A survey of recycled plastic waste as an alternative building material

- a field study of low-income housing in Bogotá, Colombia

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Abstract

This study charts the possibilities of recycled plastic and its use as an alternative building material for low-income housing in Colombia. The building materials in the study have been compared with respect to their physical properties, the cost and how they affect the indoor climate in each building.

Colombia is a country that has been subjected to civil war for many years, which has contributed to urbanization, increased poverty and reduced infrastructure. The presence of informal housing is therefore great, and most houses are insufficiently designed to withstand earthquakes which is a common phenomenon in South America. About 3.8 million households in Colombia do not have adequate housing, most of which are located in slums and about 5% of the population are homeless.

According to the Global Alliance of Buildings and Construction, the construction sector accounted for 36% of global energy use and nearly 40% of energy-related carbon dioxide emissions in 2017, thus the largest share of energy use and emissions, even though building-related transport to construction sites was ignored. Due to the large energy use, substitutes need to be developed to reduce the climate impact and increase the re-use of already manufactured products that have been created from raw materials.

Different kinds of plastic have different life cycles that lead to difficulties when they are collected. This leads to an uneven proportion between the production and the collection of waste. Plastic waste is a serious problem worldwide, it creates landfills and ends up in the natural environment. The sea is a notorious destination for the accumulation of plastic debris. The Pacific Ocean even has a great spot of it, which has a negative impact on hundreds of species of marine life. The properties of the plastic can be taken advantage of to create something sustainable that generates housing for vulnerable people with limited resources and who also contributes to a more sustainable constructive system since plastic waste is removed from the environment.

Keywords: adequate housing, indoor climate, plastic waste, seismic behaviour, material properties, developing countries, Colombia

Sammanfattning

Denna studie kartlägger möjligheterna för hur återvunnen plast kan användas som ett alternativt byggnadsmaterial för låginkomst-bostäder i Colombia. De ingående byggnadsmaterialen har jämförts gällande dess byggnadsfysikaliska egenskaper, kostnad samt hur de påverkar det termiska inomhusklimatet i respektive byggnad.

Colombia är ett land som utsatts för inbördeskrig i många år vilket har bidragit till en urbanisering, ökad fattigdom och försämrad infrastruktur. Förekomsten av informella bostäder är därför stor och de är ej konstruerade för att tåla jordbävningar som är ett vanligt fenomen i Sydamerika. Omkring 3,8 miljoner hushåll i Colombia, varav de flesta är belägna i slumområden, har inte funktionsdugliga bostäder och ungefär 5% av befolkningen är hemlösa.

Enligt Global Alliance of Buildings and Construction var byggsektorn ansvarig för 36% av den globala energianvändningen och nästan 40% av de energirelaterade koldioxidutsläppen 2017, således de största andelarna energianvändning och utsläpp, även om man bortser från byggrelaterade transporter till byggarbetsplatsen. På grund av den stora energianvändningen behöver substitut tas fram för att minska klimatpåverkan samt öka återanvändningen av redan tillverkade produkter som skapats av råmaterial.

Olika sorters plast har olika livscykler som leder till svårigheter när de samlas in. Detta leder till ett ojämnt förhållande mellan produktion och insamling av avfall. Plastavfall är ett allvarligt problem i hela världen, det skapar deponier och skräpar ner miljön. Havet är en ökänd destination för ackumulering av plastskräp. Stilla havet har till och med en stor fläck av den, vilket medför en negativ inverkan av hundratals arter av marint liv. Plastens egenskaper kan tas till nytta för att skapa något hållbart som genererar bostäder till utsatta människor med begränsade resurser och som även bidrar till ett mer hållbart konstruktivt system eftersom plastavfall avlägsnas från miljön.

Nyckelord: lämpligt boende, inomhusklimat, plastavfall, seismiskt beteende, materialegenskaper, utvecklingsländer, Colombia

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We are so grateful for the welcome that we've received when arriving to Bogotá and the Escuela Colombiana de Ingeniería Julio Garavito. We especially appreciate the help we've gotten from Nancy Torres and German Santos Ricardo Granados. During our field study we have been guided with the help of Erik Johansson, who has been providing us with great ideas and advices to create the best thesis. We have received support from Juan Andres Eslava, who has helped us getting in contact with companies during our stay. Without his help, this thesis would not be executed, and we are so thankful for his achievements. It was a hard time arriving to Colombia and adjusting to the difference in culture and language as we don't speak Spanish. This was solved quickly when receiving help from Yesica Rodríguez Blásquez, who showed us an enormous amount of hospitality and helped us adapt as a citizen.

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List of abbreviations

CAGR	Compound annual growth rate
CCAC	Climate & Clean Air Coalition
CERS	El Centro de Estudios en Riesgos y Seguros/the Center for Studies in Risks and Safety
COP	Colombian Peso
FARC	the Revolutionary Armed Forces of Colombia
FICIDET	the Foundation for Scientific Research and Technological Development
HDM	Housing Development & Management
HDPE	High Density Polyethylene
HDPP	High Density Polypropylene
HVAC	Heating, ventilation, and air conditioning System
MC	Confined Masonry
MNR	Non-Reinforced Masonry
NAFTA	the North American Free Trade Agreement
RC	Reinforced concrete
SIDA	Swedish International Development Cooperation Agency
USD	United States Dollar
WHO	the World Health Organization

List of concepts

Conceptos Plasticos	Colombian company that manufacture plastic bricks
Build Change	Build Change designs disaster-resistant houses and schools in emerging nations and trains builders, homeowners, engineers, and government officials to build them.
Monolithic Construction	A construction that works as one single, solid unit.
Prism	Prism is an assemblage of single units that is constructed to serve as a test specimen for determining properties of units working together.

1 Introduction

1.1 Background

An eager to make a positive impact on the planet emerged into finding an area of use for all the plastic waste not taken care of properly. We quickly narrowed it down to the locations of the planet where people are affected the most, that is developing countries without proper waste management. A correlation between the lack of proper waste management and poverty as well as housing shortage gave birth to the idea of recycled plastic as an alternative building material. Together with HDM (Housing Development and Management) and Escuela Colombiana de Ingeniería Julio Garavito we got in contact with a concept in Colombia where plastic waste is moulded into bricks and stapled on top of each other like LEGO. Colombia is known for its brick architecture. However, the country has a widespread problem with poorly built masonry-houses for low in-come families. The thesis was to be conducted by comparison between houses built with plastic bricks and masonry-houses. We have decided to compare the two building materials regarding crucial factors such as structural strength, thermal conductivity, heat capacity, thermal expansion, construction cost and indoor climate.

1.2 Problems

Our planet is drowning in plastic pollution and the capacity to handle plastic waste is already overwhelmed. Only 9% of the nine billion tonnes of plastic the world has ever produced has been recycled. Most ends up in landfills, dumps or in the environment (UNEP 2018). This contamination causes alterations in the soil by not degrading and becomes a dangerous nourishment for wildlife to consume. In addition, 99 % of all plastics are produced from fossil fuels, which are limited and non-renewable (Sierra Jiménez 2016).

Another problem that the world faces is the widespread existence of substandard housing for vulnerable communities and the inequality gap in developing countries. Since 1985, 6,4 million Colombians have been forced to leave their homes due to the armed conflict between the guerrilla group FARC and the state of Colombia. The majority of these refugees are still living in Colombia and about 80 % of them in poverty (Sida, 2017).

Increased recycling and education in construction will empower vulnerable communities so that they can assemble their own houses in order to become pollution free and safe. This will help mitigating global warming and help decrease the extreme poverty gap. The method of self-help housing has a high social, environmental and economic impact and is endorsed by UN's Sustainable Development Goals, especially the 11th goal, Sustainable Cities and Communities (UNDP, n.d.).

According to the Global Alliance of Buildings and Construction, the construction industry accounted for 36% of global final energy use and nearly 40% of energy-related carbon dioxide emissions in 2017. Accordingly has the largest shares of energy and emissions, even when excluding construction-related energy use for transportation of building materials to construction sites. This contribute to pollution and waste generation, affecting ecosystems and feeds the Climate Change (Global Alliance for Buildings and Construction, 2018).

Therefore, it is necessary to seek and implement solutions aimed at sustainable development, to reduce the use of non-renewable resources in the construction and plastics industries.

1.3 Objectives and aims of the study

Through analyses of indoor climate, cost and material properties of the different building materials, the study aims to enlighten the recycling of plastic waste and the feasible areas of use as an alternative building material for low-income housing. The expected result will be used to increase the awareness of plastic waste and hopefully serve as a basis for further investigations to allay adequate households.

1.4 Method

Through this study a feasible construction material for use in housing has been examined. The material is made of recycled plastics (HDPE), for instance from plastic bottles, jugs, plastic lids and textiles. A comparison has been made between a house constructed by recycled plastics and a house constructed of masonry, which is the most common building technique in Colombia.

The indoor climate has been analysed through measurements of the air temperature and humidity over a period by using small devices called Tiny Tags. For approximately one week, data has been collected of the two different dwellings that's located in similar climates. It has led to valuable information of how the indoor climate varies, which is an indicator to understand the sustainability of this material. By using a chart from ANSI/ASHRAE Standard 55-2010, the data has been furthered analysed to determine if it fulfils the recommended thermal comfort.

An analysis of the different building material's strength is made, to apprise that this material, made of recycled plastics could be used as an alternative building material for low-income housing. Further laboratories were made to understand the material´s expansion coefficient, thermal conductivity and heat capacity.

A cost analysis is established by comparing a house built with masonry and plastics, by using information gathered Conceptos Plasticos and Build Change. The comparison will be based on two houses with the same size.

1.5 Limitations

The analysis of the different building material's properties will not be deeply investigated, and the materials will be tested in dry phase. Further, it will not be possible to measure air movements due to the limitations of our data logger device, which can only measure air temperature and humidity. Therefore, the measurements will not be fully trustworthy due to the human's living factors, cavities of the construction and the limited time of the measurements. Further, the measurements will be conducted in selected geographical areas due to the limited amount of the plastic houses. The measurements will therefore be limited to the areas with similar climate.

Because of vastly amount of different buildings techniques of masonry the study will be restricted to the most similar masonry construction, confined masonry, in relation to the plastic house of the field study. The study is limited to low-income families because of its simple design. The comparison of the constructions will target axial compression of bricks, prisms made of bricks and full-scale walls with columns and bricks. All masonry construction studied in the thesis is made by “Bloque No 5” which is the most commonly used hollow clay brick used in Colombia.

The cost analysis will be approximate since it depends on several factors that we cannot control, such as delayed construction time due to poor weather conditions, shifting transportation costs due to the location of manufacturing, inflation and demand. Therefore, study will delimit the above-mentioned factors and the cost of roofing, foundation, doors and windows since it is equal for both types of houses.

1.6 Expected results

The study will be conducted to examine recycled plastics as a material for the building industry and how it can promote sustainability and accessibility for low-income housing, thus increase the awareness of plastic waste and improve ecosystems.

The thesis will hopefully contribute to further knowledge of the materials properties and how it affects the indoor climate, which will generate prerequisites for the manufacturer to improve the product of the study.

The expectation is that this survey can be useful in future studies, when investigating the abolishment of homelessness in a sustainable way, in various developing countries.

2 Facts about Colombia

2.1 Geography and population

Colombia is the only country in South America that has coastline to both the Pacific and the Caribbean. The Andes is in Colombia and are divided into three mountain ranges. Two of them continue parallel north towards the Caribbean Sea, while the third runs north-east. Between the mountain ranges, the rivers Magdalena and Cauca flow through green valley’s where most of the population lives. On one of the highlands in the eastern mountain range lies the capital Bogotá. The land lies on the border between two continental plates, which means that earthquakes and volcanic eruptions often occur. Nearly half of Colombia is covered by forests, and deforestation causes many problems. Many species have become endangered and soil erosion affects many parts of the country. Due to the overuse of pesticides the soil and water quality is poor.

Most people live in the northern and western parts of Colombia, where agricultural opportunities and natural resources are found. Approximately 60% of the country, in the south and east consists of vast grasslands which are sparsely populated.

In 2018, Colombia had a population of 48,168,996 and large parts of the population live in the big cities; Bogotá 10,574 million, Medellin 3,934 million, Cali 2,726 million, Barranquilla 2,218 million, Bucaramanga 1,295 million, 1,047 million Cartagena. Recently almost 585 thousand refugees from Venezuela has come to Colombia because of an economic and political crisis (The World Factbook, 2019).

Figure 1: Map of Colombia containing the biggest cities (Rainbow Tours, n.d.)

2.2 History

In 1499, Spanish conquerors arrived in Colombia and later established the country’s first city, Santa Marta, in 1525. Spain took a great interest in Colombia because of the large quantity of gold. This led to the development of Cartagena, that became one of the most important ports in the Spanish Empire. Colombia consisted of different ethnic groups such as indigenous, Spaniards and African descendants which gradually created political tensions in the society. The resistance against the Spanish people was great and with the help of the freedom hero Simón Bolívar, the country became independent in 1819. Conflicts remained between liberals and conservatives, which was resolved in 1953 by a military coup. After some years of military leadership, the parties began to cooperate in 1957 and shared power for 20 years. The conservative left side was excluded from this political cooperation, which led to the emergence of guerrilla movements. A decades-long conflict between guerrilla movements, the army, paramilitary and narcotic cartels have characterized the country's modern history. Finally, after a four-year long negotiation, the Colombian Government signed a final peace accord with the FARC in November 2016. The accord calls for members of the FARC to demobilize, disarm, and reincorporate into society and politics (Globalis, 2017).

2.3 Trade

Colombia has had a positive economic development - especially since the violence began to decline. The economic growth increased rapidly during the 1990s with liberalization of the economy. Subsequently the government strove to increase the security in the cities, which led foreign investors to establish in Colombia. Until the global financial crisis in 2008, the country has managed well due to a solid accelerating growth. Colombia heavily depends on energy and mining exports which makes the country vulnerable to fluctuations of the commodity prices. Colombia is the fourth largest oil and coal producer in Latin America and the third largest coffee exporter. The country's development has been obstructed due to inadequate infrastructure, narcotrafficking, poverty and an unsafe security situation. The falling world market prices for oil dropped in 2017 which affected the country's economy and aggravated due to insurgent attacks on the domestic pipeline infrastructure. Foreign investors, especially in the oil and mining industry, has been put back regards to their ambition of expansion due to local referendums.

The GDP growth has been an averaged 4.7% during the past decade but fell to an estimated 1.8% in 2017. In tandem with Chile, Mexico and Peru, Colombia founded a regional trade block in 2012 called Pacific Alliance, to promote regional trade and economic integration. In 2017, Colombia took action and addressed several bilateral trade irritants with the US, such as truck scrappage, distilled spirits, pharmaceuticals, ethanol imports, and labour rights. The objective is to accede to the Organization for Economic Cooperation and Development.

Colombia is also known for its production of illegal products such as cocaine, opium poppy and cannabis. In 2016 there were 188,000 hectares of coca cultivation, which makes it the world's leading coca cultivator. This makes Colombia the world's largest producer of pure cocaine, an estimated production of 710 tonnes. The government makes efforts to counteract the cultivation though eradication. However, the aerial eradication was suspended in 2015 which means that only manual eradication can be performed, reports says that 17,642 hectares was removed in 2016. Colombia is also the second largest supplier of heroin to the US market, able to produce approximately three tonnes of pure heroin (The World Factbook, 2019).

2.4 Climate

The climate is tropical, and the temperature is even throughout the year. However, the height differences create great contrasts. The country accommodates most of the continent's biotopes due to its dramatic topography. It can be divided into three climate zones: In Tierra Caliente (<1000 meters above sea level) the average temperature is 25-30 °C and the humidity high. In Tierra Templada (1000-2000 meters) it is an average of 18-25 °C. The Tierra Fria (2000-3000 meters) is a cold area where the temperature is 12-18 °C, with large variations between day and night. Bogotá is the fourth highest capital in the world with an altitude of 2,625 meters, which means that the temperature has a large amplitude. In the highlands of Bogotá, there are two rainy reasons, during October-November and in April-May. When above an altitude of 4500 meters the terrain called Páramo becomes plain and consists of snow. However, the glaciers are starting to melt due to climate change. The northwest coastline by the Pacific Ocean is dominated by tropical rainforest and is one of the rainiest areas in the world. On the gazing Caribbean coast, the landscape is plain, like the major parts of the country (Landguiden, 2018).

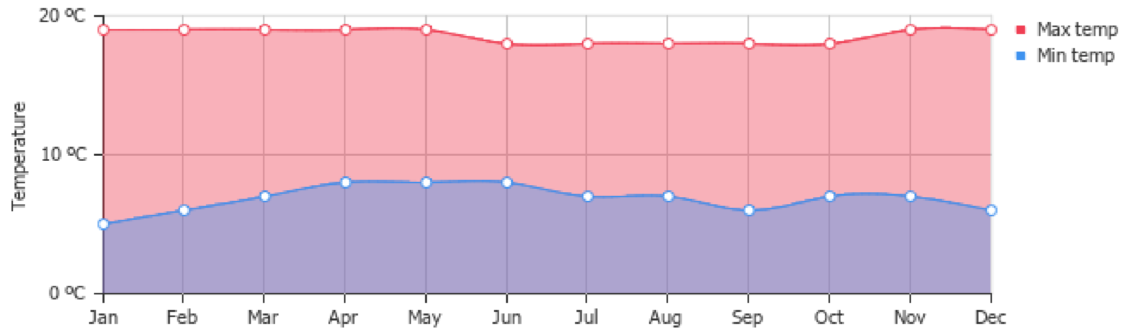


Figure 2: Average min and max temperatures in Bogotá, Colombia. (Weather & Climate, 2019)

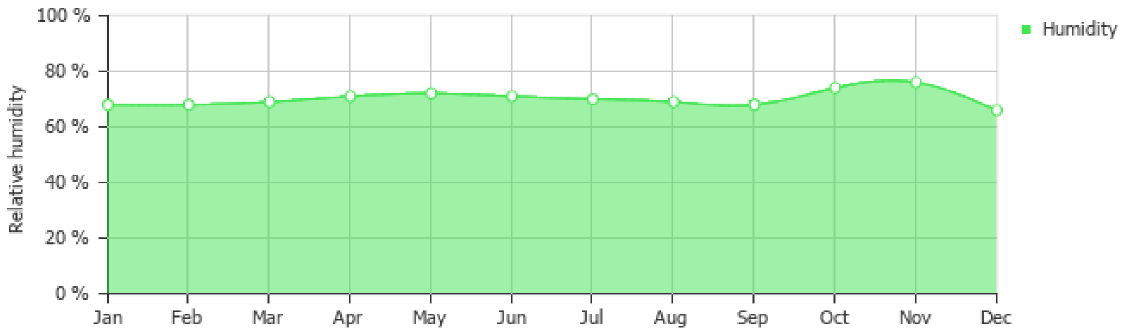


Figure 3: Average relative humidity in Bogotá, Colombia (Weather & Climate, 2019)

2.5 Seismic activity

Earthquakes are one the most lethal natural disaster around the world.
In South America, the pacific coast is highly vulnerable due to its location, along two tectonic plates. Earthquakes have occurred commonly in the past decades and destroyed thousands of homes, most of them informal dwellings. The urbanization is an ongoing event, increasing informal housing which are susceptible to collapse during a seismic activity. Bogotá is in an area of medium seismic risk according to the
Colombian Regulation of Construction & Earthquake Resistance (Reglamento Colombiano de Construccion Sismo Resistente) (NSR-10, 2010).

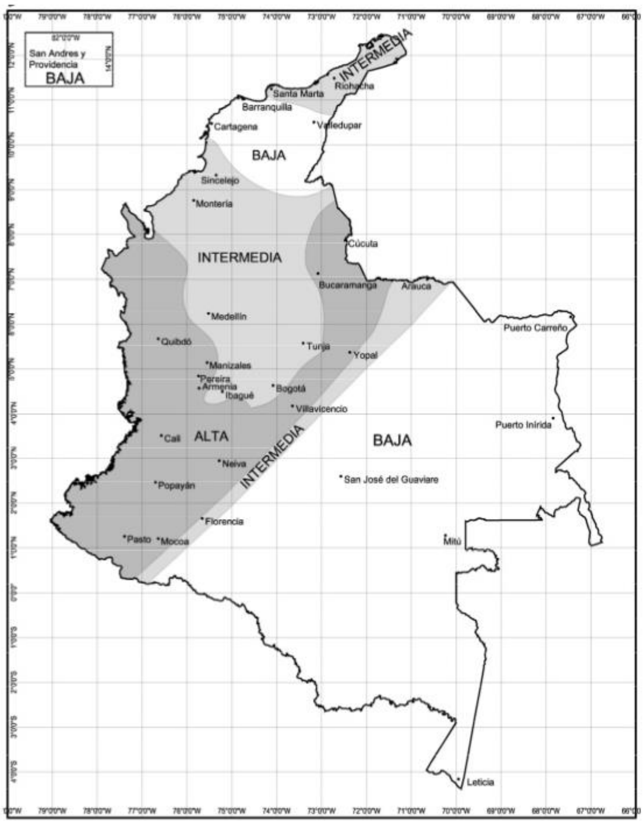


Figure 4: Zones of seismic risk in Colombia (NSR-10, 2010). Baja: low, Alta: high, Intermedia: intermediate.

Bogotá accommodates millions of people and a large percentage of these are low-income groups who lives in small masonry houses, which has inadequate resistance against earthquakes (Witte 2018).

2.6 Poverty and inequality

Since 1985 6,4 million Colombians have been forced to leave their homes due to the armed conflict between the guerrilla group FARC and the state of Colombia. The majority of these refugees are still living in Colombia and about 80 % of them in poverty (Colombia Reports Data, 2019). Colombia is the world’s seventh most inequitable country and the second most unequal country in Latin America. According to the Word Bank, Colombia’s top 10% earners received 40% of the wealth that was generated in 2017, despite an abatement over the past decade (Alvaredo et al. 2018). About 1/3 of the population in Colombia lives below the country’s poverty rate. A person is considered poor in Colombia if he or she earns less than $90 a month. The birth rate has fallen since the 1960s from 6 children per woman to just above replacement level today. This is a result of the increased literacy, family planning services, and urbanization. The national poverty has diminished throughout the years and was measured to 29.9%. The prime areas where the poverty has been reduced is in the countryside apart from the big cities that are struggling to maintain their efforts to improve living conditions for the poor. Bogotá has struggled lowering unemployment rates, and with no real social welfare system in place, urban dwellers who lose their jobs are easily condemned to poverty (Alsema 2018).

About 3.8 million households in Colombia do not have adequate homes and these houses are often located in slum areas. There is a large percentage, about 5% of the population that is homeless. (Habitat for Humanity, n.d.).
Three-fourths of all dwellings were made of bricks, adobe, mud or stone; nearly 15% had external wall of wattle or daub; 7% were wood; and 3% were mostly cane (Nations Encyclopedia, n.d.).
The designation of countryside is so called slums, where the houses are in poor shape and a potential hazard for people inside of them due to their weak construction. The factors creating these problems are expensive construction materials and lack of resources and knowledge.

Another issue in Colombia is the highly fluctuating weather conditions such as heavy rainfall, temperature differences, earthquakes and floods (AccuWeather, n.d.). These circumstances should be considered when building a house in Colombia. Unfortunately, this is not possible in the slums due to the factors mentioned above.

3 Building techniques

3.1 Introduction

In this chapter, a contemplation of a few different building techniques in Colombia regardless social stratum will be shown to provide a widespread introduction of how housings are built in Colombia. The following building techniques will not be further investigated. This survey will only focus on clay and plastic bricks.

3.2 Guadua

The native bamboo specie Guadua has been commonly used in South America to build structurally sound housing for thousands of years. In recent years, various non-profit bamboo experts have worked with national government in Colombia, Peru and Ecuador to allow bamboo building, becoming the first countries in South America to do so (2001, 2012 and 2017)

The structure of a bamboo house is made of columns, which are tied together to create a rigid frame. Smaller bamboo that is not fully grown or straight are split and used to support lighter elements as purlins or screens. The walls are fitted with horizontal non-uniform columns, which are flattened into bamboo strips and attached with bamboo studs to form a “cage”. The floors and ceilings are fabricated in a similar way. A mixture of clay and hay can be stuffed in the walls cavities and is left to dry for approximately one month and then coated with two layers of fine clay, sand and cement to create a solid unit. After the 1999 earthquake in the departments of Quindío y Risaralda, assessment found that 90% of the casualties occurred in non-bamboo homes (Witte 2018).

Figure 5: House made of Guadua (Bamboo Import, n.d.)

3.3 Bahareque

Bahareque is a similar building technique to the previously mentioned. It has been used in rural areas in Colombia for hundreds of years to make inexpensive and surprisingly durable houses. The structure's material varies regarding what is the most easily available locally. Traditionally the construction consists of an elevated timber and/or bamboo frame on top of stones or bricks, coated with a mixture of small wooden pieces. The wall is then plastered with manure or soil, occasionally with straw added to increase strength (López et al. 2004). Bahareque is not just for low-income families, it can also be constructed for different degrees of formality, from rural informal single storey housing to urban two storey formal housing (Kaminski et al. 2016).

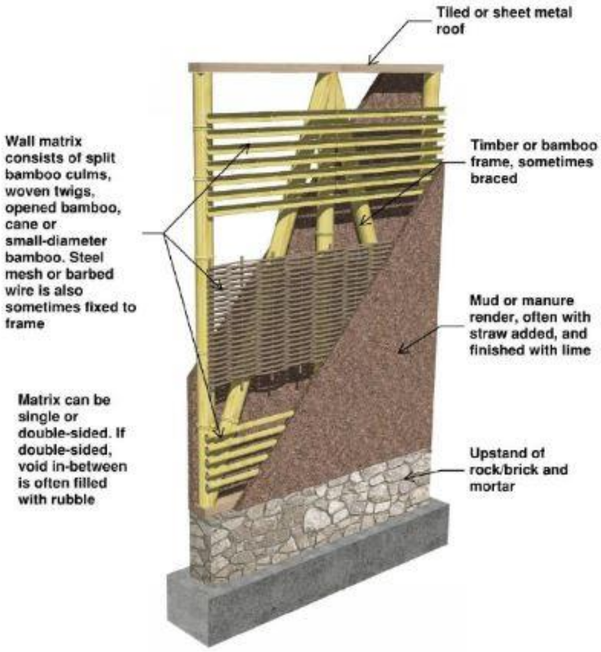


Figure 6: Construction of Bahareque (Kaminski et al. 2016)

3.4 Tapia pisada

Tapia pisada, is a technique for building walls by stomping raw materials, such as earth, lime and gravel in between two stands to great a solid unit. Rammed-earth walls are simple to construct, non-combustible, thermally massive, strong, and durable. This technique was observed and is common in Bogotá and in the surrounding towns (Macondo, n.d.).

Figure 7: Construction of a wall of Tapia pisada (Flickr, 2011)

Figure 8: Finished wall of Tapia Pisada (Flickr, 2011)

3.5 Adobe

Adobe is the oldest and most widely used building material around the world and has been used since 8000 B.C. Adobe is a brick-like composition of soil, water, and organic materials such as straw, wheat husk or cow manure, which

Figure 9: Adobe house in Nicaragua (Construir es Nicaragua, 2016)

is dried in the sun to harden. The blocks are usually joined together with mud mortar. The designs can vary depending on the climate, in the coastal areas the walls are thinner than in the cold highlands. Adobe buildings has inadequate resistance against earthquakes due to its weight, low strength and brittle behaviour. This building technique is used by approximately 50% of the population in developing countries, mainly among the rural population and roughly 20% of the urban and suburban population (Houben et al. 1994. see Blondet et al. 2011).

Figure 10: Adobe bricks drying in the sun (Diefenbach, 2010)

3.6 Masonry

The main structural construction materials are reinforced concrete and masonry. Masonry is common in seismic regions of Latin America, and in Colombia it has been used since 1930's. It is the most used system and it is applied to single story dwelling houses and apartment buildings up to five stories when using only masonry (Wasti et al. 2003).
Masonry is the composition of two elements: bricks and mortar. These two components are consolidated with the aim to make a construction as close to a monolithic construction as possible. It is also common that reinforcement, e.g. steel is used to strengthen the construction further.
Explain that your study will focus on clay brick, since is the most
Clay bricks are produced by mixing clay with water until the optimum humidity is obtained, then formed into the desired shape. In Colombia the use of hollow bricks is common, which can be formed by pressing the mix of clay and water through a nozzle with the wanted shape and then cut when the proper height is achieved. The bricks are then dried before burnt in an oven, and later cooled (López et al. 2013)
According to Build Change, the most commonly used hollow bricks in Colombia is "Bloque No 4" and "Bloque No 5" which have the same outer

dimensions, 30x20x12, but differs in thickness and therefore doesn't have as large cavities. No 5 is a bit more expensive due to a bigger volume, but it is still used in larger extent than No 4 due to its superior strength (Cano 2019).

Figure 11: Hollow brick, "Bloque No. 5" with outer dimensions (Ingeniero SRM n.d.).

Masonry in low-cost housing can be divided into two main groups, non-engineered masonry and engineered masonry, where the latter can be further divided into the two most popular groups; reinforced masonry and confined masonry.

3.6.1 Confined Masonry

Confined masonry consists of an unreinforced masonry wall confined with a reinforced horizontal and vertical concrete frame. It is similar to RC-frame construction with the difference that in confined masonry, the concrete frame is casted after the masonry wall has been completed. This provides an interconnection between the masonry and the concrete frame. A casted concrete frame when building confined masonry, provides better integrity of the frame and brickwork. Vertical loads are transmitted to the brickwork, improving shear strength of the wall. The brickwork can easily be constructed with zipper-like vertical edges, which naturally results in a stronger bonding of the masonry units and improves the connection between column and brickwork.

However, when building houses in low-income areas this building technique is often performed in the wrong way. The vital methods and criteria are not being used in the right way which results in a poorly strengthened house. The most common problem is when casting the columns, the bonding between the columns of each story and floor is not sufficiently tied together. Another issue is that the gables against the roof are not reinforced, which leads to a heavy and unstable object that can easily fall in and hurt the residents. The gable should therefore be confined with the columns as one unit and be attached to the roof construction. The reinforcement that is used can often come from demolition sites which can have deficiencies. The combination of too few rebars and some deficiencies will impair the structure.

An important part of a masonry construction is the mortar, which combines all the layers of bricks/stones and creates a solid unit. The strength of the mortar depends on the ratio of cement, lime, sand, and the amount of water, which is generally added "by eye" by the mason to achieve a good consistency. If the ratio is wrong, the quality of the mortar will decrease (Pauly et al. 1992, s. 106).

3.6.2 Reinforced masonry

Reinforced masonry was introduced in the 1970's and consists of hollow bricks with vertical and horizontal reinforcements, where its cavities are filled with mortar. This method is used for one-story houses and for medium-rise buildings (Wasti et al. 2003).

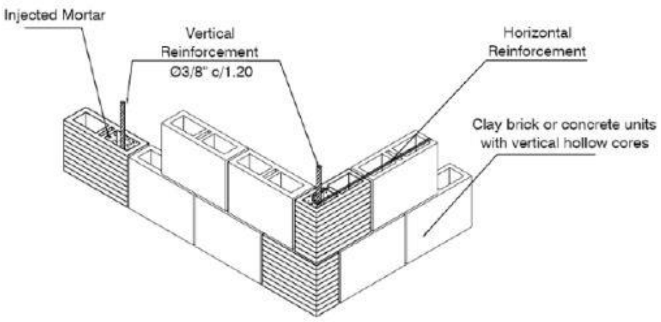


Figure 12: Details of the assembled reinforced masonry wall, (Hackmayer et al. 2013)

Figure 13: Inadequate confined masonry with poor connections (Acevedo et al. 2016)

Figure 14: RC-frame (Farsi et al. n.d.)

3.6.3 Building issues within masonry

Non-engineered masonry is common for low-income dwellings where the builder is also the homeowner, and these buildings are often unreinforced. In the building code of 1984 (MOPT, 1984), non-reinforced masonry without the use of concrete and rebar was forbidden. But there still exists a large amount of these buildings left due to poverty and lack of knowledge.
Non-reinforced masonry engenders low resistance, ductility and becomes very vulnerable to seismic events. This has been demonstrated in previous earthquakes, where buildings have collapsed because of the inadequate structural capacity (Vega Vargas 2015).

According to technical reports produced by CERS of the Universidad De Los Andes, approximately 65% of the population live in buildings vulnerable to earthquakes (CERS, 2005).

Figure 15: Non-reinforced masonry in Usme, Bogotá (Photo by authors)

3.6.4 Retrofitting

The housings in Colombia that has inadequate resistance against seismic forces can be improved by using different methods depending on how bad the construction is. The houses need improvement in some way to resist earthquakes and retrofitting is one way of doing this. This means that the houses are provided with load bearing elements such as columns and reinforced walls. The walls become reinforced by adding mesh and plaster to the surface, this makes the walls more rigid. This section is not focused on in the thesis but can be studied in the Appendix.

Figure 16: Casting of column, masonry of additional inner wall, metal mesh with plaster. (Build Change, 2018)

3.7 Roofs, windows and doors

3.7.1 General

In Bogotá, the houses are placed densely because of the large number of inhabitants and there are all kinds of different housings such as terraced, high-rise and separate. Bogotá is divided into different areas and has big gaps between the social classes. This leads to a big variety in the execution of housing. Throughout the year, the climate is very alike with minor changes, and therefore the houses do not require any insulation.

3.7.2 Roofing

Through excursions around Colombia, it is observed that the roofing can be made of various materials such as corrugated metal sheets (of galvanized steel or aluminium), clay tiles, corrugated plastic sheets, and asbestos-cement sheets. The execution is in general very basic for low-income housings, with overlapping sheets and without gutters. The supporting structure varies between different kinds of trusses and beams. The quality of the roofing is usually a lot better in higher social classes.

3.7.3 Doors and windows

Other fittings such as doors and windows are often basic and thin since there is no need for insulation. The only function is to keep away wind, rain, burglars, and to ensure an easy way of ventilating the resident. As mentioned, the windows are basic and thin with one glass, thus no double or triple glazing. The frame is made of an aluminium or a wooden frame with basic hasps to close the windows. The design of the doors varies depending on its purpose and the area of the house. It can be made of wood or steel, and often heavily secured with multiple locks, sprints or grids.

Figure 17: Masonry house with commonly used windows, door and roof (Photo by authors)

4 Plastics

4.1 The origin

Humankind has since the dawn of history endeavoured to develop materials that offers benefits not found in natural materials. It all started with the use of natural materials such as shellac and chewing gum that had intrinsic plastic properties (Plastics Europe, n.d.).
This development encouraged chemists and industries around the world to look for different molecules that could create polymers. In the 1930s, English chemists discovered low-density polyethylene during studies of extremely high pressures on the polymerization of polyethylene. This material was further developed into different classifications, which depends on the proximity of the molecular chains. The classifications are divided into low, medium and high density (Britannica, 2019).

Plastics are a wide family of different materials that can be divided into two categories: thermoplastics and thermosets. Thermoplastics is a group of plastics that can be melted and hardened when cooled. These properties make the material reversible which means it could be reheated, reshaped and frozen repeatedly (Plastics Europe, n.d.). Thermosets does not have these characteristics and cannot be re-melted and reformed because of how the chemical structure changes when heated (Modor Plastics, n.d.).

4.2 Economics and manufacturing

Plastics are being produced to improve the quality of life and has millions of applications in everyday life because of its versatility. China is the largest producer of plastics, followed by Europe and NAFTA. A global production of 348[1] million tonnes a year (Plastics Europe, 2018), the same weight as 696 pieces of the world's tallest skyscraper, Burj Khalifa (The World Federation of Great Towers, n.d.). The global plastics market size is expected to reach 721.14 billion by 2025, at a CAGR of 4% (Grand View Research, 2019).

According to Euromonitor International (2015) Colombia’s packaging market has reached the 43.4 billion units sold. During 2019 this market surpasses the 45 billion units sold. In the last 5 years Colombia’s packaging market have grown by 1,3% CAGR which contributes to the national economy (Euromonitor International 2015. see PROCOLOMBIA 2016).

Today plastics can be fossil-based or bio-based and in both cases they can also be biodegradable. Plastics has a wide variation of lifespan depending on which kind of plastic that is used. Some plastic products such as packaging plastic have a shelf life of less than one year before getting tossed in the trash, other plastics can have a lifespan of 15 to 50 years or even more.

4.3 Waste and management

The different life cycles lead to difficulties when being collected. This results in an inequitable proportion between production and the collection of waste. Plastic waste is a severe problem throughout the world, it creates landfills and ends up in the natural environment. An extreme sign of this is the ocean, which is a notorious destination for accumulation of plastic garbage. The Pacific Ocean even has a large stain of plastic waste, which causes a negative impact of hundreds of species of marine life.

[1] Not including PET-, PA and polyacryl-fibers

Figure 18: Plastic "island" in the Pacific Ocean (Galey et al. 2018)

Colombia produces approximately 32.000 tonnes of solid waste per day. The major cities like Bogotá, Medellin, Cali and Barranquilla is responsible of one third of the total amount (Rijswaterstaat, n.d.). According to Acoplásticos (n.d.), Colombians generates 28 kilos of plastic per capita a year, of which 56% corresponds to single-use plastics (versus 35 kg in Brazil, 43 kg in Mexico, 45 kg in Argentina, 50 kg in Chile and 150 kg in the US).

The remaining percentage is allocated as follows: 20% for construction, 9% for agriculture, 7% for household products and the remainder includes toys, auto parts, sports equipment, and others (Global Business Reports, 2018). Due to the replacement of different traditional materials plastic use has intensified without proper recycling, becoming a generation of unstoppable waste.

Unlike in European countries, Colombian people have little awareness about recycling and the previous legislation have not encouraged this practice. However, the Colombian government aims to professionalise its solid waste management, which is commonly referred to as “Basura Cero” (Zero waste) approach which includes multiple challenges. The objective of these legislations is to establish a greater recycling culture and awareness of responsible consumption. It could for instance be to encourage consumers to use reusable bags, as Italy in 2011 and France in 2016. Italy banned all bags except biodegradable and France banned single-use bags (Mudgal et al. 2011, Science Alert 2016). To address this challenge in Colombia, the government has been promoting eco-friendly options as substitutes to single-use plastic. As of 1 January 2017, the government took part of the banishment and forbid single-use plastic bags smaller that 30x30 cm. In July 2017, this legislation extended one step further and introduced a tax on single-use plastic bags (UNEP, 2017).

In recent years, various voluntary non-governmental organizations such as CCAC, have addressed this challenge by monitoring and reducing the consumption of plastics and striving for a world free of plastic pollution, thus it's hard to eliminate the use of plastics since surrogates are often more expensive and plastic products contributes to our quality of life.

In Europe, it seems that a brighter future lies ahead of us since people are starting to take responsibility. In ten years, plastic waste recycling has increased by almost 80% and plastic packaging recycling has increased by almost 75%. From 2006 to 2016 the volumes of plastic waste collected for recycling increased by 79%, energy recovery increased by 61% and landfill decreased by 43% (Plastics Europe, 2018).

Among plastic waste there are useable products that can be used in the production of new products, such as HDPE which will be further explained in the following chapter.

4.4 Examples of recycled plastics as a building material

4.4.1 Recycled HDPE and its area of use

In this survey the feasible usage of recycled HDPE (High density-polyethylene) plastic in the manufacture of structural elements for low-income housings in Colombia is examined. This generates an accessibility to housing for vulnerable people with low resources and a step in the right direction to a more sustainable constructive system due to removal of plastic waste in the environment.

The endeavour to search for a partial or total substitute of traditional building materials such as reinforced concrete, metal and wood elements has been an ongoing progress since the past. The world leader in structural polymer composite solutions for industry-use is the company Axion who embraced this development and started producing products such as railway sleepers, stacks, railings and bridge girders using composite structural elements. In early 2009, Axion created the first bridges in the world that were made of recycled plastics capable of carrying a 71-ton tank were built at Fort Bragg, North Carolina, USA (Chandra et al. n.d.).

The use of plastic as a structural element such as Axion’s products was investigated by Salazar (2014). The solution was to implement social housing with beneficial environmental impact and low cost, approximately 28% cheaper than social welfare housing. This type of construction can be assembled in different ways and with people who lack the knowledge of how to build houses since it only requires the basis of different elements such as bricks and columns. The construction can also be dismantled, transferred and reassembled (Salazar et al. 2013).

The use of thermoplastic as a building material is considered to be a solution that mitigates pollution produced by the traditional building systems for housing in Colombia. The contributing factors that traditional building systems have in atmospheric and environmental contamination is due to mining in quarries, heating of brick kilns and expelling carbon dioxide in the manufacturing of cement (Svensk Betong n.d., Skinder et al. 2014, Naturskyddsföreningen 2017).

Therefore, this is a great substitute for structural elements which reduces costs when constructing, in order to contribute to less extraction of raw materials.

4.4.2 Brickarp & Conceptos Plasticos

Brickarp and Conceptos Plasticos in cooperation with FICIDET developed the brick called Brickarp together and with this product they entered and won Chivas Venture, an international innovation contest. They have now gone parted ways and Conceptos Plasticos have developed the bricks further, both in the composition of the plastics and the dimensions of the bricks. The thesis bases on previous data from both products.

The housing system Brickarp, is based on a construction material that creates no pollution or negative environmental impact since it’s made of recycled plastics and does not require more extraction of raw material. These bricks contain recycled thermoplastics (HDPE/HDPP) that have high melting point and excellent chemical resistance. In addition, it is lightweight, inexpensive, modular and can easily be joined, which means that it does not require skilled labour to be assembled. The house can also be disassembled since it’s not constructed with mortar or similar. The plastic waste is bought from different organisations that gathers the waste from households, which contributes to a social, economic and ecological sustainability.

The plastic houses are built for different social classes but to this date mostly for low-income families. Places where the houses have been built are: Bucaramanga (Colombia), Costa Rica, Guapi (Colombia), Chingaza National Park (Colombia). The concept has been caught by UNICEF’s interest and they have introduced it to the African market, where a few schools has been built in the Ivory Coast.


Figure 19: Plastic house of 56 square meters (Conceptos Plasticos n.d.)


Figure 20: Preparation before construction on a concrete slab (Conceptos Plasticos n.d.)

5 Thermal comfort

This chapter is an introduction of the term thermal comfort and will explain definitions, various factors that affects the indoor climate, the program Climate Consultant and the adaptive model, ASHRAE 55-2010, which will be used to analyse climate data collected from the field study.

The indoor climate is made up of several measurable physical, chemical and biological factors. The World Health Organisation (WHO) has defined the factors of indoor climate, thermal environment, atmospheric environment, acoustic environment, actinic environment (radiation and electrical/magnetic fields), and mechanical environment (University of Bergen, 2016). The indoor climate is important for health, well-being and productive work. A dwelling with poor indoor climate enhances the risk of health problems. It contributes to problems as headaches, abnormal fatigue and irritation of the skin and mucous membranes (eyes, upper respiratory) tract are more prevalent than normal. These symptoms may be caused by the mentioned factors and in combination with various types of stress and individual circumstances like allergies or other hypersensitivity issues, the problems may be exacerbated. However, the concept of indoor climate is broad and highly subjective, thus difficult to evaluate. It is also an individual estimation since humans prefer various climates, due to clothing, activity, age and gender. The thermal environment can be related to thermal comfort which is often defined as the range of climatic conditions within which the majority of persons would not feel thermal discomfort, either of heat or of cold. There are more parameters that effects the indoor experience, air movements, temperature of surrounding surfaces, humidity, floor temperature and the airs vertical temperature gradient, which is the temperature difference in height.

Operative temperature describes the impact of air temperature and main radiation between occupants and surrounding surfaces. The operative temperature can be calculated as a mean value of the previous factors mentioned (Warfvinge et al. 2016).

Housing can be equipped with heating and cooling systems in order to adjust the temperature as needed and to keep the temperature as uniform as possible. But it’s rarely a standard for low-income housing. The indoor climate is therefore manually adjusted by e.g. opening windows. Sunlight has a great impact on the indoor temperature, considering the ratio between wall surface and window area where the sunlight can pass through. A picture is added as an example of a general measure taken to take advantage of direct sunlight. Heat from the human body as well as activities such as cooking, lighting and appliances also have a large effect on the indoor climate. By taking advantage of the previous activities and solar gain, the house can provide better comfort. The Figure 21. is provided from Climate Consultant which is a climate analysis program that has various functions that displays climate data. Figure 21. shows the source of heat and suggest feasible measure to create a better indoor climate.

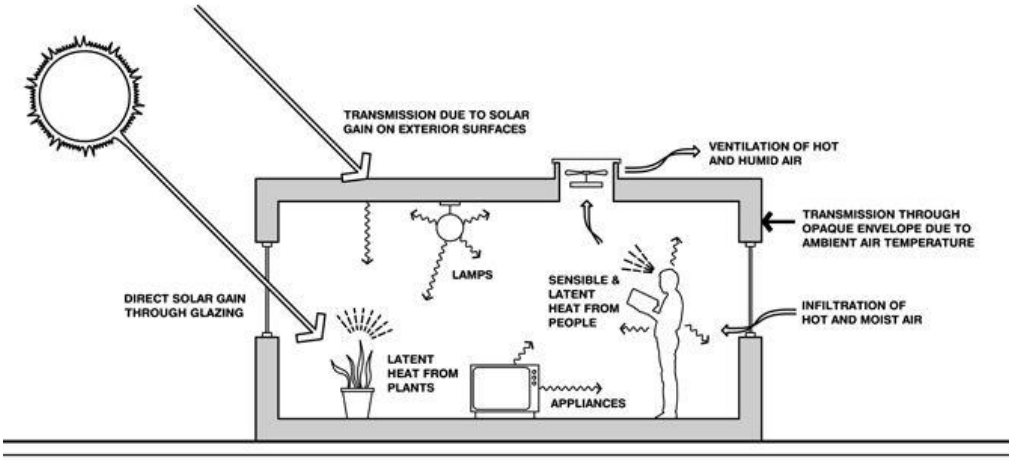


Figure 21: Example of factors that heats a house (Climate Consultant, 2019)

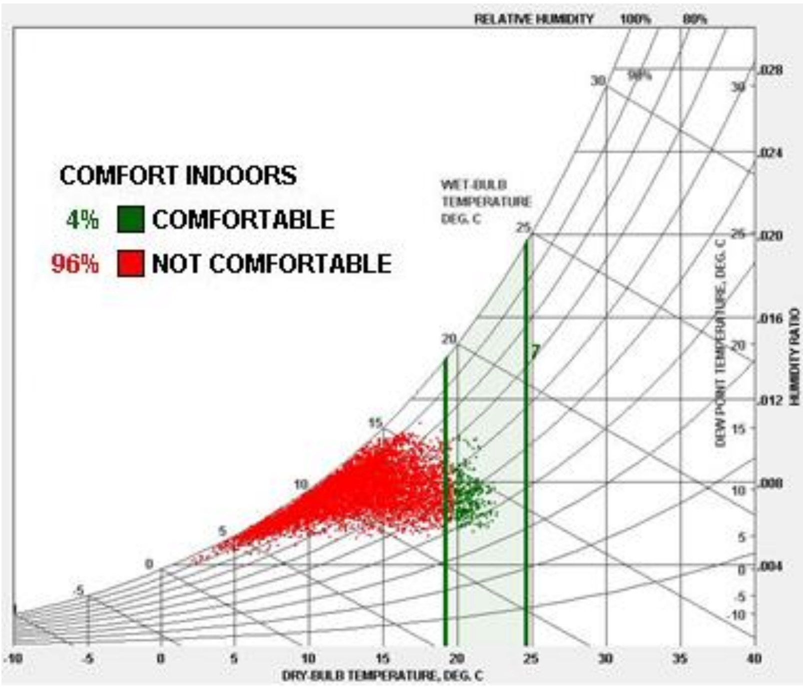


Figure 22: Comfortable indoor climate in Bogotá (Climate Consultant, 2019)

By using the program Climate Consultant (2018), with data from Bogotá, and choosing the Adaptive Comfort Model, it is observed that only 4% of the diurnal indoor climate is perceived to be comfortable during most of the day (Fig. 22). This result is established by the program Climate Consultant and provides a good picture of how the indoor climate is in Bogotá and can be used to strengthen the measurement results from the field study. However, this is a theoretical analysis as the temperature in the study is the same for the indoors and outdoors.

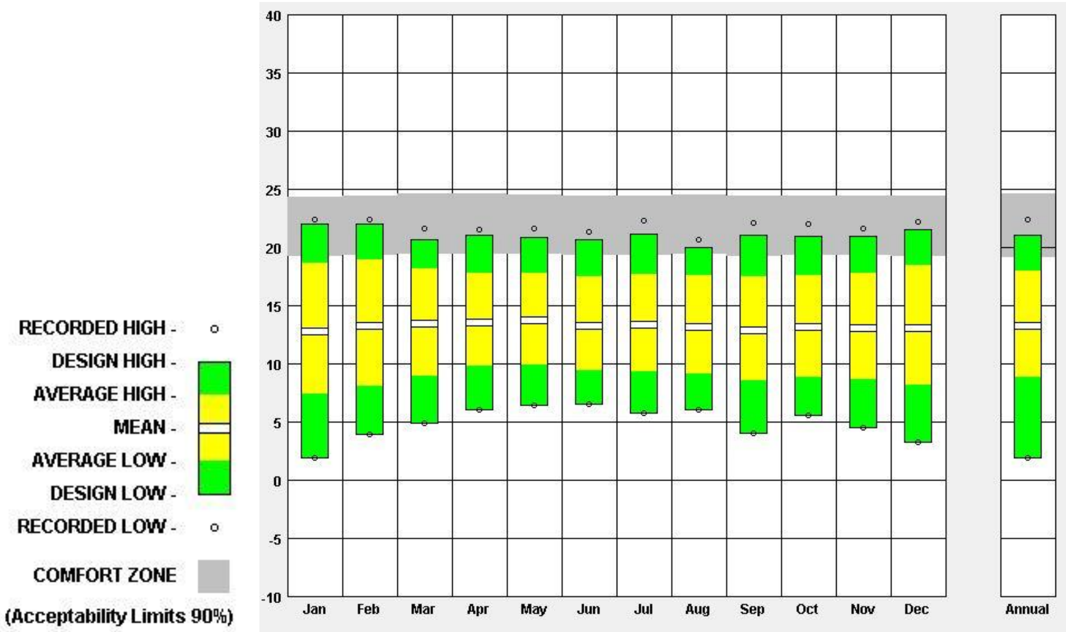


Figure 23: Relation between temperature and comfort zone over a year (Climate Consultant, 2019)

The graph (Fig. 23) demonstrates the variation of temperature in relation to the comfort zone over the year. As showed, the acceptability criteria are not being achieved during most of the year. In order to determine if the indoor climate is comfortable, we use ANSI/ASHRAE Standard 55-2010, which is an adaptive model where the comfort zone is defined with reference to indoor temperature and the average temperature of the outdoors during a month. This method is applicable when determining an acceptable thermal environment for occupant-controlled naturally conditioned spaces that meets the following criteria.
- No mechanical cooling system (e.g., refrigerating air conditioning, radiant cooling, or desiccant cooling) installed.
-No heating system in use.

In naturally ventilated spaces the occupants adjust the temperature by opening and closing windows, therefore the acceptance of comfort may be wider than buildings equipped with HVAC systems.

ANSI/ASHRAE Standard 55-2010 shows the allowable indoor operative temperature using the 80% acceptability limits. Note: The 90% acceptability limits are not used, since it works as information for further guidance.
In Fig. 24, following effects are accounted for: local thermal comfort, clothing level, metabolic rate, humidity and air speed.

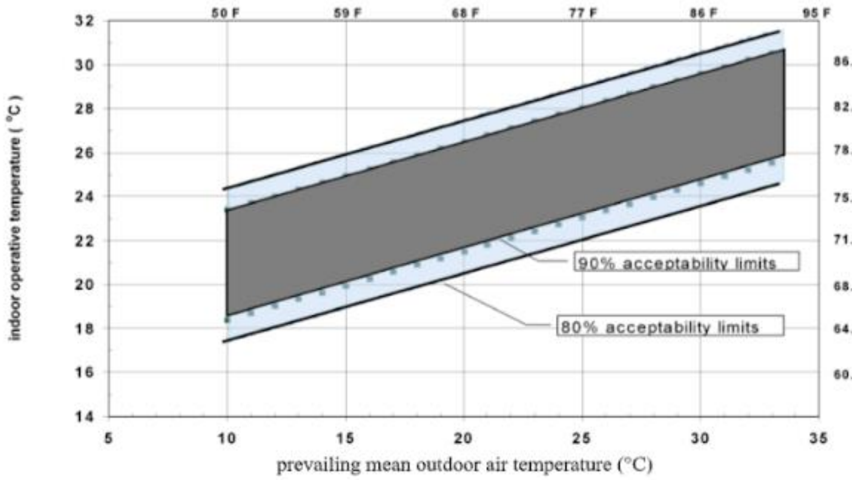


Figure 24: Acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE, 2010)

The value of average outdoor temperature in May was calculated to 14.8 °C which gives an average indoor temperature between 19 °C and 26 °C to achieve a comfortable indoor climate according to ASHRAE (see Fig. 25). These values will be used as reference lines in Fig. 44-45 to demonstrate when the indoor climate transcends the acceptability limits.

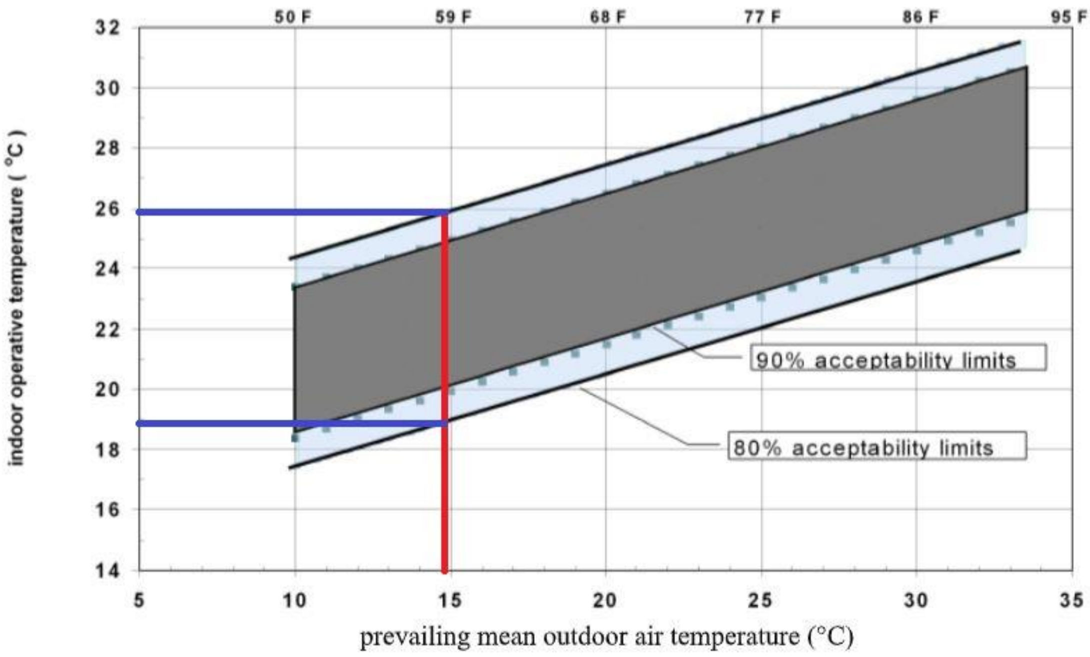


Figure 25: Acceptable operative temperature ranges for the plastic house (ASHRAE, 2010)

6 The field study

6.1 Studied houses

The study consists of two houses, where the design and the occupant’s activities are equal, and they are located in areas with similar climate. The expected needs of the dwellings regard to comfortable indoor climate are the same for the different dwellings. The houses were chosen due to its similarities and with the help from Build Change. The masonry house had previously been part of a retrofitting made of Build Change and allowed the measurements to take place in their home. The house made of Conceptos Plasticos bricks was found through a friend and the homeowner accepted the same measurements to be performed. Our survey is limited as any cavities and watertight connections are not taken into account and that our equipment only measures parts of the indoor climate. Having a comfortable indoor climate is something that should be strived for as it has a significant impact on people's health and well-being and should therefore be a necessity. Note that there is only one Tiny Tag used in the measurements in the house made of clay bricks, located in Usme. This is because of the high risk of theft if we would have placed a Tiny Tag outside the house. Therefore, we chose to collect data from a nearby weather station instead and use the pair of Tiny Tags in the house of plastic bricks.

The building-physical properties of the materials will be compared by a literature study as well as laboratory work of the plastic bricks thermal expansion coefficient, thermal conductivity and heat capacity.

A cost analysis will complement the comparisons to create an idea of the potential the plastic material has in reducing the insufficient amount of low-income housing.

6.1.1 General

The houses are located in different areas of Bogotá due to the lack of plastic houses that can be studied. However, the areas where the houses are located has similar climate and altitude, they are approximately the same size (40-50 sqm) and they are both suitable for low-income families with simple designs.

6.1.2 Masonry house

The house was located in Usme, an area in south of Bogotá. In this area Build Change conducts retrofitting of inadequate masonry houses together with the municipal of Bogotá. The Tiny Tag data logger for temperature and humidity was installed just above head height on an inner wall, in a room that the family doesn't use. This location was chosen in order to prevent following factors to affect the measurements:

- The heat from an outer wall
- Radiation or light from the roof
- Human factors e.g. sweating, cooking, showering

The inner surfaces in the house is mostly rough bricks with a few plastered walls. The roof is made of corrugated metal with some spots of transparent plastic that provides light into the building. The foundation was constructed of clay bricks and is built on a hillside.

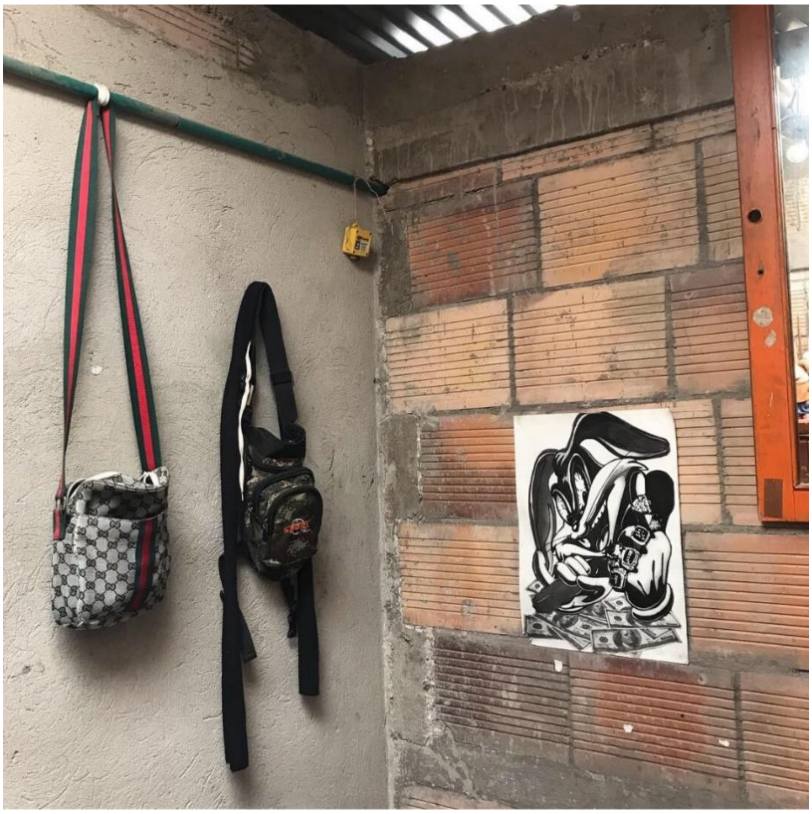


Figure 22: Installed Tiny Tag in masonry house in Usme (Photo by authors)

Figure 23: Exterior of the masonry house in which the measurements were made (Photo by authors)

6.1.3 Plastic house

The resident of the plastic house would like to appear anonymous in this thesis. To respect the owner´s request the location and pictures that could reveal the owner have been left out. What can be mentioned is that the roofing is made of the same material and the foundation is similar as the house of clay bricks. During the measurements the house was inhabited and fully used. In this location we placed two Tiny Tags. One was hanged outdoors inside of a plastic radiation shield to avoid direct heating. The location of this Tiny Tag was chosen by the different factors:

- Approximately 10 meters from the house to prevent that heat from the house interferes with the measured temperature.
- 1,5 m above the ground so that the measurement is not affected by the heated soil.
- Hanged in a string of 3 dm so that the wind ventilates.
- Under the roof of a carport with great natural ventilation, so that the device is covered from direct sunlight and rain.

The second Tiny Tag was placed in a room that the family did not use during the measurements. The location was chosen due to following factors:

- A room not used by anyone so heating from humans does not affect.
- The window shades are pulled down during the measured time to prevent the device from direct sunlight
- On a shelf in head height to prevent heating or cooling from floor and roof.

6.2 Subjects of comparison

6.2.1 Material properties

First and foremost, a building material must be able to bear its own weight and withstand the forces from nature. Therefore, the structural bearing will be compared.

6.2.2 Cost comparison

Low-income housing must be affordable in order to make it available for the social class that has been addressed in the thesis. The proliferation of unreinforced masonry houses in the lower income classes of Colombia, despite the 1984 Regulation of Construction Resistant Earthquake, is a validation that cost is a crucial factor.

6.2.3 Indoor climate

A dwelling of poor indoor climate can affect people's physical and mental health and should not be a luxury unreachable for low-income houses. Even though indoor climate is highly subjective and therefore difficult to evaluate, this thesis will compare humidity and temperature to reach a conclusion of indoor climate.

7 Material Properties

The following chapter will present material properties for the clay bricks and for the plastic bricks and compare their differences. For the first part of this chapter, structural bearing, three tests from Escuela Colombiana de Ingenieria Julio Garavito has been evaluated and compared; two tests of clay bricks and masonry written by Vega Vargas (2015) and López Restrepo (2013), and one test of the plastic material written by Sierra Jiménez (2016). For thermal conductivity, heat capacity and thermal expansion tests have been made on the plastic bricks together with the Department of Building Materials on Lunds Tekniska Högskola. To compare the results of the tests, values from Burström (2006) and Johansson (n.d.) have been used.

7.1 Structural Bearing

7.1.1 Masonry

The evaluation of masonry will be restricted to confined masonry because it is the most common technique when it comes to low-income buildings with clay bricks in Latin America and in Colombia.
As mentioned earlier, the aim of a masonry wall is to make it as close to a monolithic construction as possible. When the construction fails it does not fail all together, only certain areas, since it is not a monolithic unit.

7.1.1.1 Failure in walls of Masonry

According to Moreno et al. (2009) there are four ways for a masonry wall to fail (see Fig. 28):

Slip Failure: When horizontal load is applied, slip cracking can occur along one horizontal mortar bed as a consequence of failure of adhesion between the clay bricks and the mortar.

Cutting Failure: Also presented as the staircase due to its failure along the diagonal joints of mortar, making it appear as a staircase. The failure is a consequence of shear stress.

Bending failure: Often occurs in slender walls as cracking in the mortar joints and in the clay bricks, that occur in the corners and the centre, produced by compression failure.

Compression crush failure diagonal: Occurs in confined masonry units when the brick-body is separated from the reinforced wall of confinement elements. Large compression stresses in the corners of the wall can cause the bricks to be crushed when it is of low quality.

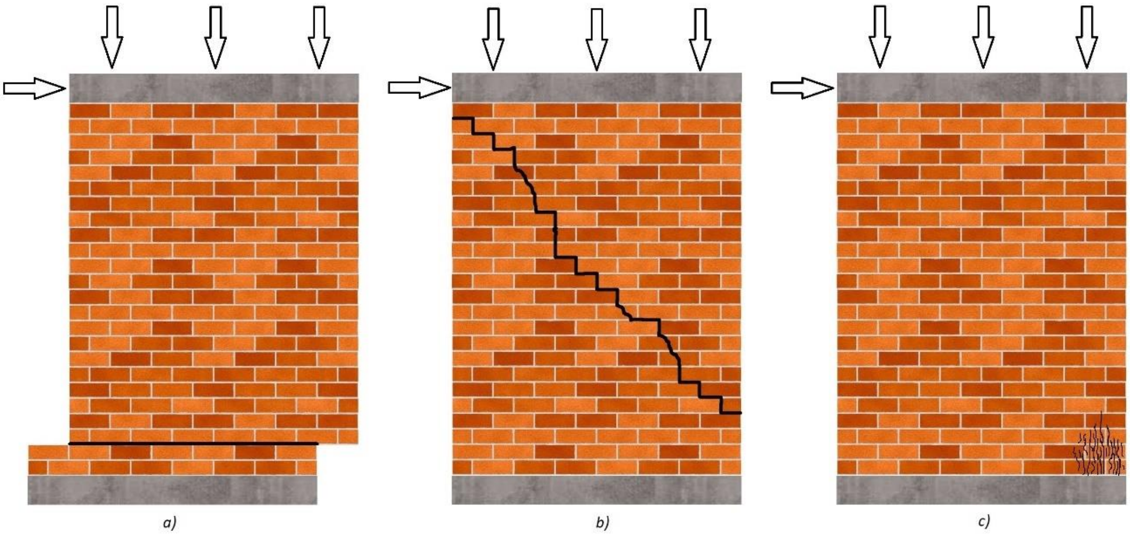


Figure 24: Common failures in masonry walls, a) Slip failure b) Cutting failure c) Bending failure (Figure by authors)

As the physical properties of the material is depending on the characteristics of the clay, such as impurities and the depth of the quarry (Takeuchi, 2010) and due to local materials and practices, two studies with similar tests is scrutinized and compared.

7.1.1.2 Compressive strength of hollow bricks

According to investigation carried out by Pauly & Priestley (1992), the bricks are made of a fragile material that presents a predominantly linear compression behaviour with compression strength between as low as 5 MPa to 100 MPa for high-fired ceramic clay units. (Vega Vargas 2015).

Two different compression tests and a chart merged of historical measurement of the bricks shows a range of results that demonstrates the variation of the strength the material. A compression test of the clay brick made by Vega Vargas (2015) is presented in Table 1. The results show that a brick of this type has an average compression strength of 9,8 MPa.

Sample nr.	Dimensions [cm]			Load [kg]	Area [cm2]	Resistance [MPa]
	Height	Length	Depth	Breakage		
1	19,7	30,0	11,8	36000	354	10,0
2	19,8	29,8	11,5	45000	343	12,9
3	19,8	28,6	12,0	45400	355	12,5
4	20,0	29,8	11,6	21600	346	6,1
5	19,7	29,9	12,0	27600	359	7,5
					Average	9,8

Table 1: Result of compression test (Vega Vargas 2015)

Another compression test made by López Restrepo (2013), in cooperation with MATCO S.A, the same test shows a compression strength of 5 MPa in average, which according to the author is a representative result for a large part of the Colombian production of these bricks.

A diagram (Fig. 29) merged from 230 historical measurements made by Escuela Colombiana Ingenieria (n.d.) shows that the strength can vary between 4 MPa (approx. 11 %) up to as high as 18 MPa (approx. 0,5 %), with the average value of 6 MPa (approx. 37 %).

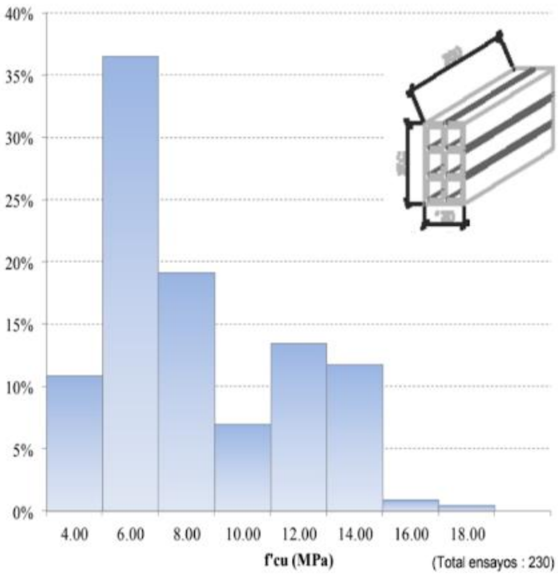


Figure 25: Histogram of compression test of "bloque No 5" (Escuela Colombiana Ingenieria, n.d)

7.1.1.3 Mortar strength

Mortar is a mixture of cement, fine aggregate and water, in some cases even chalk to make it less brittle. Which type of mortar used in the construction is of great importance and the properties vary a lot due to the ratio of the mixture. The most crucial property of mortar is the resistance to compression, and it is used as a primal parameter to define the type of mortar (Vega Vargas 2015).

Vega Vargas (2015) has conducted an axial compression test on cylinders (diameter 5, height 20 cm), in where the cylinders are loaded axially until failure. The resistance to compression depends on the amount of time it has hardened and the proportions between water and cement. The test shows an average result of 21,5 MPa, see Table 2.

Sample nr.	Age [days]	Load [kg]	Diameter [cm]	Resistance [MPa]
1	28	4200	5,0	21,0
2	28	4000	5,0	20,0
3	28	4200	5,0	21,0
4	28	4700	5,1	22,5
5	28	4700	5,0	23,5
6	28	5700	5,1	27,3
7	161	5700	5,1	27,3
8	161	4600	5,1	22,1
9	161	4300	5,1	20,6
10	157	6400	5,1	30,7
11	157	6100	5,1	29,3
12	157	3700	5,1	17,7
13	74	4200	5,1	20,1
14	74	4000	5,1	19,2
15	74	4500	5,1	21,6
			Average	21,5

Table 2: Axial compression test on mortar cylinders (Vega Vargas 2015)

López Restrepo (2013) made a similar test with mortar cylinders of the same dimensions as in the previous. However, the result was much lower in compression strength, around 11 MPa in average.

The tests show a variation between the average of 21.5 and 11 MPa. It also shows a big variation in strength depending on the time it hardens, around 20 MPa for 28 days and up to 30,7 MPa when hardened for 157 days. Further, the mortar has a higher average strength than the clay brick.

7.1.1.4 Clay brick masonry prism

When the clay bricks are assembled together into a brickwork structure, the strength varies from the components themselves. A test by Vega Vargas (2015) of two bricks with mortar in between was measured before compression and shows an average strength of 5,3 MPa (Table 3).

Sample nr.	Dimensions [cm]			Load [kg]	Area [cm2]	Resistance [MPa]
	Height	Length	Depth	Breakage		
1	41,4	46,0	12,0	18770	552	3,7
2	42,0	45,6	11,6	28150	529	5,8
3	42,0	45,0	11,8	30400	531	6,3
					Average	5,3

Table 3: Compression test on masonry prisms (Vega Vargas 2015)

The same test was made by López Restrepo (2013) and shows a lower result with an average of 1,48 MPa (Table 4).

Sample nr.	fm [MPa]	Em [MPa]
C1.1	1,52	2947
C1.2	1,35	1607
C1.3	1,56	3021
Average	1,48	

Table 4: Compression test on masonry prisms (López Restrepo, 2013)

Both tests have similarities and differences in their results. The strength is highly varied with results as low as 1,35 MPa to and as high as 6,3 MPa. The low results measured in the latter test is probably due to the lower quality of mortar (see the results for mortar strength), and in extension this shows the importance of quality in both bricks and mortar. As for the similarities of the test, they both show a sudden failure when being crushed.

7.1.1.5 Full-scale wall

The masonry walls are built to full scale and tested with lateral load as Fig. 30 shows.

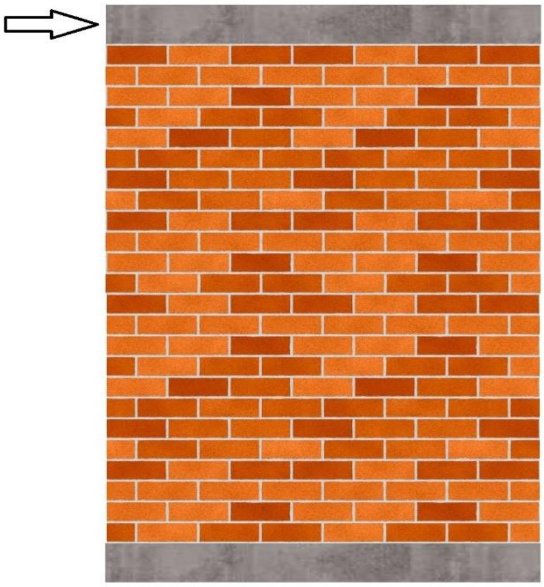


Figure 26: Direction of load for masonry tests (Figure by authors)

Vega Vargas (2015) tested two different walls, one short and one tall, but only the short wall is taken in consideration due the dimensions of the larger wall. The dimensions and build-up are shown in Fig. 31 and the result of the test in Table 5.

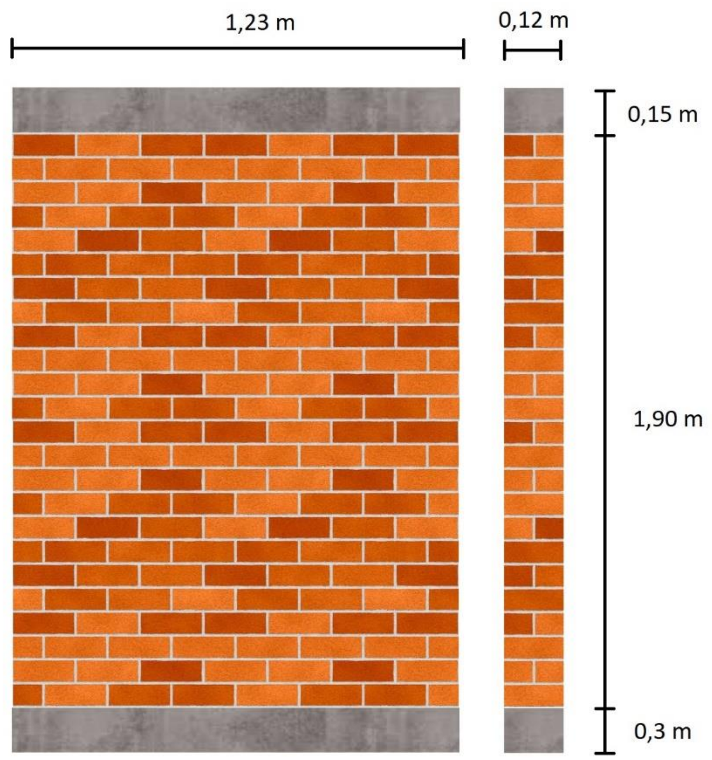


Figure 27: Dimensions of masonry walls from test made by Vega Vargas (2015) (Figure by authors)

Size			Max load
Height (m)	Length (m)	Width (m)	(kN)
1,90	1,23	0,12	1,3

Table 5: Dimensions of masonry wall (Vega Vargas 2015)

A force of 1,3 kN was subjected to the wall before failure. It showed two types of failure: slip failure and bending failure. In the lower left part of the wall a horizontal crack between mortar and bricks split the element in two. This is due to tension in the adhesion between mortar and brick. Also, the bricks in the lower right corner showed a local crushing failure due to compression.

The dimensions and the build-up of the wall tested by López Restrepo (2013) is displayed in Fig. 32 and Table 6.

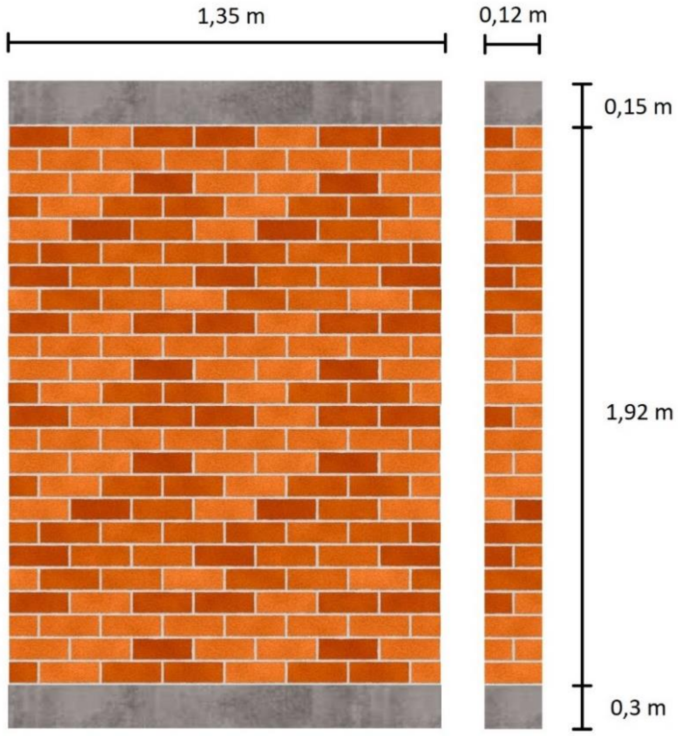


Figure 32: Dimensions of masonry walls from test made by López Restrepo (2013) (Figure by authors)

Size			Max load
Height (m)	Length (m)	Width (m)	(kN)
1,92	1,35	0,12	4,11

Table 6: Dimensions of masonry wall 2 (López Restrepo, 2013)

In this test the wall was slightly wider and higher than in the previous test of the short wall, and the results reflects that and shows a slightly higher value of load before failure. The type of failure is not presented in the original thesis and will therefore not be discussed.

7.1.2 Plastic material

To make a proper comparison between plastics and masonry, a thesis written by Sierra Jiménez (2016), at the Escuela Colombiana de Ingenieria Julio Garavito will be evalueated. In the thesis plastic bricks made by Brickarp has been tested. Brickarp created the brick together with Conceptos Plasticos, that evaluated and improved it into the product that they use today. The structure of the walls of plastic bricks is similar to the confined masonry construction, with its columns and bricks.

7.1.2.1 Compression test for plastic bricks test for plastic bricks

Brickarp bricks are manufactured with HDPE and have the dimensions 70x140x495 mm, with tongue and groove that fits together in a similar pattern to ordinary masonry (Fig. 33).
The Brickarp brick was subjected to compression tests where the tongue of the brick was cut off and placed in the groove, to make it as close to an actual load transmission as possible. Two plates of steel placed on top of the brick to stabilize and centre the loads. 3 mm/min until reaching failure in the study direction Z.

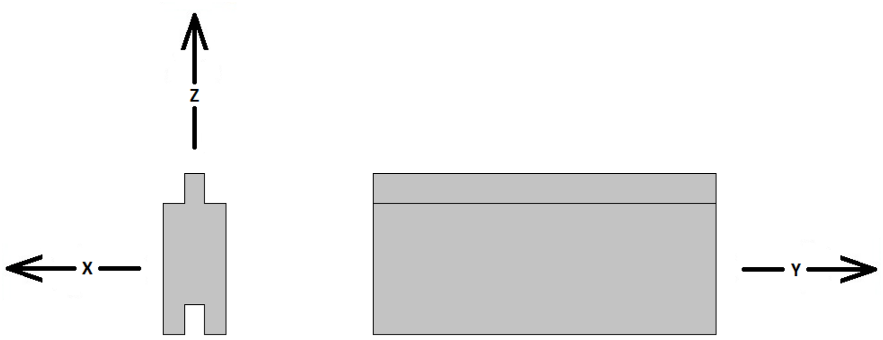


Figure 33: Plastic brick with directions (Figure by authors)

The test was made on 10 bricks, 5 with drilled holes (for electric wiring) and 5 without. The results for the different types of bricks is presented below:
With holes: Average compression stress measured in the bricks was 6.6 MPa and a standard deviation of 1.76 MPa (Table 7).
Without holes: Average compression stress measured in the bricks was 4.81 MPa and a standard deviation of 0.44 MPa (Table 8).

Sample nr.	P max [kN]	FHS max [MPa]
1	261,5	8,23
2	212,5	6,67
3	261,8	8,32
4	134,2	4,22
5	178,1	5,58
Average	209,62	6,6
Standard deviation	55,01	1,755

Table 7: Compression test plastic bricks with holes (Sierra Jiménez, 2016)

Sample nr.	P max [kN]	FHS max [MPa]
1	144,5	4,52
2	178,0	5,59
3	154,0	4,8
4	151,9	4,74
5	141,1	4,42
Average	153,9	4,81
Standard deviation	14,47	0,441

Table 8: Compression test plastic bricks without holes (Sierra Jiménez, 2016)

In general, a larger volume will result in a higher value of strength, given that the material and the geometric shape is the same. However, these results show the opposite. The bricks with holes have an average compression strength of 6,6 MPa and the bricks without holes 4,8 MPa. The bricks with holes also show the biggest variation in strength with the standard deviation of 1,755 MPa.

7.1.2.2 Tension test for plastic specimen

As the plastic gets deformed instead of breaking when compressed, it is of great importance to make a complementary test of the tension, where the sample is strained until failure. In the first test of Brickarp bricks, ten samples were extracted from the bricks, see Fig. 34, and strained in direction Y until failure.

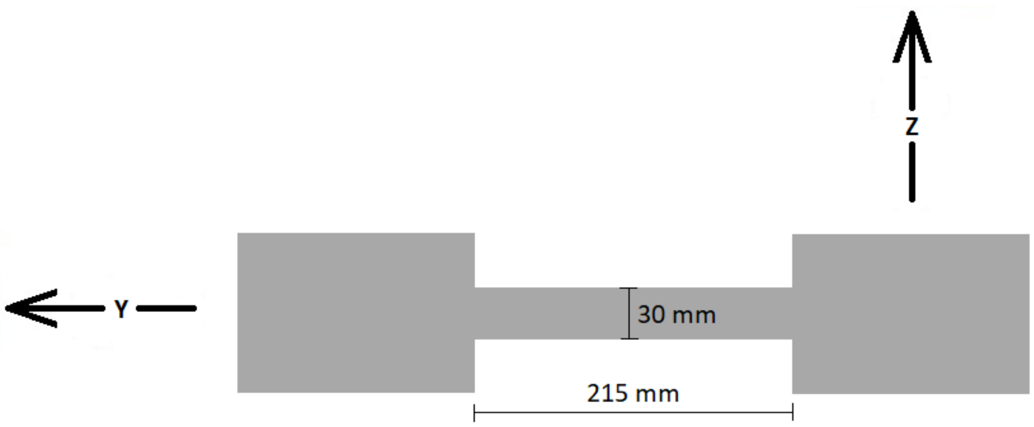


Figure 34: Dimensions of plastic sample for compression test (Figure by authors)

The result (Table 9) shows an average strength of 5,7 MPa with a standard deviation of 0,6 MPa. All samples but two failed somewhere in the thin part of the sample. Of these eight failed samples, six failed in the middle and two broke closer to the edges. All samples showed equality in the type of failure, a fragile failure with none, or no significant, extension.

Sample nr.	P max	
	[kN]	[MPa]
1	3,32	6,54
2	3,23	6,49
3	-	-
4	2,65	5,19
5	2,75	5,93
6	2,55	5,18
7	3,01	6,24
8	2,83	5,03
9	2,71	5,31
10	2,57	5,45
Average	2,845	5,708
Standard deviation	0,28	0,598

Table 9: Tension test of plastic sample (Sierra Jiménez, 2016)

7.1.2.3 Prisms made of Plastic bricks

The compression test of prisms is conducted similar to that of the single bricks. In total the prisms are made by five single bricks to complete the full dimension of 460x400x70 mm.

Average compression strength 6,08 MPa, with a standard deviation of 0,41 MPa. The results varied from 5,56 to 6,72 MPa. Even if the procedure of the test was similar to the compression test of a single brick, the outcome resulted in a different failure. Because of the height, the sample is considered as a slender prism and it showed failure in buckling as a result of this.

7.1.2.4 Full scale assembled walls made from plastic bricks

To test the material’s capacity under realistic stress a wall in real scale with dimensions 2,25x1,27m, made with bricks, two beams; a top beam and a foundation beam at the bottom, two columns; one on each side of the wall, is made up. The corners of the structure are joined with metal sheets and fastened by bolts as shown in Fig. 35.

Three real-scale walls of HDPE, used as partition walls and are also a part of the structural system, were tested and exposed to lateral static loads which resulted in an average shear load of 2,83 kN and an average lateral dislocation of 74 mm, this was the last measured result before the wall failed. The three measurements varied from 2,77 kN to 3,29 kN and a standard deviation of

Sample nr.	Maximum load [kN]	Max displacement [mm]
1	2,77	120
2	2,42	50,2
3	3,29	50
Average	2,83	74
Standard deviation	0,435	41

Table 10: Lateral compession test on real-scale plastic wall (Sierra Jiménez, 2016)

0,435 kN and the lateral dislocation was measured to 50,0 mm to 120,0 mm with a standard deviation of 41 mm, see Table 10.

Figure 35: Full-scale plastic wall tested for lateral static load (S*ierra Jiménez 2016)*

7.2 Thermal conductivity and heat capacity

The temperature in a material is a measure of unorganised movement of the molecules and atoms of the material. High temperature means more powerful movement and low temperature means slow movement. Transmission of heat occurs when molecules with high momentum collides with molecules with low momentum. Thermal conductivity, also known as λ-value, is a term used in building technical context, and refers to the overall transmission through a material, with radiation and convection included. In a dense material such as plastic, a predominant amount of the heat transmitted through a material is through molecules colliding, due to the low content of pores.

Heat capacity can be defined as the amount of energy that it takes to change a material's temperature one-degree Kelvin. The value for heat capacity is largely depending on the content of water.

As for the thermal conductivity, plastic is a dense material with low content of pores and therefore not as depending to this. The clay brick on the other hand is more porous and more dependent. The values discussed in this thesis is for dry materials. (Burström 2006)

7.2.1 Clay bricks

For hollow clay bricks, the heat capacity varies depending on the number of cavities, the size of the cavities, and the clay itself. With a value of the heat resistance from Johansson (n.d.) an estimated value of heat capacity can be calculated.

Material	Thickness (mm)	Resistance (R) [a] (m^2K/W)	ρ (kg/m^3)	Spec. heat (Wh/kgK)	Source
Hollow blocks (masonry)					
2 cavities in thickness	100	0.20	1000	0.26	2

Figure 36: Heat resistance for hollow block masonry, see the whole sheet in Appendix table 17 (Johansson, n.d.)

$$\lambda = \frac{d}{R} = \frac{0.12}{0.2} = 0.6, \qquad [\frac{W}{mK}]$$

The value for heat resistance in Fig. 36 is for a hollow brick with a thickness of 100 mm and the hollow brick used in this thesis has a thickness of 120 mm. Due to this, the value is an approximate value and not fully correct. However, the difference is so small that it could be neglected.

The specific heat capacity is 1000 J/(kg*K) and the volumetric heat capacity is calculated to:

$$volumetric\ heat\ capacity = \rho * heat\ capacity = 1700 * 1000 = 1.7 * 10^6 \left[\frac{J}{m^3 * K}\right]$$

7.2.2 Plastic

In collaboration with the division of Building Materials at Lund University a test for heat capacity and thermal conductivity was conducted with Hot Disk TPS 2500.

A cubic specimen was extracted from a brick made by Conceptos Plasticos. The cube is cut, and a sensor is placed in the gap before the cube is assembled again. A pulse of energy is subjected to the cubes and the sensor registers the amount of energy that passes through the material.
Both heat capacity and thermal conductivity is measured in the same test.

Figure 37: Plastic sample extracted for measurement of heat capacity and thermal conductivity (Photo: Lars Wadsö, 2019)

The measurements showed that the plastic material has the λ-value $0{,}42\ [W/m * K]$. To calculate the volumetric heat capacity, the heat diffusivity was measured to $\alpha = 0{,}3 * 10^{-6}\ [m^2/s]$.

$$volumetric\ heat\ capacity\ (cv) = \frac{\lambda}{\alpha} = \frac{0{,}42}{0{,}3 * 10^{-6}} = 1{,}4 * 10^6, \qquad \left[\frac{J}{m^3 * K}\right]$$

Further, the density was measured to $\rho = 1100\ [kg/m^3]$ and the specific heat capacity calculated to:

$$heat\ capacity = \frac{cv}{\rho} = \frac{1{,}4 * 10^6}{1{,}10 * 10^3} = 1270, \qquad \left[\frac{J}{kg * K}\right]$$

7.3 Thermal expansion

A materials volume change when it is exposed to heat alterations. In most cases the material expands when heated and shrinks when cooled (Burström 2006). ASM International (2002) describes the definition of thermal expansion as following: "The coefficient of linear thermal expansion (CTE, α, or α1) is a material property that is indicative of the extent to which a material expands upon heating. Different substances expand by different amounts. Over small temperature ranges, the thermal expansion of uniform linear objects is proportional to temperature change.

To evaluate how the thermal expansion coefficient affects the materials, a rough calculation has been made of the outer wall temperature and compared with the lowest measured temperature. Since this is an evaluation of the maximum thermal expansion, the worst case during the measured time period will be used. Therefore, the highest measured temperature outdoors and the temperature indoors at the same time (see Fig. 47-48) was used in accordance with sun radiation to calculate the outer wall temperature.

The outer wall temperature is calculated with a simplified version of equation, 5.1.7 from Arfvidsson (2017)

$$T_{surface} = \frac{\frac{T_{exterior}}{R_{se}} + q_{sun} * a_{surface} + \frac{T_{interior}}{(R_{wall} + R_{si})}}{\frac{1}{R_{se}} + \frac{1}{R_{wall} + R_{si}}}$$

The intensity of the sun and the colour of the bricks are important for this calculation and therefore different data was used to see how big roll they played. All data of sun intensity used in these measurements will be approximated to hit the wall surface with an angle of 45˚.

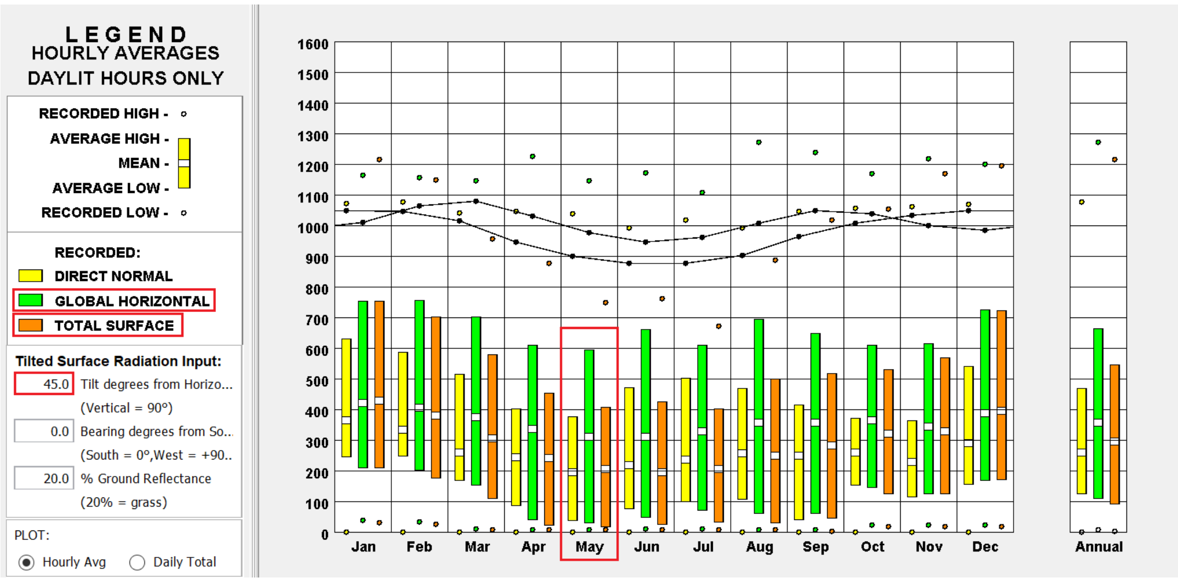


Figure 38: Radiation in May with an angle of 45˚. (Climate Consultant, 2019)

The angle and direction that the sun hits the wall, as well as the amount of shading objects is unknown. Therefore, the value will be somewhere in between the "total surface" and the "global horizontal" (see Fig. 38). The following table (Table 11) displays the calculated temperature of the wall, depending on three values of solar radiation (400, 500, 600 [W/m^2]) and the absorption coefficient that is depending of the colour of the wall. Since the different bricks have a colour that varies from light brown to dark brown as well as light grey to dark grey, the coefficient will also vary between three estimated values (0.7, 0.8, 0.9).

$T_{exterior}$ [K]	$T_{interior}$ [K]	Sun radiation [W/m2]	Absorption coefficient	Ts [K]
19.5	25	400	0.7	31
19.5	25	400	0.8	32.6
19.5	25	400	0.9	34.2
19.5	25	500	0.7	33.8
19.5	25	500	0.8	35.8
19.5	25	500	0.9	37.7
19.5	25	600	0.7	36.5
19.5	25	600	0.8	38.9
19.5	25	600	0.9	41.2

Table 11: Surface temperature (Ts) depending on different values of sun radiation and absorption coefficient (Table by authors)

The minimum temperature during the measurements is at 10.0 ˚C and the maximum temperature on the wall is calculated to 41.2 ˚C, a difference of 31.2 ˚C. These temperatures will be used to calculate the maximum thermal expansion for each material.

7.3.1 Clay bricks

A measure of the coefficient of linear thermal expansion for clay bricks depends on the composition of the clay and varies between 4-6 10^{-6} (1/K). Compared to different metals (aluminium: 24 10^{-6} (1/K) and copper: 17 10^{-6} (1/K)) and wood (pinewood in the direction parallel to the fibres: 34 10^{-6} (1/K)), the size of the thermal expansion in the clay brick is relatively small.

$$\Delta L = \Delta T * L * \alpha$$

$$\Delta L = (41.2 - 10) * 30 * 6 * 10^{-6} = 0.0056 \quad [mm]$$

The above calculation is for one brick with the length of 30 mm. A calculation for the same length as the wall of the plastic house will be made to make a comparison:

$$\Delta L = \Delta T * L * \alpha$$

$$\Delta L = (41.2 - 10) * (495 * 15) * 6 * 10^{-6} = 1.38 \quad [mm]$$

7.3.2 Plastic brick

In collaboration with the Division of Building Materials at Lund University a test for thermal expansion was conducted. The coefficient of thermal expansion was measured on two rods of length 195 mm that were cut from the horizontal flanges of a brick. Semi-spherical studs were attached to each end of the rods. Measurements were made of the lengths of the rods at 22, 40, 50 and 60 °C, relative to an invar rod held at 22 °C. The plastic rods were heated in an oven and insulated during the short measurements. Both rods had nearly identical coefficients of thermal expansion of 130 10^{-6} (1/K).

Figure 28: Test of the thermal expansion coefficient (Photo: Lars Wadsö, 2019)

The bricks have a length of 495 mm and the thermal expansion coefficient is measured to 130 10^{-6} (1/K).

$$\Delta L = \Delta T * L * \alpha$$

$$\Delta L = (41.2 - 10) * 495 * 130 * 10^{-6} = 2{,}01 \quad [mm]$$

The shorter wall of the measured house has approximately a length 15 bricks, which gives a total expansion of $2{,}01 * 15 = 30.1\ [mm]$ when the temperature fluctuates. These measurements and calculations are only meant to enlighten the issue with using a material with high thermal expansion coefficient, and not to be taken strictly. Temperature measurements of the wall surface and indoor and outdoor temperature will have to be measured extensively over a longer period to determine a more reliable result.

7.4 Analysis of Material properties

Type of test	Clay bricks		Plastic brick
	Vega Vargas 2015	Lopéz Restrepo 2013	Sierra Jimenez 2016
Compression strength single brick [MPa]	9.8	5	5.7
Compression strength mortar [MPa]	21.5	11	
Tension strength [MPa]			5.7
Compression strength prism [MPa]	5.3	1.48	6.08
Lateral compression strength full-scale wall [kN]	1.3	4.11	0.435
Thermal conductivity λ-value [W/(m*K)]	0.6		0.42
Heat capacity [J/(kg*K)]	1000		1270
Volumetric heat capacity 10^6 [J/(m^{3}K)]	1.7		1.4
Dry density [kg/m^3]	1700		1100
Thermal expansion coefficient 10^{-6} [1/K]	4-6		130
Total expansion of a 7,425 m long wall [mm]	1.39		30.1

Table 12: Summary of values presented in the chapter of Material Properties (Table by authors)

Comparison of compression strength between hollow clay bricks and plastic bricks shows that the compression strength of clay brick number 5 varies between 4 MPa and as high as 18 MPa, with an average of 6 MPa, whilst the plastic bricks show a variation between 4,8 and 6,8 for Brickarp-bricks. The most significative difference between the plastic bricks and clay bricks can be observed in Fig. 40 which shows the result after compression test of a plastic brick. As the plastic bricks are compressed, they are deformed, while clay bricks are brittle and cracks when the load is too heavy.

Figure 40: Plastic brick compressed and deformed (Sierra Jiménez 2016)

Although the dimensions of the real-scale walls differ and the construction is not identical, the comparison of strength is interesting in the aspect of evaluating if the plastic wall's strength is satisfactory. The strength is measured to 1,3 and 4,11 kN for the masonry walls and 2,83 kN for the plastic walls. The value for the plastic walls is regarded to be fully sufficient. However, the largest distinction lies in the type of failure. Whilst the masonry wall is fragile and breaks with a sudden failure, the plastic wall is elastic, and the bricks dislocated and gets deformed instead of breaking.

Measurements show that the rod has value of approximately $130 * 10^{-6}$ (1/K), which is considered to be a high value compared to other plastics. In Table 13, three commonly used plastics is presented with values together with the measured value (Martin 2019, Wadsö 2019).

Type of plastic	Min value 10^{-6} (1/K)	Max value 10^{-6} (1/K)
HDPE - High Density Polyethylene	60	110
PET - Polyethylene Terephthalate	60	80
PP - Polyprophen, 10–40 % Talc filled	40	80
Conceptos Plasticos brick	130	130

Table 13: Thermal expansion coefficient for commonly used plastics (Martin 2019, Wadsö L. 2019)

The expansion coefficient for the plastic material is almost 22 times as big as for clay bricks. A normal size wall built of plastic (the short wall of the measured plastic house) of 7.4 meter expands more than 30 mm, which is considered to be a large value compared to the modest 1.39 mm of the clay brick wall.

8 Cost Comparison

8.1 Material

8.1.1 Confined masonry

The cost of constructing a confined masonry house depends on how its formed and which kind of bricks that are used. The comparison is done using data from Conceptos Plasticos, where two similar 40 sqm houses has been compared. Since there are hundreds different kinds of bricks, both from factories and made informally, we compile a general cost that is based on the cost data from Conceptos Plasticos and Build Change. The retrofitting will be included as an extension (see table 16 in Appendix), since it will offer a sense of how expensive it is to build a new house in Colombia (Blaisdell et al. 2015).

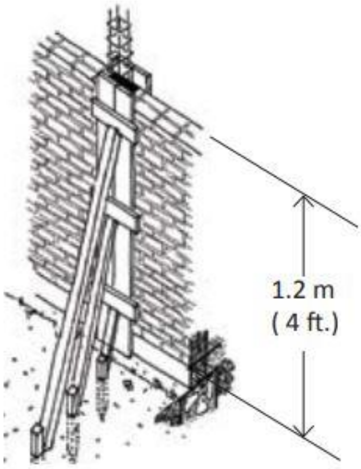
8.1.2 Conceptos Plasticos/Brickarp

Conceptos Plasticos delivers a house system that can be designed in a desired way or in one of five standard versions from their portfolio. The houses can be built in different sizes and are equipped with separate rooms that can be used as a bedroom, a living room, a dining room, bathrooms, and a kitchen. The construction is similar to confined masonry, which has load bearing columns and it could either be constructed on the concrete foundation or elevated. It is supplemented with roofing, wooden or plastic trusses, basic doors and windows. The house system includes a rough shell with trusses and labour. Scilicet, the house system provided from Conceptos Plasticos does not include roofing, doors or windows.

8.2 Labour

8.2.1 Confined masonry

Confined masonry construction is a common building technique in Latin America, the progress in wall construction is limited to a maximum of 1.2 m height per day, as shown in Fig. 41. This is because the mortar is still fresh, and the wall may go out of plumb. Afterwards, the columns must be casted which is a time-consuming element (Schachter et al. 2015).
Beyond this, the casting of concrete takes a lot of time due to its hardening. Concrete gains strength over time and in general the strength is measured after 28 days. The table below shows how the strength increases over time.



Strength of Portland Cement Concrete:		
3 days:	approximately	20 %
7 days:	"	45 %
28 days:	"	60 %
3 months:	"	85 %
6 months:	"	95 %
1 year:	"	100 %

Figure 41: Maximum building height per day and strength of Portland Cement (Schachter et al. 2015)

Due to these factors it takes a long time to complete a masonry house. However, the house may be finished but it's not safe to inhabit before the hardening process has reached a sufficient strength.

8.2.2 Conceptos Plasticos/Brickarp

The plastic houses are transported in small parts to the construction site and according to Conceptos Plasticos, it takes approximately two weeks for a family to assemble a 56 sqm house with basic knowledge of construction and with basic techniques. The cost is a fixed cost that includes the assembly manual and delivery of the house.

8.3 Maintenance

8.3.1 Confined masonry

Generally, bricks are a very durable material, but common occurrences in masonry are deformations such as cracks or fissures in walls, broken or deteriorated bricks, corrosion of reinforcing steel, efflorescence, high wall moisture. These problems can be caused by poor-quality materials, inadequate constructive practices, deficient structure with too few confined walls in both directions or inadequate foundation over soft or loose soils. This can eventually lead to severe consequences when an earthquake occurs (Blondet 2005). However, this is something that is very subjective and will not be included in the cost analysis.

8.3.2 Conceptos Plasticos/Brickarp

Aside from being fire and earthquake resistant, the alternative building material provides a durable shelter that requires no maintenance, given if the walls are not fitted with coating. According to Conceptos Plasticos the house system can be painted, plastered and tiles can be applied, just like in masonry houses. Therefore, the maintenance depends on the buyer and their material choices.

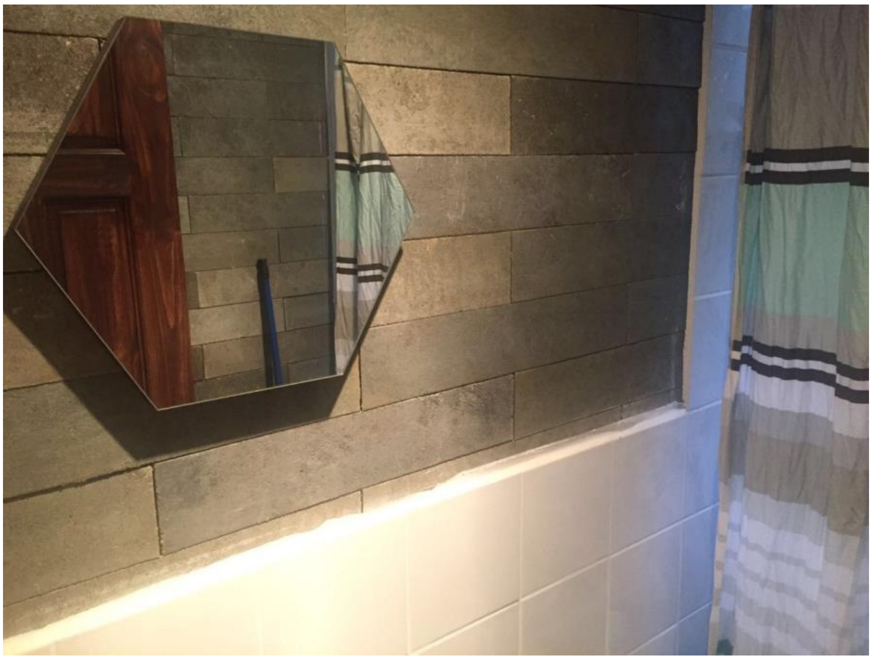


Figure 42: Example on a bathroom with tiles and mirror attached (Conceptos Plasticos n.d)

8.4 Summary

Conceptos Plasticos has made a comparison between two buildings, one made of masonry and one made of plastic which is shown in Table 13. Note that the comparison is not for the studied houses in the thesis, but for two similar size houses. In this cost analysis the price for the foundations differ which the houses in the study does not. The cost analysis also disregards insulation since it is rarely used in Colombia. If the plastic material is used in colder climate this would be an additional cost that could vary in price between the constructions. Both houses are built by construction workers and not by the families since it's easier to compare. This cost could therefore be excluded if the opposite was done. The plastic housing is an advantageous building method since it is both cheaper (approx. 24%, see Table 13), takes less time and requires minimal building knowledge. As can be seen there are no unforeseen costs, this is because the delivered house is well projected and needs no additional work to be finished. However, the field study shows that it is not simple to build the plastic house since it sometimes requires power tools and high precision when mounting, which leads to a more complicated installation and more expensive than what is said.

	Plastic bricks	Clay bricks nr.5
Preliminary work	1,718 kr	1,718 kr
Foundation	13,920 kr	28,550 kr
Columns & beams	20,471 kr	31,514 kr
Masonry	42,879 kr	22,988 kr
Carpentry	5,717 kr	5,717 kr
Transport	2,863 kr	11,075 kr
Unforeseen	- kr	6,666 kr
Total	87,568 kr	108,229 kr
Total per m2	2,189 kr	2,706 kr
Cost from 2018, currency used: 1 COP=0,0028 SEK		

Table 14: Cost of different types of housing (Conceptos Plasticos)

All costs that have been used in the cost analysis has been either in USD or in the COP and have been adjusted to the current Swedish currency and can therefore differ slightly.

9 Indoor climate measurements

9.1 Introduction

Measurements were made on the indoor climate of the two houses in the study. By using the Tiny Tags, humidity and temperature variation could be gathered during a period. By using the collected data, the houses comfort zones can be studied to determine if the indoor climate criteria are achieved and see how the indoor climate varies throughout the day.

9.2 Results of measurements

Measurements of temperature and humidity shows the variation over two weeks in the month of May, and it is similar to normal values for Bogotá. Because of problems with communication and logistics, we have not been able to measure the indoor climate in the plastic house for as long time as we wanted, the measured data is therefore limited. Note that the time laps of the graphs are different, since the measurements were installed at a different time.

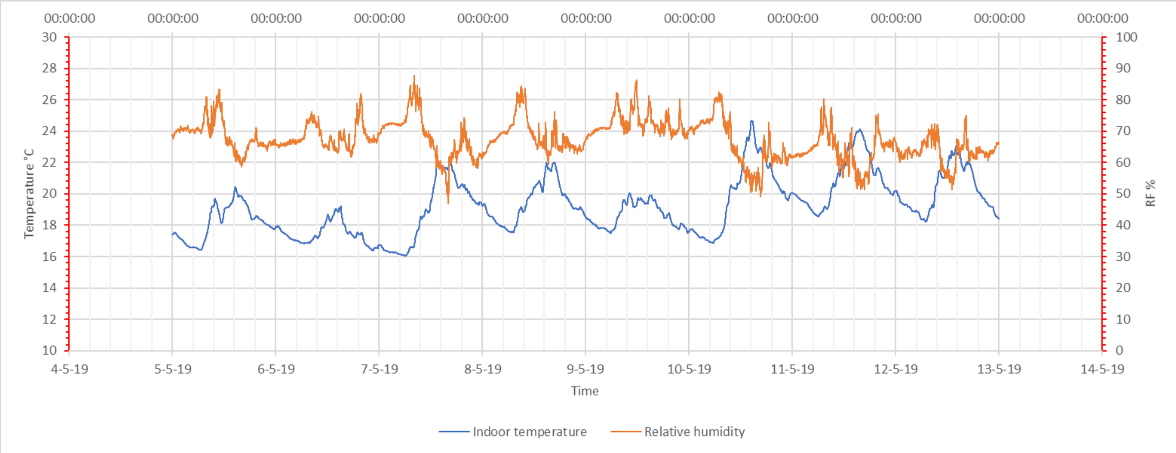


Figure 43: Indoor temperature and humidity for masonry house in Usme, Bogotá. (Figure by authors)

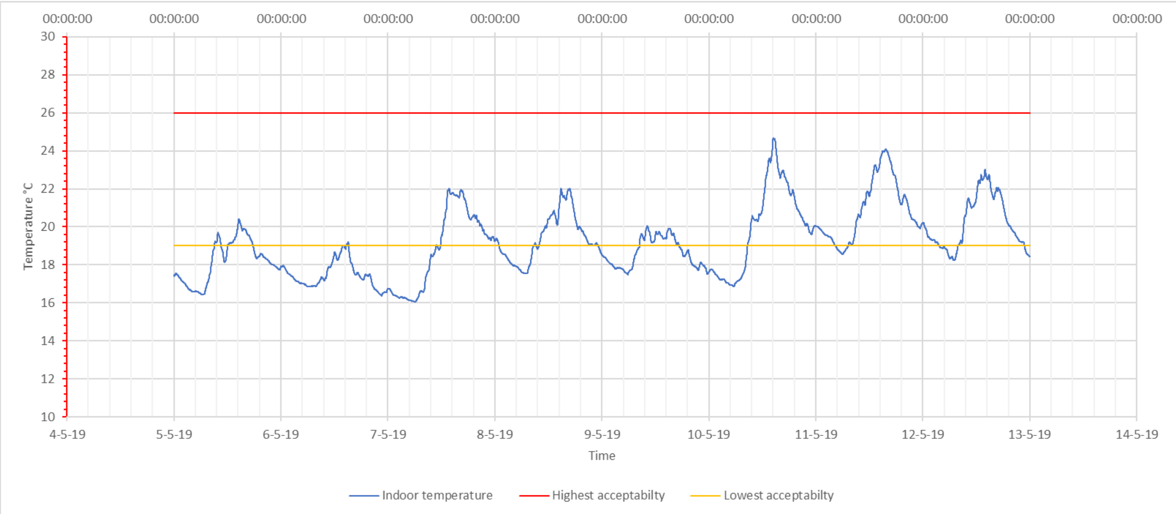


Figure 44: Indoor temperature with reference-lines of accepted comfort for the indoor climate. Masonry house in Usme, Bogotá. (Figure by authors)

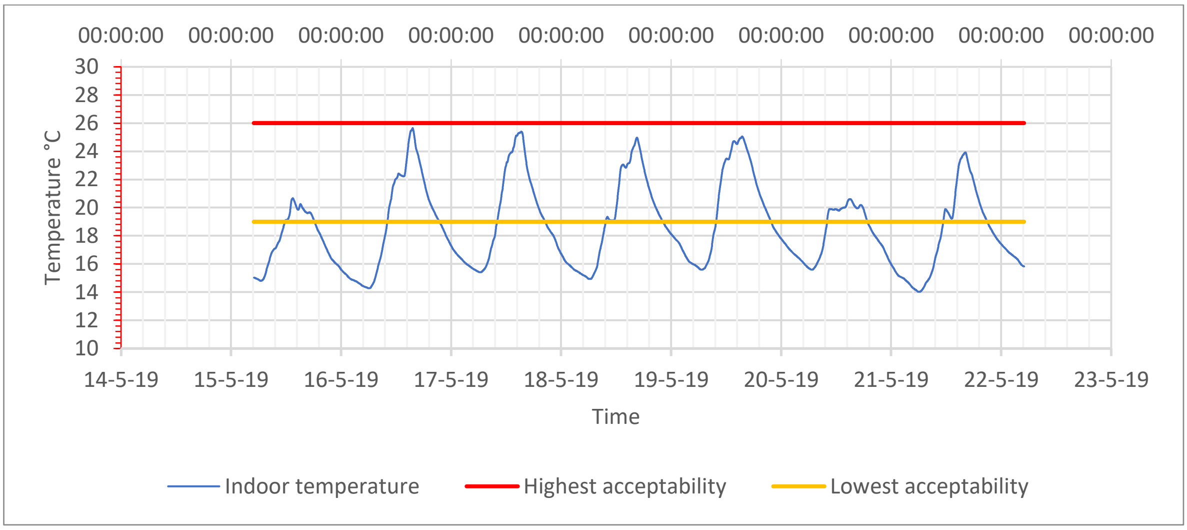


Figure 45: Indoor temperature with reference-lines of accepted comfort for the indoor climate. Plastic house. (Figure by authors)

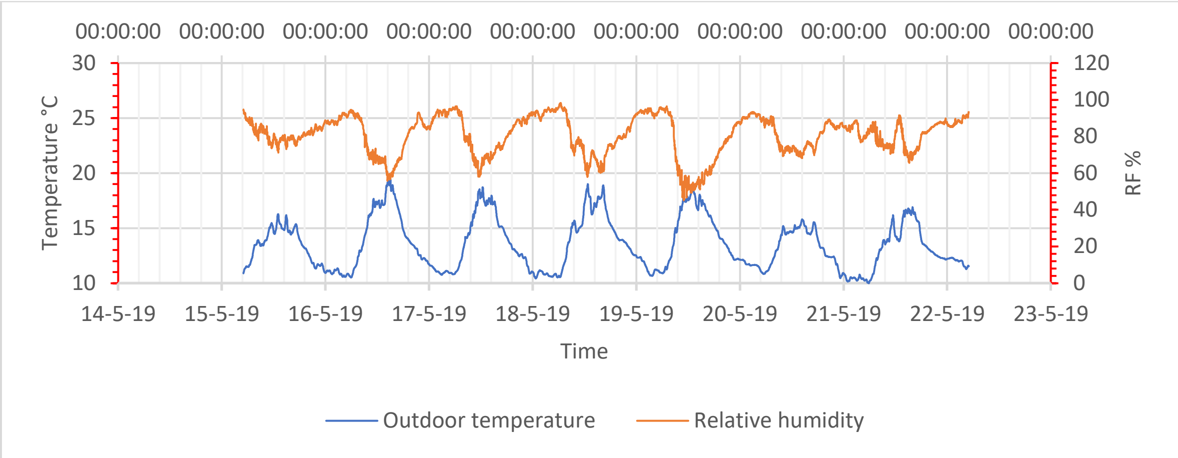


Figure 46: Outdoor temperature and humidity measured nearby the plastic house. (Figure by authors)

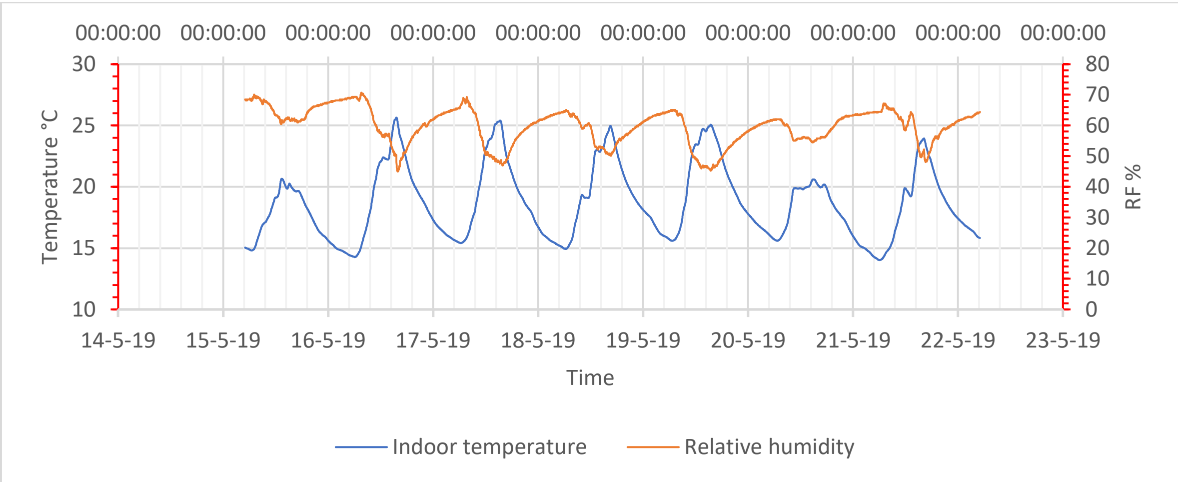


Figure 47: Indoor temperature and humidity measured inside the plastic house (Figure by authors)

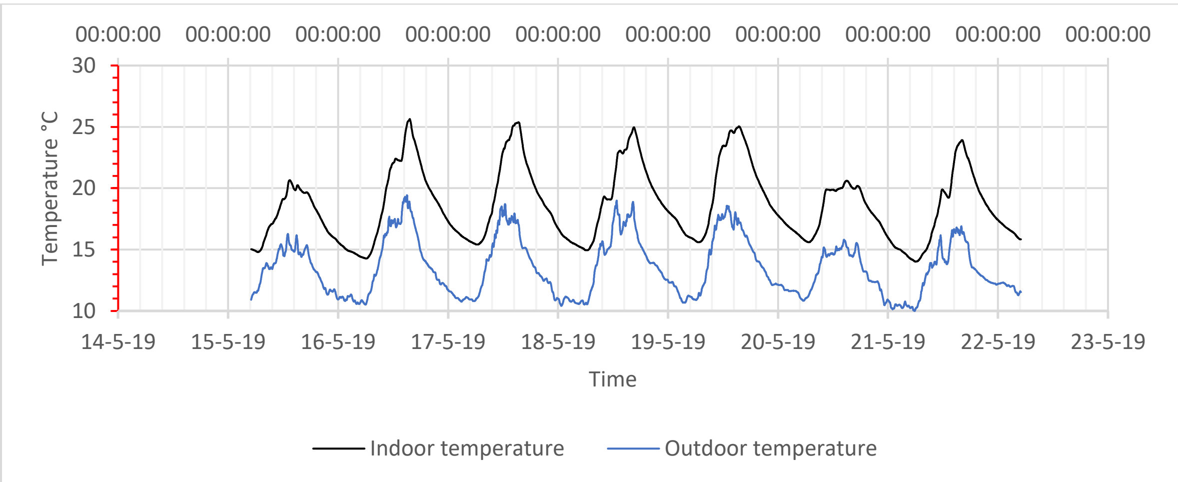


Figure 48: Indoor and outdoor temperature inside and nearby the plastic house (Figure by authors)

9.3 Analysis

When the highest temperature is reached indoors, the outdoor temperature is also the highest. This is not strange since it is a light construction that transfers heat and cold rapidly. The difference in temperature indoors and outdoors is approximately the same, 5°C, during all 24 hours of the day. The measurements show a clear difference between the two houses. The plastic house meets the comfort requirements considerably better than the brick house. This can be a pure coincidence as the measurements have only been in progress for a shorter time, a longer measurement period would result in more reliable values and results. Beyond this, one can still see that the indoor climate is not within the comfort requirements throughout the whole day. The nights are well below the comfort zone while the days meets the requirements. Another noticeable pattern is that the relative humidity is mirrored against the temperature, which is considered to be a standard behaviour.

10 Discussion and conclusions

In this chapter the pros and cons, suggestions of use, improvements and proposition of further investigations for the plastic bricks will be discussed. To prevent any misunderstanding, the term brick only refers to the plastic brick in this chapter.

10.1 Advantages of the plastic material

According to the authors of this thesis, sustainability is the main factor that distinguishes the plastic material from other materials, especially when it comes to ecological sustainability. Plastic waste keeps increasing and recycling it into a building material could be a solution to prevent this worldwide problem. As plastic waste is commonly associated with countries and regions with widespread problems of poverty, this solution could have a great impact on the above-mentioned issues and influence the ecological as well as the social sustainability. The fact that it is a solution that does not demand great knowledge in construction and can be built by the homeowners or the community, also contributes to social sustainability. Further, the solution of recycling a material instead of producing a new material can be economical if the proper waste management system is available and if there is a sustainable source of plastic waste.

When constructing a new building, the plastic material is a cheaper option than masonry. Since this is a concept under progress, it will probably be even cheaper if the current modest production develops into a large-scale production. The cost of labour and construction will also decrease if the concept gets more standardized.

10.2 Issues and challenges of the plastic material

The large thermal expansion coefficient and the probability of cracks appearing between bricks when exposed to diagonal pressure is considered as the biggest issue of the construction, due to the gap it creates between bricks. First and foremost, the movement of the bricks limits its area of use. For example, it will not be possible to use as a load bearing material in areas of fluctuating climate and temperatures due to its expansion. To prevent the changes of volume due to heat changes, the construction will need to be highly insulated. Further, if the bricks are used as fillers in a load bearing construction of e.g. metal, cracks will appear between the bricks and create a construction that leaks. Plaster and paint could work as an aid to tighten the construction from drafts through the wall. However, it is likely that the thermal expansion and the movements from expanding and contracting will create cracks in the plaster and paint. Equatorial areas with a climate that is fairly invariable during the seasons could be an area where the product could be useful as a low-income material or as a shelter used for catastrophic events where houses have lower requirements and needs to be built quickly.

We feared that the material, due to its dark colour, would be heated by the sun during sunny days and therefore create an indoor climate that was too warm to be considered as comfortable. From the measurements of the indoor and outdoor temperature it is clear that the problem is not that it gets too warm but instead, the opposite, too cold in the area of the measured houses. However, the measurements show that the indoor climate gets hotter in the plastic building than in the masonry building and therefore we stand by our hypothesis that the plastic material gets heated by the sun in greater extent than the masonry building. Since the thesis is based on tests made in a relatively cold climate, compared to the rest of Colombia, we need to point out that it could face problems if constructed in warmer and more humid areas, e.g. the Caribbean coast or Amazonas.

As for properties in strength, the plastic material is equal to clay bricks and masonry in many aspects and deviant in some. The biggest distinction is the structure and how it behaves when failing. Clay bricks is a strong and brittle material but breaks instantly while the plastic material stretches and fails slowly. Due to this fact, it could be used in seismic areas to prevent sudden

collapses of bearing structures and therefore prevent fatalities caused by falling objects.
In May of 2019 when this thesis is written, the bearing structure of the plastic material has not yet been approved by the authorities of Colombia, which is an indicator that it still has flaws that needs to be improved.

10.3 Suggestions on the best way of using it

We consider that the concept could be used with some modifications. Below, we list some areas of use for the material as it is today:

- Housing:
  - As a solution to decrease homelessness
  - In areas with an abundance of plastic waste
  - In areas with high risk of earthquakes
  - For low-income in equatorial areas with stable temperature
- Shelters for refugees
- Temporary buildings such as construction site offices.
- Smaller storehouses or composts in gardens

10.4 Improvements

Even if the concept could work in some cases, it is recommended that development of the material is proceeded. A list of possible solutions and improvements is listed below:

- Create bricks that interlocks in the short, vertical side with e.g. a hook or a grooved profile. This could prevent or reduce cracks between bricks as a consequence to heat expansion. (Fig. 49)

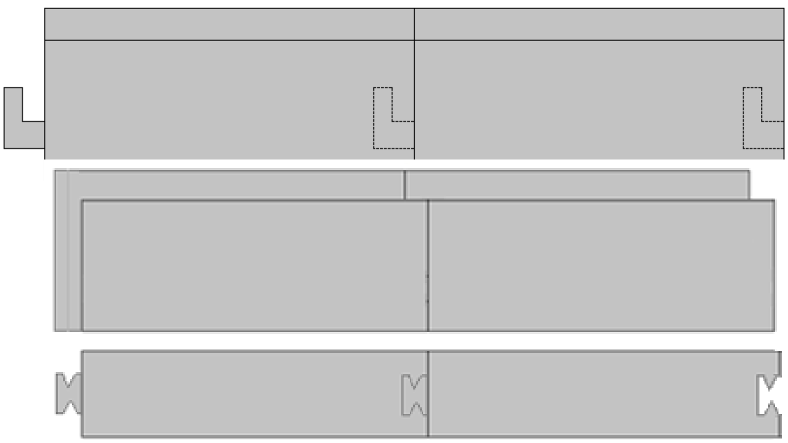


Figure 49: Brick with a grooved profile (Figure by authors)

- Create new shapes of the same material to substitute concrete e.g. walking tiles, smaller foundations for decking.
- Construction used under water where it is not affected by temporary temperature changes, salts, minerals and corrosion. Due to a relatively low density, about half the value, an anchor-like structure could be used to prevent floating.

10.5 Further investigations

As this thesis is an overall review of the plastic material and its properties, it has not been possible to investigate all properties. Therefore, some further investigations would be interesting to conduct:

Measurements of the plastic brick's compression strength proved interesting differences between bricks with holes and bricks without holes. These values could be a coincidence and a result of too few and inadequate measurements. It could also be a result of different production processes. Due to insufficient knowledge about the production process, the authors decided not to speculate further, but point out the issue and leave it open for investigations made in the future. In best case scenario, the reason could lead to improved production process for the bricks without holes.

Since this material is a product from a company with high production secrecy, the exact content of the bricks is unknown due to ongoing patent. The thesis is based on results of actual investigations and tests. To evaluate the results further and draw conclusions, the content of the bricks would be of great use. The company has restrictions on what information they present, which we consider somehow strange. The basics such as investigations on its content should be shown to make sure it's a sustainable product. This could easily be done with a heating-test. The test would be conducted in increasing stages of heating. During the test, the material will be scrutinized to detect melting points of different plastics and further, the specific plastic type can be determined. It will also show if the plastic component has been blended with any fillers or stabilizers, such as talc or any hazardous substances.

During the investigations of the material a pungent smell from the plastic bricks was noticeable. The smell clearly came from the material, but the reason of the smell could not be determined. Either, the smell could be an outcome of the sealed transport from Colombia to Sweden, or it is caused by emissions from the plastic waste used in the production process. Plastic materials often emit substances in larger quantities than many other building materials. As this material is recycled from different types of plastic waste, there is a risk that the emissions could be harmful for the residents. Regardless of the reason to why the smell has occurred, it is grounds enough to make further investigations on the emissions.

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12 Appendix

According to Build Changes previous twelve retrofitted houses, Bogotá in 2018, the total cost was approximately 351,438 COP/m2 (1020 SEK), including materials and labour (Table 16). However, the cost does not only cover the seismic strengthening of the house, it also includes additional work that increases the habitability criteria of the urban standard (Build Change, 2018).

Anexo No. 2. OBRAS DE REFORZAMIENTO Y MODIFICACIÓN - CONSTRUIDAS POR BUILD CHANGE					
No.	Nombre Propietario	Presupuesto Inicial General	Presupuesto Final General	Área m2	Costo Final / m2
1	Maria Amalia Suarez	$21,548,559	$26,040,778	63.6	$409,446
2	Maria Pilar Bohorquez	$17,951,688	$22,581,193	46.75	$483,020
3	Isabel Martinez	$19,613,486	$21,134,676	73.2	$288,725
4	Gabriel Virguez	$19,603,200	$19,814,949	60	$330,249
5	Sandra Camargo	$23,180,851	$24,153,720	60	$402,562
6	Mario Camargo	$27,742,234	$31,460,427	66	$476,673
7	Rosa Maria Diaz	$26,441,189	$31,585,084	147.66	$213,904
8	Maria Consuelo Vasquez	$19,547,409	$22,879,449	92.36	$247,720
9	Edelmira Rodriguez	$19,382,443	$22,366,001	72	$310,639
				Mínimo	$213,904
				Máximo	$483,020
				Promedio	$351,438

Table 15: Cost of retrofitting houses (Build Change, 2018)

Table 2 Density, thermal resistance and specific heat for cavities, hollow blocks, roofing and cladding materials, soils

Material	Thickness (mm)	Resistance (R) [a] (m^2K/W)	ρ (kg/m^3)	Spec. heat (Wh/kgK)	Source
Cavities					
unventilated airspace[b]	5	0.11	1.2	0.28	1,4
	10	0.14	1.2	0.28	4
	20	0.16	1.2	0.28	4
	50–100	0.17–0.18	1.2	0.28	1,4
Hollow blocks (masonry)					
burnt clay					
1 cavity in thickness	50	0.09	1100	0.26	2
2 cavities in thickness	100	0.20	1000	0.26	2
3 cavities in thickness	150	0.27	1000	0.26	2
3 cavities in thickness	200	0.33	900	0.26	2
4 cavities in thickness	200	0.36	1000	0.26	2
4 cavities in thickness	250	0.42	900	0.26	2
5 cavities in thickness	250	0.47	1000	0.26	2
6 cavities in thickness	250	0.51	1000	0.26	2
6 cavities in thickness	300	0.57	1000	0.26	2

Table 17: Full table of heat resistance for hollow block masonry (Johansson, n.d.)

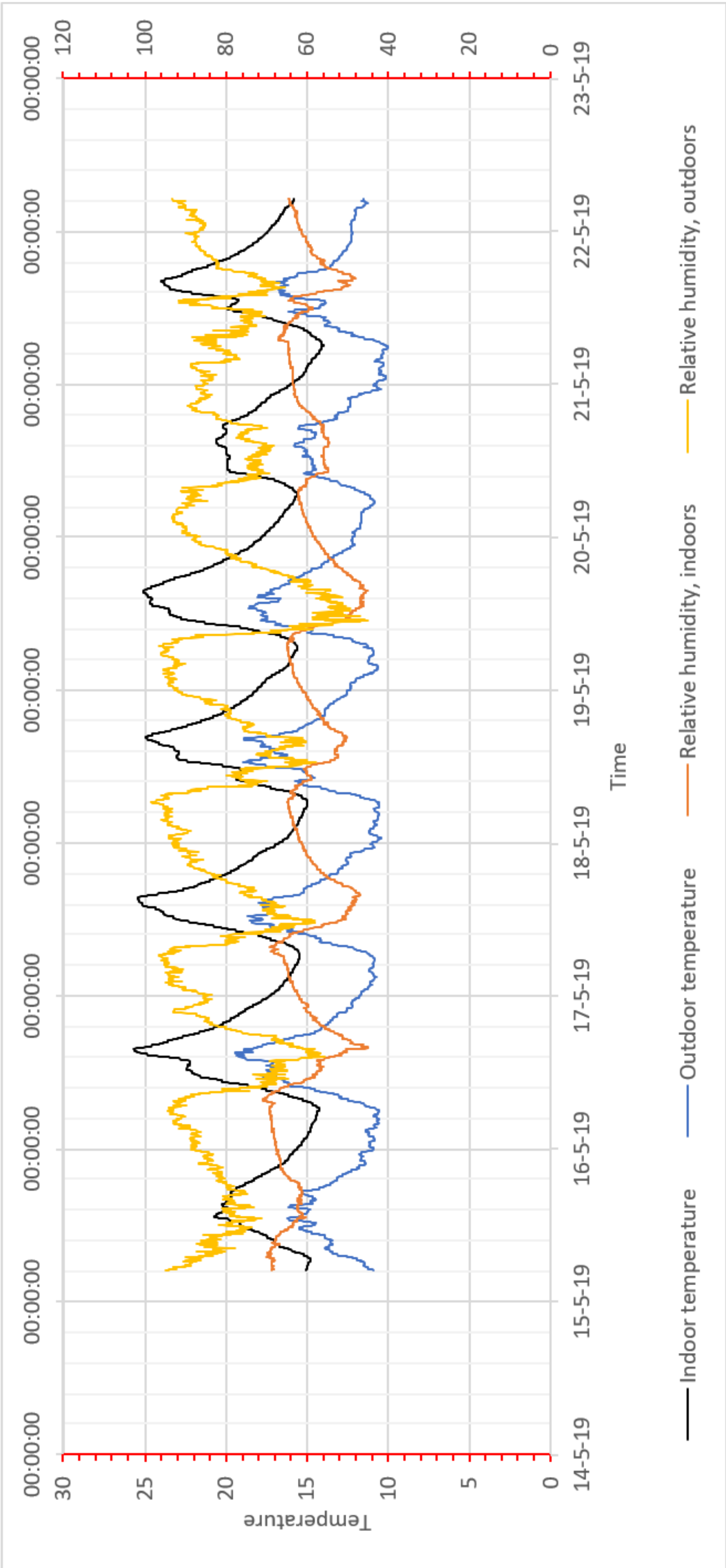

Figure 50: Temperature and humidity from the masonry house in Usme, Bogotá and the plastic house (Figure by authors)