethodes met aarde bijna volledig verdrongen door de holle betonnen blok. De grootste oorzaken hiervoor zijn de beperkingen in bouwvoorschriften en de inferieure status van het materiaal aarde. De motivatie om een alternatief te ontwikkelen voor de cement gebaseerde bouwmethodes is makkelijk te vinden, als gelet wordt op de enorme hoeveelheid energie die nodig is om cement te produceren (ca. 4,8 MJ/kg) en de veroorzaakte uitstoot van CO₂-gas (ca 1,2 kg/krige cement).

De mogelijkheid om gips toe te voegen aan aarde, en het daardoor geschikt te maken voor gietmethodes, is nog niet eerder diepgaand onderzocht. Het is verwacht dat de waardering van de toekomstige bewoners voor een dergelijke methode hoog zal zijn aangezien er moderne bouwmethodes kunnen worden toegepast. Een paar voordelen van gips boven cement zijn dat gips lokaal en op kleine schaal kan worden geproduceerd en dat er maar weinig energie nodig is voor de productie omdat de gips gecalcineerd kan worden op ongeveer 125°C in plaats van 1100°C.

Met de bovenstaande feiten als basis, is het aangenomen dat deze bouwmethod met potentiële verbetering is voor de cement gebaseerde bouwmethodes zoals holle betonnen blokken.

De volgende onderzoeksvragen zijn vervolgens gesteld:

- Wat zijn de optimale mix omstandigheden voor, en materiaal eigenschappen van, gips gestabiliseerde aarde (GsA)?
- Welke bouwmethodes zijn in ontwikkelende landen geschikt voor GsA? en,
- Is GsA geschikt voor de bouw van wanden voor goedkope woningbouw in ontwikkelende landen?

Het onderzoek bestaat uit literatuur studie, laboratorium onderzoek naar een werkende vertrager en de materiaal eigenschappen van GsA, voorbeelden van toepasbare bouwtechnieken en een poging om GsA te vergelijken met de huidige bouwmethodes voor wanden voor goedkope woningen in ontwikkelende landen.

Enkele deelconclusies zijn dat een mix van aarde met 24% gips een druksterkte heeft van 5N/mm² na 28 dagen en dat Gelatine, naast andere substanties, een effectieve vertrager is voor GsA. De eerste studies wijzen uit dat de werking van gips, in tegenstelling tot die van cement, niet negatief beïnvloed wordt door slib- en kleideeltjes. De natte druksterkte blijkt de grootste zwakte van GsA te zijn (2 N/mm²).

De eindconclusie is dat GsA waarschijnlijk niet kan concurreren met holle betonnen blokken en gestabiliseerde geperste stenen. Hoofdredenen hiervoor zijn de grote
hoeveelheid gips die nodig is in de mix, de lage natte druksterkte, en de extra technische voorzieningen die nodig zijn. Daarnaast lijkt het erop dat de complexiteit van gietbouw niet geschikt is voor zelfbouw in ontwikkelende landen. Indien er echter meer onderzoek gedaan wordt naar de vochtbestendigheid en de natte druksterkte verbeterd kan worden, dan kan GsA een interessant materiaal worden.
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Foreword

In the autumn of 2005, I was pointed at the fairly new building method called Cast Earth by Ms. Emilia van Egmond - de Wilde - de Ligny. After a small survey on building methods for Housing for Low income Families in Developing Countries, the conclusion was drawn that this method could be beneficial to this target group and to the construction sector in general. As no fundamental knowledge about this method was public at the start of this project I decided to do research on this subject in my final Master Thesis. Due to other obligations I was not able to start the research until spring 2006.

In this report all use of sources such as literature, illustrations and websites are indicated with a direct reference between [brackets]. If no reference is given, the work is from the hand of the author of this report.

In order to provide extra information, a CDrom is provided with the report. On this CDrom information can be found such as computations, digital sources and background information. It would take many pages to add these documents to the report on paper.

I would like to thank the persons who were willing to give supervision to this research for the knowledge they shared with me and their enthusiasm: Peter Erkelens, Jos Lichtenberg and Emilia van Egmond – de Wilde – de Ligny.
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I hope this report will increase the readers knowledge and understanding of the material that was investigated.

7 June 2007
Robbert Vroomen
Part I

Introduction

to the Problem, Aim, and Design of the Research
1 Research set-up

1.1 Introduction

This chapter will deal with the description of the problem-field, the aim of the project and the research questions. Furthermore attention will be given to the relevance of this study and the limitations and assumptions that were defined.

1.2 Problem Field and possibilities of Gypsum stabilised Earth

Most large cities in developing countries have been confronted with a very rapid urbanization for some decades now [55] which has caused an enormous housing deficit [18]. As a result most of these cities have a large number of slum areas in which a large part of the inhabitants does not have the basic standards of living [1,53].

In 2003 a total of 960 million people are living in urban slums in developing countries. 20% of this total was found in Africa, 60% in Asia and 14% in Latin America and Oceania. In most African cities, between 40 and 70% of the population live in informal settlements. The total number of slum dwellers on the African continent is expected to increase with about 4.5% annually [55].

Today more than one billion of the world's city residents live in inadequate housing; worldwide, 18% of all urban housing units are non-permanent structures and 25% do not conform to building regulations [55].

In the UN HABITAT agenda 1996 it is recognized that “access to safe and healthy shelter and basic services is essential to a person's physical, psychological, social and economic well-being” and that “Our objective is to achieve adequate shelter for all (...) through an enabling approach to the development and improvement of shelter that is environmentally sound.”

According to UNCTAD poverty is the fundamental reason underlying the existence of slums in the developing world. The rapid urbanization is not accompanied by an equivalent rate of economic development. This means that the millions of rural inhabitants attracted to urban areas by real or imagined job opportunities end up living in slums, in which they have to provide their own low-cost housing. Recent study suggest that this situation is even growing, because the poor urban population is even growing poorer and the gap between rich and poor is growing. [53]

According to Gachigi “… the causes of this problem are manifold, both international and national in scope, and in truth only solutions at those macro levels van eliminate the problem. However that does not in any way obviate the need for solutions based on appropriate technologies.” [18]

The author fully understands that this situation can not be solved with a new construction technology only. However Gypsum-stabilised Earth can potentially decrease the housing construction costs of low income groups, if introduced successfully. This would increase the living standards.
Building with soil seems one of the possible answers to the increasing costs of construction:

Van der Velden, among many others, promotes the use of earth as follows: “Considering its rich tradition (Gerneke, 1992) and taking into account such factors as the local climate, the use of local raw materials, the small environmental impact, the labor intensity, and the lower costs, earth construction seems an appropriate technology for housing in South Africa.” [58]

Webb: “In dry arid regions of the world unstabilised soil has been used as a building material and many earth dwelling have survived for centuries. [61, p115]

Contrary to their need for low cost housing, a preference among low income families can be observed for the expensive construction method of concrete blocks.

Webb: “…presidents and peasants alike have become disillusioned with cement. Its production is expensive, both in capital and energy; it consumes ever scarcer natural sources; and it results in houses not suited to many Third World climates […] ‘The widespread addiction to cement and tin roofs is a kind of mental paralysis’, wrote Tanzanian President Julius Nyerere in 1977. ‘We are still thinking in terms of international standards instead of what we can afford to do ourselves.’” [61]

Du plessis: “Earth construction techniques went into disfavour mainly due to the technological changes brought on by the Industrial Revolution and the consequent new demands of the consumer market. It remains one of the major problems that traditional rural construction methods, which are often more environmentally friendly, are mostly abandoned in cities because of a false idea of ‘modernity’.” [12, 42]

Van der Velden: “Though still widely practised in most developing countries, earth construction is often regarded as a symbol of poverty (Houben & Guillaud, 1994: 180-181). Local experience has proven the great attractiveness of ‘modern’, environmentally unfriendly, building materials”. [58]

And Martin: “In Zambia we put enormous effort into facilitating the use of soil cement blocks, and had the building regulations changed to permit mud blocks: to no avail. The residents saw this as their only chance to get a foot in the first rung of the ‘proper house’ ladder, and built in concrete block even though they were thereby sacrificing space. The symbolism of the concrete block house was irresistible.” [31, 25]

Some disadvantages are identified in the use of cement based building methods:
- A lot of energy (ca 4,8MJ/kg [49, p303]) is required for cement production.
- A lot of CO\text{2} is released in cement production (ca 1,2kg/kg).
- Production can only take place on large scale which leads to:
  - a capital intensive process,
  - a labour extensive process,
  - a high import factor, and,
  - increased costs for transport to distant areas.
- The demolition of any concrete structure will lead to a lot of non reusable waste

A result of such a situation was found in the north of Ethiopia by the author. Near the city of Shire, which is only 300 km away from the production plant at Mekele, the price for 25 kg of cement was 50 to 60 Birr. This equals 3 day wages of a layman. Here also, most of the buildings were constructed with concrete blocks [59, p55].

Given the citations above, it is clear that this symbolism is a strong motivator to choose an expensive and unsustainable method over an adequate alternative. If the emotions behind this symbolism could be transferred to a more economic and sustainable construction method, a lot of positive developments could arise. As the symbolism can be traced back to the appearance of the material and the idea of modern production, the alternative should possess the same characteristics.

Earth-Gypsum construction could be such alternative material. It combines most of the advantages of both traditional and modern building methods:
- Little investment needed.
- The major factor input is labour, which is available in most cases.
- The primary material is available in a lot of places.
- The building speed of this method can be high.

and most important,
- The appearance and the production of the building method is perceived as modern.

From this first analysis, the conclusion is drawn that Gypsum-Earth construction is possibly an alternative for current low-income housing construction in developing countries. In order to enable any further product development, basic material knowledge should be developed and possibilities of the material analyses.

1.3 Preceding Research in Gypsum-stabilised Earth

The construction method 'Cast Earth' was invented by Harris Lowenhaupt (USA) in 1992. At the time of June 2006 the invention was not patented yet, the inventor however, is not willing to share this knowledge because of commercial reasons. Only a small part of his knowledge has been published on his website [29]. Here Lowenhaupt describes some of the basic information of the material such as the amount of gypsum needed for proper stabilisation and the structural capacities of the rendered mix. The information of the website has been structured in a text-document and is provided on the CDrom.

The use of gypsum as a stabiliser in compressed earth blocks has been mentioned by Webb [61]. He warns for the low durability of the blocks made with such a mix due to the low water resistance. Further he suggests utmost care with this material in areas where dampness will occur, as very little is known of its behaviour.
At the start of this project no other sources of information on Gypsum stabilised Earth construction were known.

1.4 Global Problem

The global problem can be defined as:

_The lack of fundamental knowledge about the material Gypsum-stabilised Earth, its structural characteristics and the appropriate construction methods._

1.5 Objectives

The overall objective is defined as follows:

_To create better understanding of the characteristics of Gypsum-stabilised Earth in order to enable the development of a construction method for low-cost housing in developing countries._

Given the situation as described above the research objective is:

_To attain fundamental knowledge about the gypsum earth mix, its structural characteristics and appropriate construction technologies._

1.6 Conceptual Model

This research project is part of the product development of Gypsum stabilised Earth as a construction method for low income housing in developing countries. The conceptual layout of the total process is sketched below. The large frame demarcates the borders of this project.

---

**Figure 1:** An overview of the complete product development process for Gypsum stabilized Earth

A  
> Research by Lowenhaupt

B  
> Application of the method in USA

C  
> Survey on possibilities for Developing Countries

D  
> (Re)development of material knowledge

E  
> Structural Design

F  
> Building Techniques

G  
> Assessment of Suitability

H  
> Marketing

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A  
> Research into the appropriate mixture and retarder by Lowenhaupt.

B  
> The application of the technology in USA by Lowenhaupt. Most of the relevant information has been kept private.

C  
> Survey on possibilities for low-cost building.

Before starting this project, a survey was done on the possibilities of Cast Earth for the designated target-area. The outcome of this survey was positive: Cast Earth can be applied in a lot of developing countries and the method seemed attractive due to expected lower costs than conventional modern methods and expected better performance than adobe methods.
This master thesis:

D  Development of knowledge of mixture and retarder.
E  Structural design to comply with the structural demands.
F  Development of building techniques in relation to low cost housing.
G  A brief study on the suitability of GsE, based on comparison with other materials.
H  Marketing

1.7 Research Questions

Based on the objectives described above, the following research questions were defined:

- What are the mix-conditions and material properties of GsE?,
- What are suitable construction techniques? and,
- Is GsE suitable for application in low cost housing construction in developing countries?

1.8 Research Path

The research path is designed according to the research questions. In figure 1 the structure of the research can be found with the applied methods. The different methods of research are represented by different colours.

Figure 2: The internal layout of the research

1.9 Relevance

Scientific relevance

The main relevance of this research is academic. It can be found in the field of applied material-science. Very little knowledge is available yet on the mix of Gypsum and Earth and its application in construction. If successful, this research will enlarge the basis of knowledge needed to develop a building system with GsE.

Social relevance
The social relevance of this project can be found in the possible application of the gained knowledge on the level of product innovation for the construction sector.

The relevance for a better (i.e. less expensive) wall construction method in low income housing is clear as: “Approximately 60% of the total expenses regarding low-income houses go to construction and materials while 40% goes to legal and administrative issues. In low-income houses, walls constitute approx 50% of the material cost (including finishing) and approx. 45% of the construction time”[2].

If a new wall construction method could be developed which is better suited for low income families than present methods, this would benefit low income families, local communities and the general interests of developing countries. As this research is meant to create the knowledge needed to develop walls with GsE the social relevance is high.

1.10 Assumptions and Limitations

Field of Application
The construction system that is to be developed is meant to give an alternative to Low income Families in Developing Countries. Therefore the application is targeted at single storey buildings. This type of building is assumed to have a medium-weight roof (50kg/m²) with a maximum span of 4 meters. If the construction method is able to fulfil the structural requirements for such a system, it can also be applied as infill-wall in concrete skeleton-constructions.

Circumstances of the target economies.
As stated above, the main focus of this study is on developing economies. The reader should be aware that no standard developing country exists. This is true for a lot of aspects, a few of which are: social structure, economical situation, education, frontier of technology and climate. As this project is an explorative study into the possibilities of gypsum-stabilized earth construction, only limited attention can be given to individual situations.

Limitations
This project is aimed at the exploration of the possibilities of Gypsum-stabilised Earth construction in developing countries. Therefore, the products developed in this study should be understood to be product concepts and not the result of a complete product development cycle. Any product development that will be carried out in this project is meant to create understanding of the possibilities of the material and demonstrate the possibilities to possible stakeholders. It is hoped that if the conclusions of this study are positive, the product concepts will be an encouragement for further research and design.

Abbreviations
The following abbreviations are frequently used in this report:

- GsE Gypsum-stabilised Earth
- CEB(‘s) Compressed Earth Block(s)
- HCB(‘s) Hollow Concrete Block(s)
Part II

Basic information and Material Properties
of Gypsum Stabilised Earth
2 General

2.1 Introduction

In this chapter general information is given as an introduction to the following chapters. In section 2.2 the method ‘Cast Earth’ is described. An introduction to gypsum-stabilised earth is given in section 2.3. In section 2.4 more information is given on gypsum, as this is the innovative component in the mix.

2.2 Cast Earth

The product method ‘Cast Earth’, as developed by Lowenhaupt, can be characterised as a large scale casting method. Gypsum is used to be able to increase the plasticity of the earth-gypsum-mix without negative results. Without gypsum, any addition of more than 8% water to earth will induce excessive shrinkage of the material during curing. This will lead to cracks and subsequent failure [43]. It takes more than 10% added water to render earth castable.

If Gypsum is added to about 20 mass%, the mix can be made more fluid by adding more water without the occurrence of cracks after curing. This can be explained by the volume increase of gypsum upon setting. A gypsum-earth mix can thus be applied with a casting-method such as used in normal concrete casting.

Figure 3: An example of a house constructed with Cast earth, source: Website Lowenhaupt [29]

In this report the name ‘Cast Earth’ is considered as the trademark assigned to the method developed by Lowenhaupt, although no patents or trademarks have been claimed. In order to avoid conflicts, the method which is subject of this report, is referred to as Gypsum-stabilised Earth (GsE).

2.3 Gypsum-stabilised Earth

Compared to Concrete construction and Adobe construction, a large number of advantages can be found in GsE. Table 1 presents a qualitative comparison on the performances of the three methods.
Adobe blocks | Gypsum-stabilised Earth | Concrete construction
---|---|---
Material costs | Very low | Low | High
Labour involved | High | Medium | Medium
Image of product | Very Low | High | Very High
Durability | Low | Medium | High
Energy required | Very low | Low | Very High
CO₂ production | None | Very Low | Very High

Table 1: A qualitative comparison of Adobe, GsE and Concrete

The main advantages of GsE over Adobe:
- The quality of the wall is higher, both in structural and durable sense.
- It is suitable for labour extensive methods as it can be poured.
- Because of the alternative binder, a larger variety of soils such as Red-coffee soil (a lateritic soil) and Black-cotton soil (a clayey soil) seems suitable. ¹
- The product image is expected to be far better than adobe [48 & 58].

The main advantages over concrete blocks:
- The costs are expected to be far lower as no expensive cement is used.
- The costs for transport are minimal as gypsum can be produced locally.
- The energy requirements are far lower because gypsum requires calcination at 125°C only instead of sintering at 1100°C.
- The CO₂ release is very low compared to that of cement (1.2kg/kg cement [40]).

Now that a general insight in Gypsum-stabilised Earth is given, more will be explained on the components.

2.4 General information on Gypsum

The properties of gypsum are not commonly known to the public. As it is essential for the understanding of Gypsum-stabilised Earth, a short introduction of the material Gypsum is given below.

More technical aspects, elaborated information and a literature study can be found in the report, which is provided on the CDrom.

2.4.1 Types of Gypsum

Three types of gypsum can be produced from the natural Calcium-Sulphate. The basic type is Hemi-hydrate. The other two are Anhydrite III and Anhydrite II. Hemi-hydrate can be produced in two versions: the α-version and the β-version. A table with technical information on these types of gypsum can be found in Appendix D.

¹ In a lot of developing countries one of these soils is predominant. See the map of Houben and Guillaud in Appendix E. Both types of soil are not suited for Adobe and Concrete construction. According to Lowenhaupt Cast Earth can be applied with any kind of soil.
The Hemi-hydrate gypsum of the β-version is most simple to produce. The calcination can be done under normal pressure and with simple production requirements [41]. Therefore this type of gypsum seems best suitable for low cost housing production in Developing countries.

Sources of the raw material
Gypsum can be extracted from nature, but is also produced as a by-product in some industries. Some examples are the desulphurisation of flue gases, the production of fertilizer and some cleaning processes. As far as is known the flue-gas-gypsum can be used without problems. The application of gypsum from other industrial processes is still questionable, partly because of the higher levels of radioactivity.

Additives
Several substances can be added in order to change the properties of the gypsum and render them applicable for specific applications. Some functions are: retarding, accelerating, plastifying, affixation etc. More in information can be found in section 3.3.

2.4.2 Methods of production
Hemi-hydrate β-gypsum can industrially be produced in different types of ovens. Two main types of kilns are the Rotating kiln and a Kettle kiln [40]. These can produce up to 600 tonnes of gypsum per day. In these kilns the coarsely grounded gypsum (up to 60mm) is heated to a temperature between 120°C and 180°C. Before the gypsum is fed to the kilns, it is dried in a separate or integrated heater.

According to different authors however, it is attractive to calcinate gypsum on a smaller scale in Developing Countries. Production on a smaller scale would create possibilities for small businesses and local entrepreneurship. Small scale production would benefit rural situations if local markets can be created. Both Spiropoulos (in rural areas) and Spence & Cook (in general) seem to agree.

Spiropoulos (on lime production): “In rural areas productive activities tend to be mainly traditional agriculture, sometimes only just above the subsistence level. Apart from work done in the fields the population is usually unemployed and consequently there is a lack of cash income. The industrial experience of the local population is limited and the technical skills level is low. In addition, it is usually difficult to recruit well trained technicians and managerial staff to work in remote areas and then to keep them there at a cost which can be supported by a small project. The risk of project failure in such areas is usually high. To reduce this, the lime works must have as small an output as necessary to supply the local demand. It must be of a low technological level to enable the use of locally available resources. This assists in reducing capital costs to a minimum and also enables operation, and maintenance and repair work to be executed by the local population without the need for highly trained technicians or managerial effort. Further, in most cases it will be desirable to arrange that the most labour intensive methods are used to maximize employment.” [50]
Spence & Cook (on fired brick production): “… When the cost of machinery and tools per worker is calculated, the comparison is even more remarkable. The cost of creating one workplace in the cement industry is 3500 times larger than the cost of one workplace in the brick industry [………]. Where capital is scarce, therefore, it is clear that the small-scale and traditional industries are greatly to be preferred.” [49]

Although the products described above are different from gypsum, most of the logic is also applicable to gypsum production. A small-scale kiln seems optimal in all situations where labour is abundantly available. Next to that, small scale production enables decentralisation, allowing very great transportation economies to be made. [22, p2]

A small scale process for Gypsum calcinations can easily be set up: The raw gypsum is quarried or mined after which it is broken into lumps of manageable size. Calcination takes place in some form of pan, kettle or kiln. [20]

A simple pan essentially consist of four tile bricks walls, 1 meter high, forming a rectangle of about 2 by 4 meters. This structure is covered by a roof of steel sheets. On top of the roof the Di-hydrate gypsum is placed in layers. The gypsum is heated to a temperature of 120-170° C by a fire in the space below.

In gypsum industry, the processes can be controlled to set and regulate the quality and characteristics of the gypsum. In small scale production, this is not possible. Therefore this gypsum is of lower quality. This should be taken into account if applied in practise.

2.4.3 Availability

The availability of gypsum is a key condition in the question whether casting with earth-gypsum mix can be a competing building method as the costs for transport can constitute to a large part of the total price.

Deposition

Gypsum is a salt (Calcium Sulphate) that is deposited when large volumes of water evaporate. Depending on the conditions this requires long periods of time. Based on chemical content every 1000 metres of sea leave 15 meters of salts. Of these salts only 3.7 percent is gypsum and 0.3 percent is lime. This would be a layer of 55 cm of gypsum deposits. The occurrence of gypsum layers of 500 to 600 meters thickness is still left unexplained. [17.a]

All land, which was once covered with sea water can be expected to contain layers in which one or more types of salts can be found. Both in developing countries and in developed countries large quantities are quarried [40].

Some developing countries known for their Gypsum production are: [51].

<table>
<thead>
<tr>
<th>Africa:</th>
<th>Algeria, Egypt, Ethiopia, Libya, Morocco, Niger, South-Africa, Tanzania, Tunisia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latin America:</td>
<td>Dominican Republic, Guatemala, Jamaica, Mexico, Argentina, Colombia, Peru, Bhutan</td>
</tr>
<tr>
<td>Asia:</td>
<td>China, India, Iran, Jordan, Laos, Pakistan, Saudi Arabia, Syria, Taiwan, and Thailand</td>
</tr>
</tbody>
</table>

A large number of these countries was already producing gypsum in 1975 and have seen an increasing production [51]. A list of all gypsum producing countries with their production in provided on the CDrom.
Based on these outcomes one can conclude that natural gypsum is available in a lot of places. In cement production, gypsum is used as a set retarder [40]. Therefore gypsum is available, whether locally produced or imported, wherever a cement plant is located.

In this thesis no further research is done after the availability. It is generally assumed that gypsum can be made available to the market, at least in small amounts.
3 Research on the Mix Conditions and Material Properties

3.1 Introduction

At the start of this project little information was available on the mix conditions and material characteristics of GsE. Therefore laboratory research was carried out on these aspects. All laboratory research in this project was executed between July 2006 and April 2007. A total of 13 large and small tests were done, with a total number of 135 unique casts.

At the start the focus was on the finding of a retarder. Other aspects were the impact of changes of different components e.g. water, gypsum, aggregate, plastifier. In each test the setting time, curing time, weight, moisture and strength were observed in order to find the relation between these aspects.

In this chapter the laboratory tests are discussed (3.2) after which the conclusions are drawn (3.3 to 3.5). As time progressed, it became clear that the list of relevant aspects was too long for the restricted time available. Therefore a list with all interesting aspects that were left un-investigated is presented in section 3.6.

3.2 The Laboratory Tests

In this section an overview of all successful tests is given, with their goal, methods and results. More in depth information on the methodology and instruments can be found in the a separate report added to the CDrom.

Test 0: Try-out

A first test was done in order to get familiar with the casting method, the mix, the laboratory circumstances, the instruments and methodology.

The focus was on the mix consistency, the setting time and the circumstances under which the casts were best made. A total number of 8 casts was made in which the mix was varied, an acid was added to obtain a mix with an acidity of pH7, and the lubrication of the moulds was varied.

The general findings were:
- Extensive sieving of the aggregate is required (at least 5 hours), before all grain sizes have fallen to the correct sieve.
- The mix can best be mixed manually as the open time window is very limited.
- The mixing is done in a small tub with a stick rotating at a pace of around 1Hz.
- The consistency is best when a total of 23 WT% of water (water/total solids).
- Theoretically the optimum amount of hemi-hydrate gypsum is 24 WT% (gypsum/total solids)
- To obtain a mix with pH7, an amount 1,1ml of 30% HCl is optimal (i.e. 0,25 WT% acid/gypsum).
- The lubrication of the moulds is important as the acid and humidity in the mix will cause the surfaces of the steel moulds to oxidise. Both Vaseline and hydraulic oil proved to perform well.
- The bending tension test can best be done on an other machine than the one used for split tension strength and compressive strength. A continuous change of pressure heads would otherwise be necessary. For this purpose an old pressure bank was found adequate.

**Test 1: Curing time**

The aim of this first real test was to find the relation between the curing time and the mass- and strength development. A total of 16 identical prism-sets was cast and tested after curing times varying between 2 hours and 30 days.

The results of this test can be observed in the graphs below. In Graph 1 the development of the weight is set out in relation to the time of curing. The numbers in the legend of this graph represent the code of individual prism sets.

Graph 2 shows the strength development in relation to the curing time. Both Compressive strength, Tensile strength, and Split tension resistance are given.
Graph 1: The relation between the curing time and the weight of the prism-sets

As can be observed in Graph 1 the casts have a nearly identical weight loss over time. The minimum weight is reached after about 14 days. Almost 100% of the free water that was theoretically present in the prisms has evaporated by then.

Graph 2: The relation between the Curing time and the developed Strength

Some interesting aspects can be identified in the lines depicted in Graph 2:
1. The dry compressive strength, dry tensile strength and split resistance of the basic mix is respectively approx. 5 N/mm$^2$, 1.5 N/mm$^2$ and 0.75 N/mm$^2$ (after 28days).
2. The three types of strength have a remarkably identical course. In general the Tensile strength equals approximately 1/3rth of the compression strength. The Split tension resistance is about 2/15th of the compression strength.
3. The initial strength of the casts is high. However after the first 6 hours the strength decreases.
**Test 2: The amount of Water added**

This test was done in order to find the relation between the amount of amended water and the material properties such as setting time, weight and strength.

In this cast the amount of water was varied between 21.0 WT% and 28.5 WT%. A total of 12 prism-sets were cast and tested after different curing times (1 day, 7 and 28 days). The results of the test can be observed in Graph 3 and 4.

The ‘Pourtime’ and ‘Drytime’ as given in Graph 3 are explained to the reader in the list of definitions (Section 8).

**Graph 3: The relation between the Water added and the Setting times**

**Graph 4: Relation between Water percentage and the Compressive Strength after three different curing periods.**

In this graphs some interesting aspects can be identified:

1. The open time of the mix is directly dependent on the amount of water added.
   
   Both the ‘Pourtime’ (the latest possible moment to pour the mix) and the ‘Drytime’ (the moment that the cast reaches a defined penetration resistance) are almost linear related to the amount of water added.

2. The amount of amended water is very decisive for the final strength of the prisms.

3. The relationship between the amount of amended water and the final strength is almost linear. The negative relation can be explained by the lower amount of voids that is left by evaporating free water.
**Test 3: Type of Aggregate**

The standard aggregate that is used in the tests is a Füller-graded composition of 0,25-8mm. In this test an aggregate was used with a grain size of 4-8mm only in order to find the relation between the change in grain size and the setting times and strength. For this aggregate composition, the theoretical optimum amount of gypsum is higher (35%) due to the larger amount of voids in the aggregate. Several casts were made with varying amounts of gypsum and water to assess the optimal gypsum amount. In total 8 prism-sets were cast and tested in two groups after respectively 1 day and 7 days of curing.

The mean compressive and tensile strength resulting from these prisms can be observed in Graph 5.

![Graph 5](image)

**Graph 5: The Compressive and Tensile Strength, after a curing period of 168 hours, of mixes with a normal (green) and rough (yellow) aggregate composition**

From these results one could conclude that the use of a rough aggregate is favorable over the ‘standard’ aggregate (i.e. Füller-graded) as the strength of the casts increases. However if the amount of gypsum added is taken into account, the outcome is different. This is identified as the effectiveness of gypsum. The effectiveness, both compressive and tensile, is formulated as the strength relative to the amount of gypsum added.

$$\eta_{\text{compressive}} = \frac{\text{Compressive strength (N/mm}^2\text{)}}{\text{Gypsum added (grams)}}$$

$$\eta_{\text{tensile}} = \frac{\text{Tensile strength (N/mm}^2\text{)}}{\text{Gypsum added (grams)}}$$

The effectiveness of gypsum in a mix with normal (0,25mm-8mm) aggregate and a mix with rough aggregate (4-8mm) is given in Graph 6 (see next page).

Based on these outcomes one can conclude that the ‘real’ differences in strength are smaller but still interesting.

In this test no conclusions could be drawn about the consequences of the varied amount of water and gypsum added as the results showed too little difference.
Graph 6: The effectiveness of gypsum in mixes with normal aggregate and rough aggregate.

Test 4: Plastifier
This cast was done in order to find the relation between the use of plastifying agents and the setting time and strength. A plastifier is normally used (in concrete casting for example) to decrease the consistency of a mix with the same water factor, or to decrease the water-requirement with the same consistency.
A total of 8 prism-sets were cast and tested at different curing times. Two different plastifiers were applied:
- Normal dish-washing soap: this is a liquid of which the plastifying effect on cement is generally known. This plastifier can be added to a maximum of 0,2%.
- Tillmann OFT ON2: this is one of the many commercially available ‘super-plastifiers’. This plastifier can be added to a maximum of 1WT%.
The results of these tests were compared to those of a non-plastified mix (the results of test 2). These wmixes were applied with different amounts of water to assess the relation between water addition, setting time, and strength.
The water factor is expressed relatively to the ‘normal’ water factor (21%), to be able to compare results with differing circumstances.

Graph 7: The relation between the Water Factor and the start of the setting with three different Plastifying Agents.
A number of interesting aspects was identified in this test:

1. With both Soap and Tillman OFT ON2, the minimum water factor can be decreased to 0.7 compared to 0.9 in the mix without plastifying agent. Due to this decrease in water use, the final strength has increased and the open time decreased.

2. The casts with Tillmann OFT ON2 show an improved compressive strength when compared to the normal casts.

**Test 5 & 8: Retarder type and amount**

In cast 5 the retarder type and quantity was varied. This was done in order to find a relation between these variables and the setting time and strength. A lot of data was gathered from this test, but more testing was needed to draw conclusions. Therefore Test 8 was done to gain more results. Test 6 and 7 did not yield any relevant results, but were for verification purposes only.
In total, 38 prism-sets were cast with varying retarding substances. They were all demoulded after 24 hours and tested after curing times varying from 24 hours to 28 days. The main results of this test are illustrated in the graphs below. In Graph 10 the performances of all retarded mixes are illustrated relative to the performance of a non-retarded mix. In Graph 11 the performance of Gelatine retarded mixes can be observed.

Relativity is introduced in the compressive strength for being able to implement values obtained from prisms tested after different curing times. The relativity is introduced in the setting time to be able to combine the performances of the prisms in two different setting times.

\[
\text{Relative Compressive Strength} = \frac{\text{Compressive strength of retarded mix (N/mm}^2\text{)}}{\text{Compressive strength of un-retarded mix (N/mm}^2\text{)}}
\]

\[
\text{Retarding Factor} = \frac{\text{Mean Setting time of retarded mix (min)}}{\text{Mean Setting time of un-retarded mix (min)}}
\]

A few interesting aspects can be observed in Graph 10:
- Most retarding substances evoke a slight increase in compressive strength. This is true for all agents with exception of the acids.
- The best combination of setting retardation and strength preservation can be found with the Gelatine admixture at a solution rate of 0.20WT% (code 5F) and 0.30WT% (code 8D) and the Keratin admixture with a high solution rate of about 0.25WT% (code 5O).

Based on Graph 11 one can draw the conclusion that the optimum solution rate of Gelatine is between 0.20% and 0.30%. Within this range the retarding factor is between 4 and 7 while the compressive strength is preserved or even improved.

Graph 10: The relation between the Retarding Substance and the resulting Compressive Strength and Retarding Factor, both relative to the un-retarded mix
Test 9: Gypsum added

This test was done in order to find a relation between the amount of amended gypsum and the resulting characteristics of the casts. In this test the amount of gypsum was varied between 5 and 30WT% with its required chemical water. In all tests 0.1WT% gelatine is added to enhance the applicability of the mix. The results can be found in Graph 12 and Graph 13.

From these graphs some aspects can be deducted:
- The relations between the amount of amended gypsum and both the compressive and the tensile strength are almost linear.
- The effectiveness of gypsum is almost the same for all percentages between 10 and 30WT%. The slowly dropping lines in Graph 13 indicate that, economically speaking, a slight preference can be found to increase the wall thickness while keeping the gypsum amount constant, instead of increasing the gypsum amount while keeping the wall thickness constant.
Test 10: Mixing period and order of casting
This test was meant to find out whether the mixing could be done with intervals and whether the order of casting of the prisms was relevant for the results. As to little attention was given to these tests, no conclusions can be drawn.

Test 11: Strength under different humidity levels
This test was designed to find a relation between the humidity level of the surrounding air during curing, the moisture content of the prisms and the developed strength. This aspect is interesting as the strength development of gypsum can be highly affected by the moisture content of the material.\(^2\)

In order to be able to compare the results, a reference of 60% RH and 20°C was created in a climate room. The humidity was varied through the use of executors (i.e. air-tight containers of glass) in which a equilibrium-humidity was created. In one executor an equilibrium of 22% RH was created with a supersaturated salt (PotassiumAcetate, CH\(_3\)COOK) and in another executor an equilibrium of 100% RH was created with an volume of plain water. This way three climate conditions were created with different humidity levels, in each of which two sets of prisms were placed.

No usable results were found in this test as other conditions of the test changed during curing. Due to the limited air reservoir in the executors (only 5ltr), the curing of the prisms slacked. The amount of salt was another problem. After 10 days of curing the salt was not able anymore to keep the humidity constant as no free salt was available anymore. Therefore the test data were not usable.

The only conclusion that can be drawn from this test is for future test-design: More attention should be given to the requirements and circumstances under which the humidities are conditioned. More air mass should be available to the curing prism-sets and an other type of climate control should be found for the test with low humidity conditions.

Test 12a: Long term compressive strength, with and without retarder
A test was designed to find the amount of stress relaxation of Gypsum stabilised Earth. The stress relaxation factor (creep) can be found according to method, derived from Kreijger [27]: A number of prisms is loaded with pressure until failure. Each prism is loaded with another fraction of the characteristic compressive strength (90%, 80% 70% etc.). Due to the stress relaxation, each prism will collapse after a certain period. When the loads and moment of collapse of each of these prisms are set out in a graph (see Graph 14), the relationship between load and time of collapse can be extrapolated to infinity, indicating the long term compressive strength of the material.

The results of this test would have been very interesting, as it is known that the stress relaxation of gypsum is considerably high. However, it was impossible to execute this test as the pressure bank which is required for this test, was not available for such long period. Therefore the prisms meant for this test were used in test 12b.

\(^2\) More information and literature references can be found in the digital report provided on the CDrom.
Test 12b: Wet strength with and without retarder

In test 12b the relation between the duration of submersion in water and absorption and the retained strength was studied. The most relevant result of this test was the wet compressive strength after 24 hours of submersion and the water absorption. Those two figures can be compared to values found in literature.

For this test, six sets of prisms were cured for 40 days. In three of those sets the setting was retarded with 0.2 WT% gelatine, the other three sets were without retarder. Of each version, one set was left dry and the other two sets were submerged in water for respectively 25 and 120 hours. After their submersion the weight gain and compressive and tensile strength of the sets were tested and compared to the performance of the dry prisms. The surfaces were also examined visually.

All surfaces of the submerged prisms showed material loss (see Figure 9 and Figure 10). Although the solvability of β-gypsum in water is low (6.7 gr/ltr), the long term effect could be serious as each drop of water running down the wall will take some gypsum away. Further tests should be done on this aspect.

The values resulting from the structural tests are shown in Graph 15. On the left Y-axes the weight gain due to water absorption is given. On the right Y-axes the retained strength (compressive as well as tensile) is given.
Based on the outcome of this test, some aspects can be identified:

- The water absorption is between 11 and 12WT% after 24 hours. After 120 hours submersion the absorption is about 13WT%.

- After 24 hours the compressive strength of the un-retarded prisms has fallen from 6.8 N/mm$^2$ to about 2 N/mm$^2$, and in the next days it further decreases to 1.5 N/mm$^2$. The tensile strength of these prisms decreases from 2.4 N/mm$^2$ to 0.5 N/mm$^2$ in the first 24 hours. After 120 hours of submersion a tensile strength of 0.3 N/mm$^2$ is left.

- The compressive strength of the retarded prisms has fallen from around 6 N/mm$^2$ to 2.2 N/mm$^2$ after 24 hours. No further decrease in compressive strength is found in the following days. The tensile strength of these prisms drops from 2.3 N/mm$^2$ to 0.7 N/mm$^2$ after 24 hours. A further drop to about 0.6 N/mm$^2$ can be observed after 120 hours of submersion.

- The retarded prisms to perform better than the un-retarded ones in their wet strength, both compressive and tensile.

**Test 13: Dutch Soil with varying amounts of gypsum**

This test was done to test whether gypsum is also an effective stabilisation for a soil with a natural composition. The effectiveness of gypsum in a natural occurring soil with colloids and clay content are doubtful as all other tests were done with a soil composed according to the Fuller-curve. It was the plan to use Red Coffee Soil (a latrite soil) and Black Cotton soil (a high clay content soil) in this test. These two soils are greatly available in a lot of Developing Countries$^3$ but they are unsuitable for both Adobe and

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$^3$ In a lot of developing countries one of these soils is predominant. See the map of Houben and Guillaud in Appendix E.
concrete construction. Especially in urban areas it would be very interesting to be able to apply these types of earth in a form of Earth construction [18]. However no soil samples were available for testing due to legislative matters. Instead a Dutch soil was used. This soil was taken from a 2 meter deep excavation in Maasbracht, central-Limburg, The Netherlands. The soil was sieved for 12 hours in order to find the grain size composition (see Graph 16). All large content of biological origin, and soil parts larger than 4mm where taken out of the soil.

Graph 16: Grain size composition of Dutch soil after 1 and 12 hours sieving.

In Graph 16 a dotted line can be seen at 60micrometer. Parts smaller than 60micrometer are defined as colloids (silt or clay). It can be observed that around 8% colloids are present in the soil. With this soil 6 casts were made with a varied amount of Gypsum added to the mix (8 to 24%).

The prisms were cured for 28 days after which their compressive and bending-tension strength was tested. The relation between the amount of gypsum and the strength can be observed in Graph 17. To be able to evaluate the effect of the different soil type the results of test 9 (the ‘normal’ Füller graded aggregate) are also shown.

The mixes of both types of soil show similar strength development (see Graph 17). Therefore it can be concluded that the effectiveness of gypsum is not negatively affected by the grain size composition of the Dutch soil.

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4 The clay particles present in both soils expand when the humidity rises. In Adobe this will lead to micro-cracks, which will evolve into macro cracks eventually. In concrete the activity of the cement is reduced, decreasing the final strength of the concrete.
Graph 17: The strength of two types of GsE in relation to the amount of gypsum added: The mix with Dutch soil is given in red and blue points. The normal mix (with Füller graded aggregate) is given in purple and orange lines.

3.3 Mix recommendations

In the sections below, the ingredients of the mix are discussed. It should be clear that the figures and numbers given below are only valid for this particular situation. They can not be applied to any other situation, whether in laboratory or in practise, without prior tests.

3.3.1 Aggregate

Based on the outcomes of test 3 and 13 it is found that the effectiveness of gypsum is about the same for all applied aggregates. This would mean that in principle any soil locally available can be used. In these laboratory test all aggregate above 8mm is left out because of the restricted sizes of the test prisms. In practise larger aggregate can be applied, but even then it is advised to screen the soil to exclude large biological matters such as leaves, twigs and roots. A screen with mazes of 16mm could be fit.

3.3.2 Gypsum

Gypsum is expected to be the most expensive component of the mix. The amount of gypsum added should therefore be chosen carefully. Based on chemical theory, the optimum amount of gypsum added is 21% for Füller graded soil. As shown in test 9, the effectiveness of gypsum in this particular soil composition is about the same for any percentage of gypsum addition between 10% and 30% (see Graph 13). The amount of gypsum added can be therefore be changed according to the required strength.

3.3.3 Water

Based on the results of this research it can be concluded that when the amount of water is decreased, the open time decreases and the structural performances increase. In test 2 an optimum (i.e. minimum) amount of water was found of 21% (without plastifier). As water is a scarce commodity in most developing countries the usage of water should be as low as practicable possible. No saline water should be used as the activity of gypsum will be affected negatively by it.
In test 2 it was found that the total water requirement is directly related to:
- The amount of gypsum added and its water-gypsum-factor
- The moisture level of the aggregate
- The desired plasticity of the mix
- The possible application of a plastifier (see section 3.3.4)
Therefore the optimum water usage should be determined for every specific mix composition.

3.3.4 Plastifier

Based on the outcomes of test 4, the application of a plastifier is advised if easily obtainable. The water requirement can be decreased further to about 17%, resulting in a lower water usage and an increased structural performance. With the lowered water usage, the open time is decreased further.

Two types of plastifier can be applied:
- The normal plastifiers: Plastifiers such as normal dish washing soap can be added to about 0,2% of the gypsum amount. With this amount, the water requirement can be decreased to about 17% resulting in an increase in compressive strength of about 30%. The application of such a plastifier is justified by the reduction of water usage and the increased compressive strength as it is obtainable with relatively small costs for the most households.
- The Super-plastifiers: Commercially available Super-plastifiers such as Tillmann OFT ON2 can be added to about 1% of the gypsum amount. With this amount, the water requirement can be decreased to about 17% resulting in an increase in compressive strength of about 80%. An extra advantage can be found: The open time is increased with some 10%.
As these plastifiers are not generally available to low income families in developing countries, it should only be used if the costs of import can be justified by the improved strength or decreased water requirement.

3.3.5 Retarder

Two effective retarding substances were found in this project: Keratin and Gelatine.
- Keratin: Hydrolysed Keratin is a sulphur-rich protein that is obtained by grinding horns and hoofs and bringing them in solution through hydrolysis in 30% HCl, heated to 100 °C for 24 hours. Its optimum amount is 0,25 WT% (related to the amount of gypsum), resulting in a retardation factor of around 4.6.
- Gelatine: Gelatine is a protein that is obtained by boiling cartilaginous cuts of bones. The gelatine will dissolve into the water resulting in broth which will naturally form a jelly or gel when cooled. The commercially available gelatine is best applied as a solution to the mixing water as it should be thoroughly mixed. Its optimum amount of admixture is 0,20 to 0,30 WT%, resulting in a retardation factor of 7 to 10.
As Gelatine can be obtained more easily and has a better result, it is advised as the retarder for Gypsum-stabilised Earth Construction.
3.4 Structural capabilities

3.4.1 Compressive strength

**Dry compressive strength**

A lot of national standards define the dry and wet compressive strength as decisive for the acceptance of the material for permanent constructions [61]. According to British standard 6073 and 3921 the dry compressive strength should exceed 2.8 N/mm². Based on the results of tests 2, 8 and 9 it can be claimed that Gypsum-stabilised Earth with 21% gypsum can meet this requirement. According to the water added to the mix (between 28.5% and 21%), the dry compressive strength after 28 days varies between 3 N/mm² and 7 N/mm² respectively. It is expected that the compressive strength will further increase over time.

One can conclude that the amount of gypsum added could be decreased in order to save costly gypsum. In test 9 it is found that the minimum requirement of 2.8 N/mm² is reached when 13% gypsum is used.

**Wet compressive strength**

Based on the results found in Test 12b, the conclusion can be drawn that both the wet compressive strength of the unretarded and the retarded mix is respectively 2.0 and 2.2 N/mm². Although the wet compressive strength of the unretarded mix drops below 1.9 N/mm² after 120 hours, this is not decisive.

According to Webb [61] a material can be expected to withstand the weathering by water if the absorption of water is less than 15% in the first 24 hours of submersion. As the results of test 12b show an absorption of 11 and 11.8%, it can be said that these first values are promising for the water resistance of GsE.

**Creep**

According to literature, gypsum will be show a high amount of stress relaxation when loaded for long periods. A test was designed to find the creep-factor. However, as the test failed, no further information is found about the creep-factor.

3.4.2 Tensile Strength

**Dry tensile strength**

Based on the results of test 2 it can be claimed that Gypsum-stabilised Earth with 21% gypsum, will have a wet compressive strength between 1.2 and 2.2 N/mm², according to the water added to the mix (between 28.5% and 21% respectively). Based on one isolated outcome it is expected that the compressive strength will further rise in time.

**Wet tensile strength**

Based on the results found in Test 12b, the conclusion can be drawn that unretarded and the retarded mix have a wet tensile strength of respectively 0.5 and 0.7 N/mm².
3.5 Weathering

The term Weathering can be defined as the effect of the weather on a structure or structure. The weather resistance would than be: How will the material cope with rain, sun, and wind?

Based on the outcomes of test 12b, it can be concluded that the wet compressive strength is promising, compared to the wet compressive strength of Adobe. As this property is an indicator for the weather resistance, it can be claimed that the weather resistance of GsE is better than the weather resistance of Adobe. However, in this research project no further tests are executed on this subject. It is advised to apply the same design precautions for a wall of GsE as applied in a wall of Adobe until more is known about the weather resistance characteristics of the material. The general design rules for Adobe construction are:
- a large overhang of the roof
- a protective cover for the walls
- a protection of the footing of the walls

More research should be done after this. Testing methods are described by Webb [61], Minke [35, p196] and Houben & Guillaud [23] and others.

In literature some possible interventions were found by the author:
- To apply a cactus emulsion on the exterior of the walls. (IAEE manual for Earthen constructions, [24])
- To apply the residue of boiled seed pod husks of the Dawa Dawa tree on the exterior of the walls (Webb [61, p102])
- To mix animal dung, molasses, crashed ant heap or urea through the mix. (Webb [61, p102])
- To impregnate the outside of the walls with lineoil (Minke, [35])

3.6 Recommendations for follow-up research

Due to the limited time for this research project, attention was given to a limited list of aspects only. Anyone willing to enlarge the knowledge basis about this mixture is invited to do so. The following interesting aspects and questions were identified:

1. A water test should be done with alternating wet-dry conditions in order to find behaviour of cast earth under rainy conditions.
2. A combination of best retarder and plastifier should be tested for several water/gypsum factors, several water amounts, several gypsum amounts and be tested after several curing times.
3. Tests should be done on the suitability of soil types such as Black Cotton Soil (very clayey) and Red Coffee Soil (high laterite content) for GsE-walls [18].
4. Different sizes of prisms should be tested.
5. The stress relaxation or creep should be tested under dry and wet conditions.
6. Molasses should be tested for its retarding effect.
7. The coefficient of thermal conductivity and heat absorption capacity should be studied.
Part III

A Study on possible Construction Technologies
of Gypsum Stabilised Earth
4 Conditions and Circumstances

4.1 Introduction
Together with the research on the material properties of Gypsum-stabilised Earth, a study was done on the possible construction methods for the material. In order to be able to select construction methods and give an idea of their suitability for the application field, the circumstances and conditions were surveyed. This chapter will describe the conditions and circumstances for the building method. An overview of the factors that play a role, is given in Figure 11.

![Figure 11: The circumstances and conditions for the construction technology with reference to the sections in which they are dealt with.](image)

4.2 Target groups/Stakeholders
The target group is the first aspect that comes to mind when a construction method is to be developed. A product innovation can only be successful if the requirements and wishes of the primary and secondary stakeholders are satisfied as much as possible.

4.2.1 Primary stakeholders
The primary stakeholder is the future owner of the house. In this study, this would be an individual or family with low income living in a developing country. It is impossible to define one set of requirements valid for all stakeholders as there are a lot of differences with the stakeholders. One could think of differing conditions such as income level, employment sector and the housing situation. Therefore a set of requirements is formulated which can be found the owners of low cost housing in South Africa [58]. It is expected that this is applicable to most situations.

<table>
<thead>
<tr>
<th>The method:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- is perceived as a modern method</td>
</tr>
<tr>
<td>- is low cost</td>
</tr>
<tr>
<td>- has a long lifespan</td>
</tr>
<tr>
<td>- can be adapted</td>
</tr>
<tr>
<td>- has a good indoor climate</td>
</tr>
</tbody>
</table>

![Figure 12: The requirements of the future owners](image)
4.2.2 Secondary stakeholders

Next to the future owners of the housing, the governmental bodies play a decisive role in the acceptance of a new material. If the application of the material would have strong positive effects on a Nation, the government could choose to promote the application of the material through promotion or subsidies. Where the interests of the owners are largely focussed on the quality of the housing and the financial aspects, the interests of the government should largely be focussed on the sustainable development of the nation. Therefore ecological, social and other economical aspects are relevant as well.

| The method: | - requires little energy  
|            | - requires little finite sources  
|            | - generates few CO₂ emissions  
|            | - creates (small scale) job opportunities  
|            | - enables skill-acquiring  
|            | - avoid imports through substitution |

Figure 13: The requirements of a government

4.3 Scenarios of housing delivery

The way in which the housing will be constructed is decisive for the method by which it is constructed. Four scenarios can be identified for the delivery of low cost housing in Developing Countries [644] (see Table 2)

Table 2: A highly generalised list of delivery systems for low cost housing in Developing Countries, derived from BESG, Towards the right for adequate housing, 1999, [6, p32]

| Self help: | The basic scenarios in which the family constructs the house itself. Little professional labour is used because of the limited financial capacities. All materials are gathered in nature or purchased from a local supplier. |
| Organized Self help: | Whether governmentally organised or privately initiated, a group is organised in which the efforts are bundled to improve the results. The materials can be bought cheaper, skills can be acquired and more professional labour can be contracted. Usually a construction manager is appointed to manage the process. |
| Small contractor: | A contractor is paid to construct the house. The materials are mostly provided by the owner. Some laymans work can be done by the owner. The construction is erected in phased according to the available funds. |
| Conventional contractor: | In this scenario a contractor is paid to provide labour and materials. The owner can afford a loan. The quality of the final result is high because the contractor can invest in equipment and training. The house is inspected and certified upon completion. |

Although it seems illogical, there is evidence that it is possible to have large contractors construct low-income housing commercially. [32]
Based on the following citations, it was decided to study the possibilities of GsE in the field of the Self help scenario, both in individual and organised schemes.

On the African Ministerial Conference on Housing and Urban Development, 2005, the following was pronounced:

“...recent studies have shown that the current slum upgrading best practice is participatory upgrading (UN-Habitat, 2003). The best slum upgrading programmes are those that ...... are capable of reaching the poorest of the urban poor; and that are based on community participation through formalized processes requiring contributions from slum dwellers.....”[1, p6]

According to the UN-Habitat Agenda of 1996:

“In many countries, particularly developing countries, more than half the existing housing stock has been built by the owner-occupiers themselves, serving mainly the lower-income population. Self-built housing will continue to play a major role in the provision of housing into the distant future. Many countries are supporting self-built housing by regularizing and upgrading programs. [53 par73]

The possibilities within the self-help scenario can be utilised best if a group of families can be organised. In an organised group:

- more skills are present in the group which can be applied and transferred,
- the materials can be bought cheaper,
- more investment capabilities are present for professional help, management and equipment,
- the social and economical structure of the group is developed,
- the political power of the individuals is combined in a group, and,
- the project risks are born by many, reducing the individual risks.

In an individual project though:

- less overhead costs are made, and
- less risks exists on social friction, in case of project failure

The first scheme should therefore be promoted (see also Rodríguez & Åstrand, 1996, [44])

If a construction method should be suited for the self-help scenario, the following requirements should be met:

<table>
<thead>
<tr>
<th>The method:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- can largely be constructed with own labour</td>
</tr>
<tr>
<td>- does not require large investments</td>
</tr>
</tbody>
</table>

Figure 14: The requirements for successful application in a self-help scenario

If the housing is constructed by individuals in a self-help scenario, these requirements are very strict. In an organised scheme, the requirements are less strict.

4.4 Climate

In section 3.5 it is explained that gypsum stabilised earth should be considered weak as adobe as long as more knowledge is absent. Therefore the building details of the roof
and footing should be designed in such way that the walls will not suffer directly from the weather. The indirect effects of weather, temperature and air humidity, still have an effect on the walls. The construction technique for the gypsum-earth wall, will make little difference for its resistance to the direct weather: rain, sun and wind. But it can make a difference for the indirect effects. The construction method of the wall should be so that the climate inside the building is optimally for the inhabitants. As a full treatment of this topic is outside the scope of this study, a few interesting findings are highlighted.

In general two different climates are distinguished in developing countries:
- A hot and humid climate: This climate can generally be found between 15° NL (north latitude) and 20° SL (south latitude). The differences between day and night temperature are small and the humidity and occurrence of rain is generally high.
- A hot, dry climate can generally be found in the adjacent regions between 35° NL and 35° SL. Here the differences between day and night temperature are large. The humidity fluctuates and generally one or two rain seasons can be distinguished.

For each a optimal construction typology is advised by Spence and Cook [49, p12-18]:
- **Hot, humid:** The thermal mass of the building should be as high as possible to function as a heat sink. The heat of the day is stored in the walls and given off in the night. Next to this ventilation should be minimised at day and maximised at night.
- **Hot, dry:** As there are little differences between day and night temperature in this climate, the thermal mass of the building should be as low as possible. Ventilation should be encouraged day and night and the overhang of the roofs should be large to increase draft.

Thus the following requirements are defined for the walls resulting from the applied method:

| In hot dry climates, the walls: | - is water resistant  
| - has a high thermal mass |  
| In hot humid climates, the walls: | - is water resistant  
| - is resistant against continuous humid conditions.  
| - has a low thermal mass |

*Figure 15: The requirements for the walls in different climates*

### 4.5 Structural demands

In first instance a computation was made of the compressive load according to the situation stated in section 1.10: A single-storey house with walls of 2,5m high. Soon it was found that the compressive load is not the determining entity for the dimensions of the wall. A complete study on the structural aspects such as buckling, wind load, seismic load, etcetera falls outside the scope of this project however. Therefore a general design guideline for low cost, single storey houses in development countries was implemented to

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6 For more precise climate differentiation see the climatological map in Appendix F.
determine the structural demand. This guideline (as given by Houben & Guillaud [22]),
prescribes a structural load of 0,1 N/mm$^2$. This figure is multiplied by a set of safety
coefficients to determine the required structural capacity (see Table 3). The safety factor
of 12, prescribed by Houben & Gaillard is very near to the factor Spence & Cook [49]
advice for adobe construction in developing countries (10x).

<table>
<thead>
<tr>
<th>Strength required by downward loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>- For single storey dwellings</td>
</tr>
</tbody>
</table>

Reduction Coefficient  x4
- Nature of the material
- Strength of the mortar
- Buckling of the wall
- Method of loading

Safety Coefficient  x3
- Variation in production quality
- Variation in construction quality
- Accidental excess loading

Total required compressive strength  1,2 N/mm$^2$

Table 3: The security factors as advised by Houben and Guillaud [22, p146]

The structure should be able to withstand the structural loads even when the structure is
at its weakest: in wet conditions.

The **wet compressive strength** should be at least 1,2 N/mm$^2$.

Figure 16: The required wet compressive strength

4.6 Competitive alternatives

In order to draw conclusions about the suitability of gypsum stabilised earth construction
a comparison is made with other construction methods which are suitable for adequate
low-income housing construction. A broad spectrum of methods is available. A selection
is made based on the requirements of structural performance, ease of construction, and
acceptance:

Adobe blocks
Compressed Stabilized Earth Blocks
Tile Brick wall
Hollow Concrete Blocks

Table 4: The alternative construction methods

These methods are described in more detail in the sections below.

4.6.1 Adobe Blocks

Adobe (Spanish) or Tûba (Arabic) is one of the oldest building materials, dating from as
early as 6000 BC. The production technique did not change much since then: A large
volume of selected soil is brought to the right plasticity by adding water and mixed with
straw or chaff to prevent the bricks from cracking during the curing period. A suitable
amount of mud is then placed in a rectangular mould which is open to one or two sides.
After the removal of any excess mud, the mould is removed and the brick is left to dry.
After 3 days the brick can be turned on the other side. After a week the bricks can be stacked after which they can dry for another 3 weeks. A well trained team of 2 men is able to produce 1000 bricks (100x180x350mm) per day. [45, p9]

In the production, only 5-10kWh/m3 is required [22, p2]. As no fuels are needed, the production of Adobe does not evoke any deforestation or release of CO$_2$ gases.

The wall thickness is normally 250 to 400mm, depending on the structural loads. In optimum conditions the compressive strength can reach 3 to 5N/mm$^2$. The water resistance of Adobe is relatively low as repeated wetting of the material will cause the bricks to crack and deteriorate. Footing and roof should be designed so that no water will directly contact the Adobe walls. To increase the water-resistance, a finish of mud, lime or sand-cement can be applied.

4.6.2 Stabilised Compressed Earth Blocks

The stabilised Compressed Earth Block (CEB) is an enhanced version of the Adobe brick. Already in the early history of Adobe, substances such as urea, plant-extracts and oil were added to the soil to improve its performance. When early in the 20th century it became feasible to compress the soil, blocks could be produced with improved strength and water resistance. In general 4-8% cement or 4-10% lime is added as stabiliser. The production can be done manually and mechanically. Compared to Adobe soil, the soil is relatively dry. A wide range of manual and mechanical presses is available on the market. For the low cost housing intended in this study, manual production is most logical.

A soil with 6% lime, can be compressed with about 10N/mm$^2$ with the BREPAK-press [61 p88]. In optimum conditions the compressive strength will then reach 6 to 7,5N/mm$^2$. A team of 5 men and one press is able to produce 250 blocks per day (290x140x100mm).

As the blocks are produced without any motorised means, the energy consumption is about the same as traditional Adobe.

With normal stabilised CEB’s the wall thickness is normally 140 to 200mm, depending on size of the mould and the press.

The water resistance of stabilised CEB’s is much higher than Adobe blocks. If well produced, the wet compressive strength can be as high as 5 N/mm$^2$. Therefore CEB’s can even be used in the foundation if the conditions are favourable. Because of its water resistance, the roof overhang can be designed much smaller than with Adobe blocks.

4.6.3 Fired Bricks

The fired brick appeared in around 3000 BC, after baked pottery had shown the effect of high temperatures on clay. The production technique has changed a lot in the last decennia. In most developing countries however, bricks are produced in the traditional way: A clayey soil is selected, kneaded and then moulded in a box. The green brick is demoulded and put aside to dry for several days. Then the dry bricks are stacked in a large pile, in which fire holes are left open. The pile is covered with a finishing layer to keep the heat inside. In this pile a hot fire is kept for about 4 days after which the pile is left to cool down. When the bricks have cooled down, the pile is taken apart and the bricks are
sorted according to their quality. Around 20% of the bricks can not be used due to failures.

According to Houben, the firing of 100,000 bricks requires some 60 tonnes of wood. Around 1150kWh of energy is required to produce 1m$^3$ of fired bricks. [22, p2] The resulting bricks differ in strength between 5 N/mm$^2$ and 20 N/mm$^2$. A team of 6 people can produce 5 to 10 thousand bricks per firing. Fired bricks have a typical size of around 50x100x210mm. Depending on the structural demands, a wall can be constructed one brick wide, two bricks wide or with a cavity. The water resistance of brickwork depends on the quality of the firing. Low quality brickwork will absorb water very well and can generate problems if applied without a cavity.

4.6.4 Hollow Concrete Blocks

In most of the developing countries Hollow Concrete blocks have gained a strong market position in the last decennia. The blocks are mostly produced on medium to small scale by small enterprises and families. The production process is simple: Sand, which is low in salinity and clay content, is mixed with cement in a ratio of 12-15 to 1 and water is added until the right plasticity is reached. This mix is put into a special mould without bottom. The mould can directly be lifted from the wet concrete as the plasticity is very low. During the first week the resulting blocks should be moistened every day to prevent burning of the cement.

![Figure 17: Fresh Hollow Concrete blocks (HCB's), produced in northern Ethiopia](image)

According to Ballerino, HCB’s “tend not to comply with set quality standards as a result of very limited in-situ manufacturing control.”[3]

Most block designs have added indents (see Figure 20) to improve the shear resistance of the wall. A team of three people can produce 300 blocks per day. The typical size of a block is 400x200x200mm.

After 28 days of curing the compressive strength of the concrete is between 5 and 11N/mm$^2$. Due to the voids in the block design, the maximum permissible load for the block is between 2,5 and 5,5 N/mm$^2$.

Due to the chemical composition of concrete, its strength is not affected by water. Therefore the material is very durable if produced well.

Compared to brick tiles the production of hollow concrete blocks is less energy consuming. The production of 1 m$^3$ of concrete requires 500kWh. The CO$_2$ production however is very high (1,25kg CO$_2$ / kg cement, [40]).
5 Construction technology

5.1 Introduction

In its original application ‘Cast Earth’, the Gypsum-stabilised Earth is cast in wall-high moulds in large volumes. This is probably the most suited construction technique for the American market for which it is intended, but it is not suited for Low Income Families in Developing Countries. Therefore other construction techniques were sought, compared and selected.

In section 5.2 a list of possible techniques is presented. In the sections 5.3 and 5.4 more details are provided on the techniques that are proposed by the author.

5.2 Construction types

Analogous to the two most used earth construction techniques: Adobe and Rammed Earth, two categories of construction techniques can be identified for GsE also: 1) Prefabricated blocks and 2) Walls, constructed on site. Within these categories several variants can be found. Below all relevant techniques are listed.

5.2.1 Prefabricated blocks

The basic block, such as the Adobe block, is massive and have a rectangular form. The blocks can be produced very easily with a wide range of mould-variants. In general; the size will vary between 210x100x50mm and 500x200x200mm, depending on their application, weight and compressive strength. A joint is required with a width between 10 and 30mm, depending on deviation of the dimensions of the blocks.

In the production of the blocks a lot of possibilities are generated for small entrepreneurs because only small investments are required and the production is not bound to the construction site.

In the coarse of time, enhancements were made to the blocks, four of which are:

1) Frogs

One or more indents can be made in the bottom or top-side of a block to increase the adhesion of the mortar. The shear-resistance of the wall will increase and the weight of the block will decrease.

2) Guided masonry

The block design can be fitted with indentions and protrusions that interlock. Thereby guidance is given to the construction worker and the shear resistance is increased further.

3) Mortar-less, interlocking blocks

The notches and protrusions can be designed in such way that little or no mortar is required any more. If well designed and executed, a rigidly interlocking system, is easy to
construct and does not require masonry skills. But in practise such system is very difficult to construct. In absence of mortar, a higher precision is required in the construction work and the size of the blocks. Any deviation, especially from the horizontal line, will lead to tension in the wall, which could possibly cause blocks to fail.

A feasible interlocking construction technique can be designed if the interlocking is made less rigidly. This would in fact be a mediation between the guided block and the interlocking block (enhancement 2 and 3). The ‘Noppensteen’ designed by Meyers & Sonke is an example of this concept. [47]

Figure 19: The ‘Noppensteen’-blocks designed by Meyers and Sonke. [48]
Source of original illustration: Houben & Gaillaud [23]

These fired clay blocks are stacked with a little layer of mortar only. Due to the interlocking, the tensile strength capacities of the bricks are activated, resulting in higher shear- and bending resistance of the wall.

4) Hollowed blocks
In the blocks voids can be created to save material and decrease weight. This can only be done when the material has a considerably higher permissible compressive strength than the maximum expected load. In practise this can be seen with Hollow Concrete Blocks (see section 4.6.4) and extruded clay fired bricks.

Judgement:
It would be interesting to produce hollow GsE blocks in the same way as hollow concrete blocks. For this reason a mould was designed and tested, which could be produced very easily. Because the outer form and inner forms can be separated, the blocks can be demoulded very quickly7. However, when the wet compressive strength of gypsum stabilised earth was tested (2,0N/mm²) it became clear that the application of hollow GsE blocks was no option.

7 Photographs of the mould are added under Appendix G
The design of a loosely or rigidly interlocking block for gypsum-earth construction would be interesting. It is not pursued in this research however as the conditions of such a system are very strict. Any deviation from the straight and horizontal line will cause friction and tension in the bricks, leading to failure. For self-help construction, the level of skills required from the workmen is too high to be successfully applied.

Based on these confinements, the massive masonry block was chosen as most suitable for self-help construction. As the construction technique is common in most developing countries, little difficulties are expected in the construction phase. The production of blocks requires more attention. It is expected that walls built with these blocks will be appreciated more than those constructed with Adobe blocks or Compressed Earth Blocks as the appearance of the blocks is similar to very smooth concrete blocks. The construction technique is described in section 5.4 in more detail.

5.2.2 Cast Walls

Continuous Formwork
The method as proposed by Lowenhaupt is, contrary to the production of blocks, geographically bound to the construction site: The formwork for a complete building plan is set up, the different wall-openings are left open and the mix is cast into the formwork.

![Figure 21: The structure of a house constructed in Cast Earth (USA). Source: www.castearth.com (2007)](image)

Because of the high initial strength of GsE the formwork can be removed within 24 hours after casting after which the roof construction etcetera can be constructed. The formwork is now available for an other house.

This construction principle is well-known in modern concrete construction. Some low cost-oriented, pre-fabricated formwork for concrete have been developed by a few companies\(^8\). A result of such method can be seen in Figure 22.

\(^8\) Four commercially available methods can be found on the websites of Arxxbuild, Polysteel, Moladi, and Casthome.
To avoid bad adherence of subsequent layers, the complete formwork should be filled in one continuous batch. As the open time of GsE is only 25 minutes, the speed of preparation and casting of the mix must be very high. This method is therefore only possible if mechanised equipment is available. For low income families the high investments for this equipment and the complete formwork can not be afforded. An alternative construction technique can be found in the traditional technique called Pisé de Terre or Rammed Earth.

**Small formwork**

A small formwork is set up and filled with earth. The earth is compacted to a dense mass by tampering. The formwork is moved around in order to add successively segments to the wall as can be observed in Figure 23.

This system can also be applied for gypsum-stabilised earth. Only one small form is needed with some added bits and pieces to adapt the formwork to all required positions such as corners and openings. Compared to the investments required for one formwork for a complete housing plan, this is very cost effective. As this type of formwork is well known in Rammed Earth construction various formwork variations have been suggested (see Betts & Miller [5], Neubauer [42], Minke [35]). A simple example of a formwork can be seen in Figure 24.
The resulting walls will be smooth, depending on the smoothness of the formwork, and require no extra finishing. Due to the massive looks of the wall, the appreciation will probably be high. Although the sections of the formwork will show their intermediate technology, the overall appearance of the wall will be very good.

Based on the analyses of the possible construction techniques, both 1) the standard block with frog and, 2) the wall, cast in sections, are interesting for low cost housing construction in developing countries.

In the sections below both techniques are further explained and provided with possible construction details.

5.3 A Massive GsE wall, cast in sections

As mentioned earlier, the construction technique for a massively cast GsE wall can be analogue to that of Rammed Earth, also known as Pisé de Terre. Therefore most of that detailing can be used for gypsum-stabilised earth. The only difference is the way of application, i.e. casting in stead of tamping, and the resulting strength.

Preparation of the mix

Depending on the size of the forms, a certain amount of mix should be prepared for casting. The time-window available for preparation and casting is 20 to 25 minutes. The following actions are required for the preparation of the mix:

1) The total required mass of mix is defined after which,
2) the mix components are batched. The only materials that define the final weight of the cast are the soil and gypsum. Almost all water will evaporate from the mix, and the other additives are not significant for the final weight. When soil and gypsum are batched, one should be aware that the required amount of gypsum is expressed in weight-percentage of the total solid parts. If for example 50kg of mix is required with 24% gypsum, 38kg soil and 12kg gypsum should be batched. The water amount should also be weighted on forehand to avoid faults. Too less water will evoke an abrupt early setting. An excess of water will decrease the final strength of the cast severely.
3) The soil, gypsum and any other solid additive is mixed thoroughly until a homogenous mix is obtained.
4) After all liquid additives are mixed through the water, the water is added to the mix. An optimum activity of the gypsum is obtained when the mix is left unstirred for about one minute.
5) After the minute of rest, the mix is stirred continuously, whereby special attention should be given to the dry lumps or mix that stick to the walls of the mixing tub.
6) When the mix has reached an even consistency, it can be poured into the formwork.
Care should be taken that no old mix is brought into contact with fresh mix as the cured crystals in the old mix will induce very quick setting in the fresh mix. Therefore the object used to prepare the mix should be rinsed before each new batch.

It should be clear that this process requires a lot of attention. The added substances, such as retarder and plastifier, need careful weighing and the time-window is very limited.

Construction of the wall
As in most earth construction, the foundation should be made of a different material such as stone or concrete. When available a water-barrier should be introduced around the foundation to prevent water from entering the construction. The inside floor should at least be 5 to 10cm higher than the outside ground level to prevent water from coming in. It is best to have a raised plinth of water-resistant material of about 30 to 50 cm above ground level. If it is possible to protect the earthen wall from rising moisture with a water barrier, this should be done. A simple but effective detail is proposed by Williams-Ellis in Figure 25. The massive wall can be constructed in sections on top of this plinth. This can be done in sections of suitable volume, depending on the production capacity for gypsum-stabilised earth. If a section is cast in layers, care should be given to the adhesion of the layers. If the lower layer has cured substantially before the new layer is cast, some objects such as small pebble should be forced into the lower layer. The new layer will then adhere better. This should always be done in the final layer of a section, to prepare it for the next section.
It is best to finish the open end of a section slantwise or with an indent to increase the coherence with the following section that will be cast later.
If possible all framing for doors, windows and plumbing should be implemented in the formwork. This will minimise later efforts required to install those elements.
The wall is best finished with a concrete reinforced beam to spread the load of the roof and to increase the constructional coherence of the building. This beam is at least 10cm high and as wide as the wall. An example of the detailing of such a concrete beam can be observed in Figure 30 in Section 5.4. The concrete beam can also be applied as the lintel for all doors and windows. If concrete is too expensive it can be substituted by timber.
The roof construction can be constructed in any possible way. Attention should be given to the overhang of the roof (at least 400mm) and to ventilation. In an optimal case the roof is provided with a cavity which can be ventilated.
Earthquake

In areas prone to earthquakes (see Figure 26), a reinforced concrete frame should be integrated in the structure. This frame is started with a beam of reinforced concrete in the foundation. On top of this beam, columns should be placed on all corners and around all wall-openings such as doors and windows. The gypsum-earth-mix can easily be cast between these columns. In an optimal situation, a horizontal reinforced concrete beam is cast at a height of 1.00 to 1.20m and on the top of the wall. It is most economical to let these beams function as sill and lintel of the door and windows.

If the use of concrete for the framework is too expensive, extra attention should be given to the corners. If they are filleted or bevelled at the inside as well as the outside, the perpendicular forces can be transferred better to the other wall, decreasing the stress in the corner (see Figure 27).

The number of wall openings should be as low as possible, whereby multiple openings in one wall should be prohibited. The roof construction and the gables should be constructed as light as possible.
5.4 Massive GsE blocks

As described in section 5.2 the massive block is probably the best suited block type for low cost masonry. In essence there is little difference between the masonry with GsE blocks and any other type of block. Chemically a gypsum-based mortar is optimally this is not practically usable because of the restricted open time of approximately 25 minutes. It is expected that a cement-based mortar will also suffice, but no research has been done yet on this combination.

As the wet compressive strength of GsE is only little below that of the Compressed Earth Bricks described by Webb [61], the same dimensions (290x140x90mm) were chosen for the GsE-blocks. Any block with a width larger than 105mm can not be placed with one hand without auxiliary instruments. Therefore a block clamp lifter [61] is required to enable a mason to lift the block with one hand.

Production of blocks

Before the wall can be erected on site, blocks need to be produced. Like any other block, GsE-blocks can be produced off site. It is expected that this will generate more chances for small entrepreneurship than on site wall casting. Some special attention should be given to the production of the blocks however. Contrary to the production of Adobe blocks and CEB’s, the element of time is very crucial in the production of GsE. As the open time is maximally 20 to 25 minutes, a strict time-discipline should be kept. Only small amounts of mix can therefore be prepared. The preparation of the mix is the same as described in section 5.3.

For massive blocks, with or without frogs, a simple mould can be used. According to Sonke [48, p104] the moulds should always be made out of young wood which is kept wet all the time. This will increase the lifetime of the moulds and the easy of release of the blocks. Several mould-techniques have been proposed for Adobe and Rammed Earth blocks before. The moulding technique proposed by Fauth for Rammed Earth blocks, seems most suitable for static casting of GsE-blocks (see Figure 28). With this type of moulding box, several blocks can be cast with one batch. As the surplus of mix for one block can easily be brought over to the adjacent block, little material is lost. Another advantage is the possibility to add frogs to three sides of the blocks.

*Figure 28: A form-box for the casting of blocks as proposed by Fauth, 1933. Source: Minke [35, p129]*

This type of mould however needs to be taken apart to de-mould the block. This can only be done after a certain curing period.
An other type of mould is similar to the traditional method of fired brick making, called ‘slop moulding’ [4]. The block is formed in a rectangular mould which has no bottom or top. The mould is placed on the ground and filled with a GsE mixture. The mould is lifted off after a few minutes only leaving the block on the ground to dry. Exact timing is needed so that the casts are strong enough to bear their own weight but also flexible enough to drop out the mould if the mould is raised. Very smooth results can be obtained if a smooth and regular form is used. An extruded profile of aluminium or steel would be ideal.

In order to test this principle with GsE, a test was done with a small mould of 30x100x 60mm. The curing time before releasing was varied until the resulting blocks were of good quality. In this particular mix-composition, a curing period of 5½ min was optimal (see Figure 29).

Figure 29: The line-up of the blocks cast with the mould.

In small scale enterprises, the production method above is very demanding. The mix-composition and the curing time should carefully be kept constant. It can therefore be questioned if this method is suited for small scale production. In high-tech circumstances however this system can probably be optimised into a extrusion process in which the GsE profile is cut by wires.

Construction
As said earlier, the construction process of a wall from GsE-blocks is very similar to a wall constructed with CEB’s or HCB’s. Special attention should be given however to avoid direct or permanent contact with water. Some essential measures are:

- A plinth erected to about 40cm above ground level, constructed from a water-resistant material such as concrete blocks.
- A moisture barrier between the plinth and the GsE wall.
- All windows should be fitted with sills to prevent water from standing on GsE.
- A roof overhang of at least 500mm is required to keep driving rain away from (a large part of the wall.
- A plaster can be applied if economically feasible. This is no all-forgiving intervention however! The measures stated above are more important.

To increase the earthquakes resistance, the same measures can be taken as described in section 5.3. Instead of massively cast walls, the framework can be filled in with GsE blocks.
Some examples of good detailing in Adobe walls have been proposed by Miller (see Figure 30 and Figure 31). This detailing would be very well applicable to walls constructed with GsE-blocks.

Figure 30: A detail for ceiling and roof construction for earth blocks proposed by Miller (1949). Source: Adobe or sun-dried brick for farm buildings [33]

Left:

Figure 31: The detailing for Sill, Trim and Head in an Adobe wall, proposed by Miller (1949) Source: Adobe or sun-dried brick for farm buildings [33]
Part IV

Discussion

on the Material properties, its Suitability
and the Research process
6 Discussion

6.1 Introduction

In this final chapter the suitability of GsE in the application field of low cost construction in Developing Countries is debated (section 6.2), the research questions are answered (section 6.3), the application in advanced economies is questioned (section 6.4) and further points of interest are stated (section 1.1 and 6.6).

6.2 Application in Developing Countries?

To reach an indisputable conclusion on the suitability for GsE for low cost housing in Developing Countries the performance of all methods should be compared on the aspects mentioned in chapter 4. Most aspects however are outside the scope of this research and require knowledge and expertise the author does not possess. Examples are the appreciation of the method and the creation of employment. So they can not be answered in this study. Furthermore, as GsE methods have not been applied yet, no data is available on aspects such as the durability and the heat absorption. Therefore the GsE-methods can be compared to the other methods in a few aspects only. These are covered in the sections 6.2.1 to 6.2.4.

In order to be able to compare the performances of the materials, a computation is made with input based on laboratory results and literature references. To increase the transparency of this computation, the values are shown in Table 5. The values relevant for the specific aspects only, are given in the sections concerned.

For any quantitative comparison in this study, the required functional unit is defined as: The walling of a dwelling with a length of 1 meter, erected from the foundation to a height of 2,5 meters, with the technical provisions for, and the structural capacity to bear the load of a roof with a load of 3 kN per meter wall length.9

<table>
<thead>
<tr>
<th>Addition for stabilisation</th>
<th>Compressed Earth Blocks</th>
<th>Fired bricks</th>
<th>Hollow concrete blocks</th>
<th>GsE wall, in sections</th>
<th>GsE Massive blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix ratio of stabiliser</td>
<td>%</td>
<td>cement</td>
<td>firing</td>
<td>cement gypsum</td>
<td>gypsum</td>
</tr>
<tr>
<td>Required width of wall</td>
<td>m</td>
<td>0,3</td>
<td>0,14</td>
<td>0,11</td>
<td>0,14</td>
</tr>
<tr>
<td>Characteristic Mass (at the time of construction)</td>
<td>kg/m³</td>
<td>1700</td>
<td>2000</td>
<td>2400</td>
<td>2100</td>
</tr>
<tr>
<td>Wet Compressive strength</td>
<td>N/mm²</td>
<td>1,0</td>
<td>2,8</td>
<td>8,0</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 5: the characteristics of the materials as applied in the computation

9 Effort was made to define a requirement on the duration of durable use. This would have given expression to the fact that some materials have a longer durable life than others. However, it became clear that a quantified performance of the materials could not be established. Therefore the this aspect has been left out of the functional unit.
6.2.1 Durability

The durability of a construction method depends on several aspects. The most important however seems to be the weather resistance. Limited information is available on the weather resistance of GsE, both from literature and from laboratory research. Therefore no exact statement can be made on this aspect. Based on the wet compressive strength and the solvability of gypsum in water one can conclude that GsE is not suited for application in humid climates. Even if the structure is able to bear the structural loads, the blocks can very easily be damaged when wet. Therefore the long term performance of the material is questionable. It is expected that a wall constructed with stabilised CEB’s, Fired Bricks or Concrete blocks will perform better in this climate because of the higher structural integrity in wet conditions.

In dry conditions, the durability of GsE is better. The effect of airborne sand and mechanical damage has not been studied. However, based on the high compressive strength in dry conditions, it is expected that a wall constructed with GsE-blocks will have a durability similar to stabilised CEB’s.

6.2.2 The Costs

The total price of a constructed wall is composed of the factors material, required professional labour and equipment. Little can be said by the author on the two latter factors. However some comment can be given on the differences in material costs. As the HCB is the direct competitor to GsE, a comparison will be made between these two materials.

Due to the lower mix rate and the smaller wall volume of Hollow Concrete Blocks, more than two times more gypsum is needed for GsE than concrete for HCB’s (see Table 6).

<table>
<thead>
<tr>
<th></th>
<th>HCB</th>
<th>GsE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilizer</td>
<td>Cement</td>
<td>Gypsum</td>
</tr>
<tr>
<td>Mix rate</td>
<td>15% cement</td>
<td>24% gypsum</td>
</tr>
<tr>
<td>Wall, width</td>
<td>Hollow, 10cm</td>
<td>Massive, 14cm</td>
</tr>
<tr>
<td>Ratio of required amount</td>
<td>1</td>
<td>2.25</td>
</tr>
<tr>
<td>Ratio of price of stabilizer</td>
<td>2.5-3</td>
<td>1</td>
</tr>
<tr>
<td>Ratio of Total Costs</td>
<td>1,1-1.3</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6: A comparison of input requirements between Hollow Concrete Blocks and Gypsum stabilized Earth.

The internationally paid price of industrially produced gypsum is about 2.5 to 3 times lower than that of cement\(^\text{10}\). Based on the assumption that this international price relation is a strong indicator for the local price relation, one could conclude that the costs for the total amount of gypsum needed for a GsE-wall is only 1.1 to 1.3 times lower than the price for the total amount of cement required for a HCB-wall. The costs of the additional required measures such as an extended roof and an improved moist barrier has not been taken into account however. This would mean that a GsE-wall would probably be more

\(^{10}\) Ex factory price of calcined Beta Gypsum: 18 USD per ton [34&57]. Ex factory price of Portland cement: 45-56 USD per ton [11&25].
expensive than a wall constructed out of HCB’s, if all the other costs for the erection of a GsE wall are equal to those of a HCB wall. As the performance (actual and perceived) of GsE is probably lower than that of HCB’s, no successful implementation can be expected. If however, the costs of construction or of gypsum can be reduced, for example by producing it locally, some opportunities may rise for GsE as construction material for Low Cost Housing in Developing Countries.

6.2.3 The Ecological impact

Two important aspects play a role in the ecological impact of a construction technique: The energy required to construct a house and the CO$_2$-emission resulting from the total process.

In order to be able to assess the performances of the materials on these aspects, a computation is made. In literature a lot of different values for the characteristics of the various construction materials can be found. In order to make the computations as transparent as possible, the values that were applied are given in Table 7.

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy required in MJ/kg</th>
<th>CO$_2$ emission in kg CO$_2$ per kg material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum [NBVG, Herpen]</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>Cement [adobemachine]</td>
<td>4.8</td>
<td>1.25</td>
</tr>
<tr>
<td>Soil [adobemachine]</td>
<td>0.028</td>
<td>0</td>
</tr>
<tr>
<td>Fired bricks [Houben]</td>
<td>3.16</td>
<td>0.19</td>
</tr>
</tbody>
</table>

*Table 7: the characteristics of the materials as applied in the computation*

The resulting totals are given in Table 8. The complete computation with all sources is added to the CDrom.

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy required MJ/fu</th>
<th>CO$_2$ Emissions Kg/lu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adobe</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>Compressed Earth Blocks</td>
<td>233</td>
<td>55</td>
</tr>
<tr>
<td>Fired bricks</td>
<td>1026</td>
<td>118</td>
</tr>
<tr>
<td>Hollow concrete blocks</td>
<td>390</td>
<td>98</td>
</tr>
<tr>
<td>GsE wall, in sections</td>
<td>191</td>
<td>2</td>
</tr>
<tr>
<td>GsE Massive blocks</td>
<td>161</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 8: The totals of the Environmental computation.*

A few interesting aspects can be observed on the energy requirement:
- The energy requirement of GsE is about half of the energy requirements of HCB’s.
- Adobe is indisputable the most environment friendly material.
- The firing of bricks is a very energy consuming process.
The following can be concluded on the emission of CO$_2$:

- Both cement stabilized products (CEB’s and HCB’s) cause a large CO$_2$-emission. Due to their lower Wet Compressive Strength and high amount of gypsum required, the CEB’s are no better alternative than HCB’s.
- A lot of CO$_2$ is released in the production of fired bricks. If the wood used for firing the bricks is grown in a responsible way, this process is theoretically CO$_2$-neutral.
- The release of CO$_2$ is almost nil in the production of GsE-walls.

6.2.4 Suitability of the construction techniques.

Although the construction techniques described in section 5.3 and 5.4 are relatively simple, both techniques suffer from the complexity of the mix-preparation. It is very well imaginable in the circumstances of self-help construction and low-technology circumstances, that the retarder or plastifier is not correctly weighted or that the batch is cast too late. If this happens, the structural integrity is severely affected. If the batch hardens in the mixing device, a lot of work is required to remove the hardened material. This happened more than once in the laboratory. If this happens once or twice a day on a construction site, the appreciation of the construction method by the workmen (the future owners) will drop considerably.

6.3 Conclusions

In this section sub conclusions are given on the suitability of GsE for low cost construction in Developing Countries. The conclusions are grouped according to the questions defined in section 1.7. A final conclusion is given in the last paragraph of this section.

**Material properties of GsE**

- Gelatine is a suitable retarder for GsE at 0,20 to 0,30 WT%. The retarding factor is 7 to 10.
- The plastifiers Tillmann OFT ON2 and soap, both known for their plastifying effect on concrete, are suited for application in GsE.
- The dry compressive strength is enough for commercial products. In wet conditions however, the compressive strength is a limitation to its successful application.
- In humid climates the material can only be applied under strict conditions.

**Suitability of GsE for low cost housing in developing countries**

- GsE can be applied in dry climates if the proper measures are taken. In humid climates however, the material would need extensive protection.
- A wall constructed with GsE-blocks will probably be more expensive than a wall constructed with HCB’s, due to the required extra technical measures.
- The casting method is not suited for Self-help construction as it requires high precision and time management skills. This is true for both for the GsE blocks and for the massive GsE walls. The production techniques of CEB’s and HCB’s is more suited for Self-help construction.
- GsE has a lower Energy requirement and release of CO2 than HCB’s, stabilised CEB’s and fired bricks.
End Conclusion

Based on the research done in this project the conclusion can be drawn that GsE is very well applicable. However, the method seems to be unsuitable for Low cost Housing Construction in Developing Countries due to:
- the high costs of gypsum in comparison with the costs of cement, and
- the complexity of the preparation of the GsE mixture.
If no change can be brought in its wet compressive strength, the material is expected to be of little competition to the Hollow Concrete Block.
Gypsum-stabilized Earth may be successful in regions with a dry climate, where gypsum can be produced locally and the costs of cement are extremely high due to the added transport costs.

6.4 Application in advanced countries

As the project was aimed at the development of technology for developing countries, the research question was targeted towards application in low-tech surroundings. During the research-process the interesting idea rose that GsE could be applied in ‘advanced countries’ for its aesthetic qualities. In a lot of architectonically designed buildings, such as the church depicted in Figure 32, 33 and 34, an earthen wall adds quality to the building. Nowadays, these walls are constructed with rammed earth, which is a very labour intensive construction method. In most of the ‘advanced countries’, this method is too expensive to be used frequently. However if the earth can be cast, the amount of labour required will decrease, reducing the total costs drastically. This method would therefore, to the opinion of the author, be a welcome addition to the construction methods available in ‘advanced countries’.

Chapel of Reconciliation, Berlin, Architects: Reitermann & Sassenroth

Figure 32: Plan, Figure 33: Exterior and Figure 34: Interior
6.5 Discussion

Material research
- In this study many relations were found between mix-circumstances and resulting performances of the casts. The number of tests however, is too small in most cases to prove any causality.
- Most of the data were collected from relative young prisms of maximally 28 days old. Most of the conclusions are based on this imperfect knowledge, and are therefore imperfect themselves. The research on older specimens will certainly give new insights and could possibly dispute the conclusions done in this study.

Construction techniques
- As no walls were actually constructed with one of the construction techniques, the conclusions are based on literature and insights of the author. Therefore care should be taken of the application of the methods as described.

Comparison of alternatives
- As mentioned earlier, limited knowledge is available on the GsE construction methods. Therefore some of the statements were only possible in a speculative perspective. This should be taken into account when these conclusions are interpreted.

6.6 Recommendations for follow-up research

Material research
- The main field of interest for further material research on GsE is the improvement of the wet compressive strength of GsE. If the performance of the material can be improved in this aspect, the material will be highly interesting for more areas of the world.
- In order to be able to construct walls with GsE, research on the type of mortar and rendering suited for GsE walls is required. The suitability of cement-based plasters and mortars should be tested.
- Further research on a suited retarder would be very interesting. If a method can be found by which the open time of the mix can be increased further without negative effects, GsE would be applicable more easily.
- Many other aspects are of interest for the application of GsE. A list of aspects the author encountered during this study is given in section 3.6

Construction techniques
- More knowledge on the construction techniques can only be obtained if the material is applied in practice. It would be very interesting to perform a pilot project in which a structure is erected in various GsE-construction methods. A lot of valuable data can be abstracted from the long time observation of such structure.

Comparison of alternatives
- More study should be done on aspects that could not be studied in this research project: Especially the economical and social aspects can be of major interest for the market-study of the material.
7 Literature

   a. Antolini P., The geology of calcium Sulfates: Gypsum and Anhydriet (1-27)
   b. Murrat M., Structure cristallochimie et réactivité des sulfates de calcium (59-172)
   c. Lucas G., Hydration of Gypsum Plaster (197-204)
   d. Murrat M. & Karmazsin E., Cinétique d'hydration des Sulfates de Calcium semihydratés (217-237)
   e. Lucas G., La Détermination du temps de prise des Plâtres retardés (335-341)
   f. Deleuil M., Le Gâchage; Application aux phosphogypslâtres de préfabrication (349-370)
g. Kuhlmann J. & Ludwig U., Properties of Plaster containing Anhydrit II (383-397)
h. Karni J., Fiber-reinforced, polymer modified Plaster of Paris (463-479)

18. Gachigi, K., Bachani, S., Kariuki, J., Ogugo, C., Tene, N.M., Rendering high clay-content soils suitable for cement stabilisation for building blocks for low income housing, After 1994, Department of Mechanical engineering, University of Nairobi, Kenya


Deel A; Eigenschappen, number 7842 and
Deel B: Materialen, number 7843


32. Matlock, R., A role for corporate social action in the delivery of urban housing, The Delta Foundation, 2000, Proceedings of Strategies for a Sustainable Built Environment, Pretoria


35. Minke G., Lehmbau - Handbuch, Der baustoff Lehm und seine Anwendung,1994, Ökobuch, Staufen bei Freiburg, Germany

36. Minke G., Building with earth: design and technology of a sustainable architecture, 2006, Birkhäuser, Basel, Germany

42. Neubauer L.W., Adobe construction methods, Manual 19 of the California Agricultural Experiment station, year unknown but later than 1953, Universtiy of California
43. Patty R.L., Minium L.W., Rammed Earth Walls for Farm Buildings, 1945, bulletin 277 of the Experimental station of the Department of Agricultural Engineering, Brookings, South Dakota.
45. Schijns, W., Kaper, O., Kila, J., Vernacular Mudbrick Architecture in the Dakhleh Oasis, Egypt, 2003, private publication, owned by Erkelens, P.
47. Sonke, J.J., De noppensteen, 1977, Stichting TOOL Amsterdam
52. Reader with the course Technology and Sustainability, June 2003, reader nr. 1710. Technische Universiteit Eindhoven, The Netherlands
53. UNCTAD, The Least Developed Countries Report, Escaping the Poverty Trap, 2002
54. UN-Habitat Agenda 1996, outcome of the Habitat II conference in Istanbul, Turkey
56. Unknown, Handleiding practicum bouwkunde, dictaatnummer 7987, Test 3, pages 3-1 t/m 3-15, 2005, Technische Universiteit Eindhoven, The Netherlands

Standards
- Nen-EN 196-1, Methods of testing cement – Part 1: Determination of strength, 1994. European committee for standardisation
- DIN 1168, teil 1 Baugipse, begriffen, sorten und verwendung, 1986, Deutsche Institut für Normung
- DIN 1168, teil 2 Anforderungen, Prüfung, Überwachung, 1986, Deutsche Institut für Normung
8 Definitions and descriptions

Below most concepts that are used in this report are defined. Some of the definitions are quoted from Ballerino [3], as this list was the basis of understanding of these concepts. Those quoted are marked with an asterix (#).

**Aggregate**: Sand with a specific composition of fine to coarse grain sizes. No Silt and Clay (grain sizes smaller than 0.06mm) is found in this composition.

**Appropriate**: Usable for constructing. This is an other meaning than when used in the term “appropriate technology”. Here it stands for the technically usable version of the building method and its aspects.

**Brick/Block**: British Standard 3921:1985 specifies a brick as an walling unit not exceeding 215 mm in length, 102,5 mm in width and 65 mm in height. All walling units exceeding one of these sizes are referred to as blocks. A large variation in blocks sizes can be found depending on the layout and wall size.

**Calcined gypsum**: The hemi-hydrate version of natural gypsum (di-hydrate) which can be created through restricted heating of the di-hydrate. More information in Section 2.4.2.

**Cast**: A cast is defined as the activity of casting one prism-set. All three prisms of one cast are identical. Within one test, more than one casts are done.

**Cast Time**: The time at which all free water in the mix is absorbed. More information can be found in the document on ‘Literaure and Methods’ added on the CDrom.

**Cast Earth**: The name of a construction method, developed by Mr. Lowenhaupt, to erect walls. Gypsum is used as a stabiliser for earth to make it castable. All information that is available about Cast Earth can be found on the web: www.castearth.com. It can also be found in the reader ‘Cast Earth’, supplied with this report.

**Basic mixture**: The chemically correct mixture without a retarder.

**Retarder**: A substance added to the basic mixture to enlarge the setting-interval.

**Drytime**: The time at which the surface of the prism is able to withstand a local pressure of 300gr on 25mm². More information can be found in the document on ‘Literaure and Methods’ added on the CDrom.

# **Dwelling unit**: “A self-contained interleading suite of rooms, which shall contains no more than one kitchen, used for human habitations and includes uses normally associated therewith but subordinate thereto and include also the letting on a permanent basis by the resident of a part of the dwelling unit, otherwise than as a separate dwelling unit to not more than four persons” defined by Port Elizabeth Zoning Scheme (1996, p.5).

# **Durability**: period for which material is able to fulfill its function satisfactorily when subjected to normal use, assuming that it is reasonably maintained at regular intervals. It can be also defined as the retention of performance and appearance over the expected service life. (Agrement Board of South Africa, www.agrement.co.za, performance criteria: durability, p.2).

# **Incremental housing**: A process, which starts with an asset, that satisfies the basic physical and social needs. Households add to their initial asset incrementally according to their financial means. (Van Wyk, 1996b).

# **Informal housing**: A shelter usually constructed with unconventional building materials acquired informally (waste from construction sites, plastic bags, paper, etc). (Van Wyk, 1996b).
1996, key words). A shelter that do not meet any recognised standard but still serve a purpose as temporary emergency housing.

**Large volume casting**: The construction method normally used in concrete casting; Large moulds are filled with concrete in high volumes. Normally the casting of one building layer is done in one cast. This method of moulds and casting could also be used for an Gypsum-stabilised Earth mix if the setting of the mix is retarded enough.

**# Life cycle analysis**: includes all steps from extraction of raw materials, production of building materials, transport, construction, use and maintenance, demolition and waste management and in some cases recycling of materials. (KTH & NTNU, 1998, Melby, p.3).

**Low Income Countries**: The term refers to the countries which are lowest on the ladder of income per capita. No strict definition can be found.

**Open Time**: the time window available to pour the mix in its final form.

**Pourtime**: the time between the start of the mix and the latest possible moment of casting.

**Prism**: a block with a large length than width and depth. In the laboratory tests prisms were cast of GsE with a normalised size of 40x40x160mm.

**Prismset**: a set of three prisms cast in one test mould. The prisms within one prism-set have identical mix-composition and circumstances as they are made in one cast.

**# Site and Services**: Subdivision of urban land and the provision of services and utilities for residential use. Site or plot is a land on which a house can be build; services can vary from pit latrines and shared water standpipes to full services to the individual plots.

**# Sustainability**: "A development that meets the needs of the present without compromising the ability of the future generations to meet their needs" (WB, 1987).

**# Squatter houses**: Concept that has different meaning depending on the country, in Port Elizabeth refers to illegal settlements and/or to illegal erection of a dwell, mostly found in inner urban, peri urban suburban areas.

**# Starter house**: The first shelter unit in which a household begins the process of incremental housing. (Van Wyk, 1996b), South African concept related with low-income housing projects.

**Test**: A test is defined as the complete set of activities are involved in the testing of one aspect of GsE. In most tests several prism sets are cast.

**# Traditional knowledge**: The knowledge that has been passed on through many generations.
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D Technical details on the available types of gypsum

<table>
<thead>
<tr>
<th>Rij</th>
<th>Chemische formule van de fase</th>
<th>Natuurgips</th>
<th>Geproduceerd Gips</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CaSO₄·2H₂O</td>
<td>CaSO₄·½H₂O</td>
</tr>
<tr>
<td>1</td>
<td>Benaming</td>
<td>calciumsulfaat-hydraat</td>
<td>calciumsulfaat-halffydraat</td>
</tr>
<tr>
<td>2</td>
<td>Vorderen benamingen</td>
<td>natuurgips</td>
<td>gipsgezaagde tech. gips</td>
</tr>
<tr>
<td>3</td>
<td>Vormen</td>
<td>α-vorm</td>
<td>β-vorm</td>
</tr>
<tr>
<td>4</td>
<td>Kristalwater (% m/m)</td>
<td>20.92</td>
<td>6.21</td>
</tr>
<tr>
<td>5</td>
<td>Dichtheid (g/cm³)</td>
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<td>2.757</td>
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<tr>
<td>6</td>
<td>Molgewicht</td>
<td>172.07</td>
<td>145.15</td>
</tr>
<tr>
<td>7</td>
<td>Kristalklasse / ruimtegroep</td>
<td>monoklin</td>
<td>I 1/a1</td>
</tr>
<tr>
<td>8</td>
<td>Hardheid van Mohs</td>
<td>2</td>
<td>3 ½</td>
</tr>
<tr>
<td>9</td>
<td>Oplosbaarheid in H₂O bij 20°C (g CaSO₄/9°)</td>
<td>2.05</td>
<td>8.8</td>
</tr>
<tr>
<td>10</td>
<td>Stabiliteit</td>
<td>&lt; 40°C</td>
<td>metastabiel</td>
</tr>
<tr>
<td>11</td>
<td>Vormingstemperatuur in het laboratorium</td>
<td>β: 45 - 200°C in droge lucht</td>
<td>α: &gt; 45°C</td>
</tr>
<tr>
<td>12</td>
<td>Vormingstemperatuur in techn. processen</td>
<td>β: 120 - 180°C droog</td>
<td>α: 80 - 180°C nat</td>
</tr>
</tbody>
</table>

Table 9: The types of gypsum and their properties (Dutch), source NBVG, 2006 [41]
Figure 35: The occurrence of Red Coffee Soil (red) and Black Cotton Soil (green) as predominant soil. Source: Houben and Guillaud [23, p41]
Figure 36: The predominant climates regions with a differentiation in hot dry climates (orange) and hot humid climates (blue). The colors added by author. Source: Spence & Cook [49, p12]:
G Photos of moulds

In this project several mould were developed by the author. Below the photos of several versions can be found.

Figure 37: The first version of the mould for hollow GsE blocks

Figure 38: The improved version of the mould for hollow GsE blocks. The application of Hollow GsE blocks proved impossible.

Figure 39: The mould for a GsE block with frog

Figure 40: The GsE blocks resulting form the mould depicted left
H Table of Contents of the CDrom

1 Information on Cast Earth
All information available on Cast earth can be found on the website of Lowenhaupt: www.castearth.com. However, this website is very unstructured. A structured version of the information of the website of Lowenhaupt is provided in the document: ‘Information Cast Earth.pdf’.

2 Gypsum producing countries and their production
Two sources are added in which the national production of gypsum is given for a lot of countries. The first list gives the gypsum production in the years 1975 to 1977. Source: Spence & Cook, 1983 [49, p126].

3 Output of the laboratory tests
All data that was found in the laboratory tests, has been gathered and processed in Excel. The two resulting Excel-files are added on the Cdrorm. The Tests 0 to 7 can be found in the ‘Output of laboratory test part1.xls’. The tests 8 to 13 can be found in ‘Output of laboratory test part2.xls’.

4 Output of computation of CO₂ emission and Energy requirement
The computation of the CO₂ emission and Energy requirement is made based on figures found in literature and digital sources. To make the computation as transparent as possible, a Excel-file with all vaules, references and computations is added digitally as ‘Computation of performances.xls’.

5 Literature study and Methodology of the research
From the start of the research, a document was created with all relevant information. This resulted in a document with the results of the literature study and the methods that are used in the laboratory research.

6 Digital versions of some important literature and sources
During the project, a lot of literature sources and were found. Some of them are highly relevant for anyone with interest in this subject. Therefore a collection of the most relevant sources which were digitally available, has been added under the directory ‘06 Important literature and sources’.