CHALMERS
UNIVERSITY OF TECHNOLOGY



Quiet and Alternative Materials from Palestine

A Comparative Study of the Acoustical Nature between Typical and Alternative Building Materials from Palestine

Master's Thesis in the Master's Programme Sound and Vibration

MAY HANNA

Department of Civil and Environmental Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015

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Abstract

A study on building acoustics of materials used in Palestine has not been made yet, neither for the typical and most commonly used materials, such as hollow concrete blocks, nor the materials which are locally produced from raw elements found in the earth crust.
In the context of political and economic instability, the shift towards building with earth-based materials is seeing future. It is coming as a result of defying the unstable import flow of cement, which is tightly related to the political situation and hence influences the quality of the building industry in general.
The aim of this research is to offer a starting point for the acoustic assessment of two types of alternative materials, Compressed Earth Block and Adobe Block, via a comparative study between them and typically used materials, especially hollow concrete block of different thicknesses.
The results, which are obtained by field measurements of airborne sound insulation in existing buildings in the West Bank and Gaza, show that the potential in sufficient sound insulation is achievable for alternative materials, however the tests taken in this research suggest they are still in need of more development.

Keywords: Building Acoustics, Airborne Sound Insulation, Conflict, Palestine, Gaza, Cement, Compressed Earth Block, Adobe

مواد عازلة للصوت وبديلة من فلسطين ـ
بحث مقارن حول الطبيعة الصوتية بين مواد البناء التقليدية والبديلة في فلسطين
اطروحة الماجستير في برنامج الأصوات والارتجاجات
مي حنا
كلية الهندسة المدنية والبيئية
شعبة الصوتيات التطبيقية
مجموعة الصوتيات المعمارية
جامعة شالمر للتكنولوجيا

Arabic Abstract - الملخص

لا توجد اي دراسات في الوقت الراهن حول الصوتيات المعمارية لمواد البناء المستخدمة في فلسطين، وذلك ان كان بخصوص المواد التقليدية والمستخدمة باستمرار مثل الطوب الاسمنتي المفرغ، أو بخصوص المواد المصنوعة محلياً من قشرة الأرض.
تشكل فكرة التحول نحو البناء باستخدام المواد الطبيعية، في ظل عدم الاستقرار السياسي والاقتصادي، أملاً لنهجية مستقبلية. هذه نتيجة تحدي ازمة الاسمنت والمشاكل المتصلة باستيراده، الأمر المتعلق بالوضع السياسي والذي يؤثر على جودة القطاع الإنشائي بشكل عام.
تهدف هذه الاطروحة لايجاد نقطة البداية لتقييم الميزات الصوتية لصنفين من أصناف المواد البديلة وهي الطوب الطيني المضغوط وطوب اللبن من خلال بحث مقارن بين هذه المواد والمواد التقليدية، بالأخص الطوب الاسمنتي المفرغ بسماكاته المختلفة.
أشارت نتائج الدراسة والتي اتخذت منهجية القياسات الميدانية لعزل الصوت المحمول جواً والتي نفذت في مشاريع قائمة في الضفة الغربية وقطاع غزة، ان امكانيات المواد البديلة في الوصول الى الحد الأدنى من عزل الصوت مستطاعة، لكن الاختبارات التي اتخذت في هذا البحث تشير إلى أنها لا تزال في حاجة إلى مزيد من التطوير.

كلمات رئيسية: صوتيات معمارية، عزل الصوت المحمول جوا، أزمة، فلسطين، غزة، اسمنت، طوب طيني مضغوط، طوب اللبن، طوب طبيعي

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1. Introduction

The situation in Palestine is quite unique because of the extent of political intervention in the development of economy, technology and industry. It is not yet comparable with today's Europe in terms of innovative construction techniques and efficiency of building materials which is why this research is mostly relevant to Palestine. Some of the discussions in this report are pertinent to the inceptive research papers on building acoustics written in Europe between 1940's and 1980's, however the context is focused on the needs of Palestinians in terms of life commodity, cost efficiency and counter-war sustainability requirements of today.

1.1. Purpose

This paper is intended for readers who have a basic knowledge in acoustics and/or building. The purpose of this study is to establish a starting point for acoustics in Palestine by comparing different models of hollow concrete blocks, which are the most commonly used building materials, with compressed earth and adobe blocks, which are the alternative materials used in the present.

If cement is to be replaced by alternative materials of the same types studied here, the question to be answered is whether these materials qualify to the minimum recommended sound insulation values for future buildings in Palestine, and how they can be improved from the acoustical point of view.

The results in this research paper are meant to be based on field measurements of airborne sound insulation in existing projects built using the aforementioned materials. Given that the measurements are not laboratory based, and therefore lack information such as the exact construction details and physical material properties, the aim is to obtain conclusions based on deriving trends from a number of field tests.

1.2. Limitations

The materials tested in this report represent the most commonly used ones, however this does not implicitly mean that all frequently used materials are tested. This report is limited to hollow concrete blocks with three different thicknesses; 10 cm, 15 cm, and 20 cm. Since the alternative materials studied in this research are based on soil, it is not

necessarily so that all soil types are covered either. The four types of blocks studies are based on soil from Jericho, Gaza and old and new soil from Fasayel.

Data concerning the materials at hand is obtained from accredited tests where available, other data is measured where possible. Precise data, however, does not cover all the materials used in this research, some was assumed from tables of similar materials or approximated based on sound insulation simulation tuning. The data considered is density, ρ, Young's modulus, E, and loss factor, η.

The theory provided in this study is also limited to a general derivation of airborne sound reduction formulas from the view point of the material physics, which acts as the corner stone for the theoretical results, and the view point of energy balance, which explains how the results were obtained from field tests. Theories on sound waves in solids, sound radiation and generation, and sound behavior in flanking and special circumstances will be mentioned only briefly.

Flanking is a problem in most of the measurements, and based on listening carefully during the tests, the main source of flanking is power which had been transmitted as airborne sound through leaks, especially through weak doors, windows, cracks in the wall and electricity cable openings. The sound transmitted through flanking elements was noted but no further action was taken to investigate the input to the final result. The reason for not investigating further to correct for flanking is the lack of information on data such as the type of junction, in addition to impracticality, cost and the unattainability of proper measurement equipment for the intensity measurements recommended in ISO 140-4.

1.3. Obstacles

Making measurements in existing projects in Palestine required transportation between the West Bank and Jerusalem, and bringing the equipment was a hassle because of the strict inspections at the Israeli checkpoints. For this reason the number of tests was not large enough to make a statistical analysis.

The equipment used to obtain the results are limited, especially those in Gaza. The impossibility of entering Gaza forced me to have the measurements done by someone else, to whom the setup was explained in full detail. The equipment used for those tests was primitive and therefore the results were studied with more care. A more thorough explanation will be found in Chapter 5.

In one of the measurements (Al Dyouk Restaurant - Jericho) the power to feed the equipment was borrowed from a small generator attached to the car battery, using long, unbalanced cables, due to electricity shortages in that area. Even though these are uncalibrated measurements, it was hard to determine whether the conditions throughout the whole experiment were stable.

2. Background

Palestine has been occupied by Israel for the past 67 years, which severely affects its natural development in technology and industry. In particular the building industry which is redefined by political restrictions, and which is entirely dependent on imported cement, a large portion of it is from Israel. One of the tools to strive toward a more stable economy and hence a more natural development in the technological and construction sectors, is to focus on sustainable building instead of depending on trade. Substituting cement products with locally made ones is one of the many aspects of sustainability, however, this type of shift requires the involvement of dedicated professionals who are credible to devise parallel quality of performance in addition to a number of other attributes to stand in the face of competitiveness and hence qualify as alternative to cement.

There are several initiatives in the West Bank and Gaza [Al-Monitor, 2014] where earth elements are being carefully inspected for their chemical composition to produce construction bricks, like Adobe blocks and Compressed Earth Blocks. These blocks are tested continuously for their usability and quality by the material designers. At this point, the role of the acoustician is to test how well these materials are performing from the acoustical point of view in the current building context in Palestine, and how it can be possible to improve it, which will be discussed throughout the report.

The aim of this chapter is not to victimize nor justify the low living standards of the Palestinians rather it is to highlight the obstacles standing in the way of a natural growth and development, putting the reader in the context of today's Palestine.

2.1. Brief Historic Overview

During the First World War the promise of a national home in Palestine, also known as the Balfour Declaration, was given to the Jews, which was welcomed and promoted by the already established Zionist movement in Europe. During that time the British were gaining a quasi-colonial authority over the majority-Arab populated Palestine, while the Ottoman Empire was weakening in control. Conflicts over land possessions and dispossessions between Arabs and Jews were starting to surge, and with the aspiration of self-rule, but with a lack of a leadership, the Palestinians found themselves clashing against two poles; the increasing Jewish migration and the British colonization.

World War II and the rise of Hitler to power brought about a massive persecution

of Jews in Europe, which resulted in an extensive growth of the Jewish population in Palestine. In May 1948 the British withdrew and the Zionists took control which led to the first Arab-Israeli war, in which hundreds of thousands of Palestinians were expelled from their original cities, towns and villages. Israel was established on over 77% of historical Palestine. What was left for the Palestinians is two detached fractions known as the West Bank and the Gaza strip, the former annexed by Jordan, the latter occupied by Egypt. Another war escalated in 1967 in which Israel seized the West Bank from Jordan and the Gaza Strip from Egypt, only to withdraw partially after a UN intervention but pertaining military administration, and fractioning the West Bank into Areas A, B and C which will be described later in more detail.

Since 1967 the occupied Palestinian territories (oPt) have been largely under Israeli control where basic civil rights are denied to the Palestinian inhabitants, with their homes frequently demolished, land confiscated, civilians detained even without trial. Furthermore, violations of international law happen regularly, such as incidents that include the building of Jewish settlements in the oPt [Beinin, Hajjar, 2014].

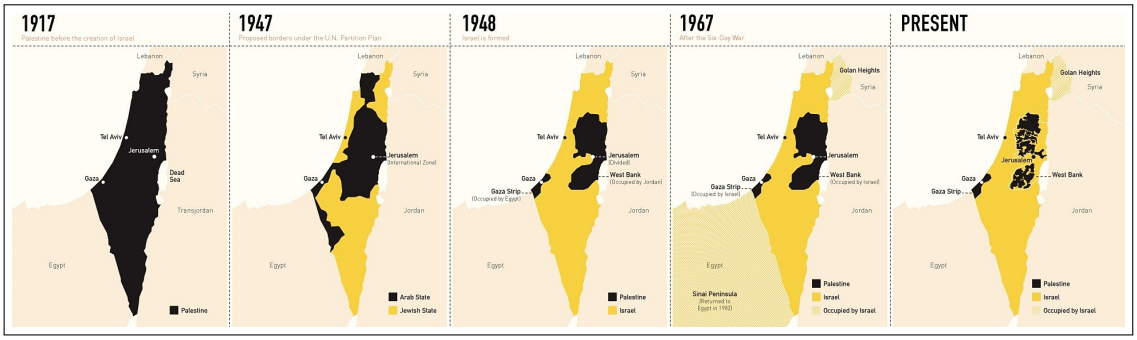


Figure 2.1.: Geographical changes on historic Palestine. **source: smpalestine.com**

2.2. Economic Challenges

The economic situation in Palestine has been passing through several stages where impositions or agreements by or with Israel played a primary role in the shaping of its situation; before the Oslo agreements, during the temporary period of self-rule and today. Imposed tariffs on the Palestinians were four times larger than their value before the 1967 war, also given that the Palestinian Territories are limited in the West Bank and Gaza Strip, Israel has furthered the limitation to Areas A, B, and C as explicitly explained and agreed upon in the Oslo Accords in 1993 and 1995 causing a yet more challenging situation for exchange and trade. In addition to that, foreign aid and donations seem to have exacerbated the economic status placing Palestine under much debt.

The first self-ruled Palestinian economy started in May 1994 [Naquib, 2015], with the establishment of the Palestinian Authority agreed upon in the Oslo Accords. The agreement that incorporated the Paris Protocol, a "contractual agreement [that governs] the economic relations between the two sides, and which will cover the West Bank and Gaza Strip during the interim-period". The self-government failed to reach the goals of building up a healthy independent economy. This was shown in rising levels of unemployment and poverty, decrease in trade, and in other general economic conditions in the years after the predefined five years of self-rule. Today, at both the political and economic levels, no matter how far the negotiations go in peace agreements, the growth and development of the Palestinian economy are prevented for several reasons; the increased rate of land confiscation by Israel, building and expanding Jewish settlements in Palestinian lands [Naquib, 2015], as well as severely restricting any Palestinian economic activity in Area C of the west bank, which is the largest part of the West Bank, the richly endowed with natural resources and most contiguous, compared to Areas A and B that are smaller territorial islands [World Bank, 2013].

The Palestinians have received over $23 billion in aid since the signing of the Oslo Agreement in 1993 [Al-Shabaka, 2013]. The World Bank, which shapes the foreign aid policy towards the Palestinians, had certain goals with the aid; promoting peace, sustainable growth and an independent Palestinian state. It is safe to say, that if one were to look outside of Ramallah, the economic capital of Palestine, none of these goals have been achieved. The reality is as follows; in 2010, half of the Palestinians were living in poverty, half of Palestinians suffered from food shortages, and unemployment was at 47% in Gaza and 20% in the West Bank. The accomplishment of Palestine's Finance Ministry was shown in economic growth (9.3% in 2010), but unfortunately for the Palestinians this growth was not based on a developing economy, but completely on foreign aid.

2.3. Land and Building Context in Palestine

The development of the building industry is affected as much as other economic and civil sectors in Palestine due to the political situation, despite the fact that it is one of the largest economic sectors in the West Bank and Gaza. Much of the land has restrictions on the movement of people, on exchange of goods and on access to natural resources which severely stalls aspirations of collaboration within different Palestinian cities and almost completely halts exchange of materials, techniques and technologies with other countries.

As stated previously, the Palestinian territories of the West Bank are divided into three sectors; Area A, which is under full Palestinian civil administration and security, Area B which is under Palestinian civil administration and joint Israeli-Palestinian security, and Area C which is under full Israeli civil administration and security. Gaza's

borders are controlled by Egypt and Israel and even with the governance of Hamas, Israel still has control of most basic civil needs. In some of these areas, building permits are issued from Israel.

Finally, tens of thousands of illegal Israeli settlements were built and are still built within areas designated for Palestinians, especially within Area C. This exacerbates the fragmentation of Palestinian land and causes impediment to its development [Farsakh]. For the record, about 27000 Palestinian homes and other structures were demolished in the West Bank and East Jerusalem Since 1967 [ICAHD].

2.3.1. West Bank

The total area of the West Bank is around 5600 km^2 and its total Palestinian population as estimated by the Palestinian Central Bureau of Statistics (PCBS) is 2.8 million. It is worthy of noting that the West Bank is home to over 700,000 refugees who fled other war zones throughout the history of the conflict, and they reside in 19 refugee camps which are not subject to any regulatory laws because they were treated as temporary zones and their related administrative complexity goes beyond building and urbanization.

Areas where the Palestinian Authority has control over land administration and planning is summarized in Areas A and B, whereas area C is under Israeli control.

Area A and B

Most industrial centers with a growth potential and major cities like Nablus, Hebron and Ramallah are encompassed within Area A of the West Bank (WB) which comprises 18% of the WB's total area and lodges 46% of its population. Area B consists of the rural parts of the West Bank including villages and small towns. It comprises 21% of the area and holds 36% of its population [Al-Jazeera].

Building laws and regulations are issued by Palestinian authoritative representations, passing through executive and judicial authorities like ministries and governmental organizations, legislature and finally through the parliament, each reserving responsibilities concerning the issuing of laws and regulations, passing them on and ensuring their functioning and effectiveness [Tuffaha, 2009]. The problem in these areas is that they are "densely populated and built-in", which results in a dire "need of extra land to expand housing and make it more affordable" [World Bank, 2013], leading to an increasing attention on construction land in Area C.

Area C

This is the largest among the three areas and the only continuous area within the West Bank. It comprises 61% of the area and 18% of the Palestinian population. It is rich

with natural resources such as water, agriculture fertile land, minerals, stone for mining and quarrying, construction industry potential, which are essential as infrastructure for Palestinian industries. Only 1% of this area, however, is available for construction for Palestinians due to restrictions enforced by Israel [World Bank, 2013].

Studies [OCHA, 2009] show that less than 6% of the total permits requested by Palestinians for building in Area C had been granted between 2000 and 2007, and the reasons for rejection are stated below:

- Land designated for Israeli settlements and "state land"
- Areas for military use and training
- Barrier or buffer zone
- Nature reserve

In addition to that, the application for a permit requires several proofs, some of which are deemed impossible for some Palestinians due to other consequential laws enforced by Israel, like the law of the "absentees". However, due to the growing Palestinian population, the demand for building housing units, infrastructure, commercial and social buildings etc. is increasing. In light of these restrictions, Palestinians are compelled to build without issuing permits, resulting in a high risk of demolition. Over 2000 homes had been demolished in Area C between 2011 and 2015 [OCHA, 2009].

The problems shaping Area C are reflected in East Jerusalem, as can be seen in the section below.

2.3.2. Jerusalem

East Jerusalem is mainly Arab inhabited while West Jerusalem is mainly Israeli even though there is not a distinct segregation barrier on the ground between East and West. The status of Jerusalem remains debatable since Israel annexed it during the war in 1967. Jerusalem is one of the pivotal issues of the conflict but most of it is under Israeli rule and had been proclaimed as the Israeli capital to date since 1949. According to the PCBS the Palestinian residents of Jerusalem mount to roughly 300,000 in 2015, most of whom were offered Israeli citizenship after the 1967 war but many have refused and are today only *residents* of Jerusalem.

Similarly to Area C, Palestinians struggle to obtain permits which results in 33% of units which are built without issuing them, risking demolitions or threats. Studies [OCHAJ, 2012] show that over 300 buildings were demolished in East Jerusalem between 2001 and 2015.

Renovation is yet another issue facing Arabs especially in the Old City of Jerusalem and East Jerusalem, and it can also be noticed in Arab inhabited areas of Israel. The

procrastination and stalling of permissions to renovate, according to the residents of Jerusalem [Wold Bulletin, 2013], is causing houses to degrade.

2.3.3. Gaza

The area of the Gaza Strip is around 360 km^2 with a population of 1.8 million people as of 2014 making it one of the most densely populated areas of the world.

Despite the withdrawal of Israel from the Gaza Strip in 2005, Gaza remains sieged and under surveillance by Israel's high-tech military, despite not having any troops on the ground [Sperotto, 2010].

The crisis in Gaza involves strict Israeli control over food, household items, reconstruction materials, fuel, agricultural, fishing and medical materials, among a long list of controlled entry items into Gaza [Wiki, 2011] [Amnesty].

Construction materials used to make up over half of the entry bulk before the blockade, and until today the import of those materials is restricted to 0.05% of its amount during that time. An official document in the Israel Ministry of Foreign Affairs website [MFA, 2012] recalls the restriction on the following building materials:

- Portland cement (bulk or bags or drums).
- Natural aggregates, quarry aggregates and all foundation materials.
- Prepared concrete.
- Concrete elements and/or precast and/or tensed concrete.
- Steel elements and/construction products.
- Concrete for foundations and pillars of any diameter (including welded steel mesh).
- Steel cables of any thickness.
- Forms for construction elements of plastic or galvanized steel.
- Industrial forms for concrete pouring.
- Beams from composite materials or plastic with a panel thickness of 4mm and thicker.
- Thermal insulation materials and/or products excluding roof tiles, plaster/mortar glue, mosaic tiles, building stone/coating stone/exterior stone.
- Concrete blocks, silicate, Ytong or equivalent (of any thickness).
- Building sealing materials or products which include Epoxy or polyurethane.

- Asphalt and its components (bitumen, emulsion) in bulk or in packages of any sort.
- Steel elements and/or steel working products for construction.
- Elements and/or products for channeling and drainage from precast concrete with diameters of over 1 meter.
- Trailers and/or shipping containers.
- Vehicles except for personal vehicles (not including 4X4 vehicles), including construction vehicles.

2.4. Legislation

Acoustics is a ripe area for exploration in Palestine due to the absence of experts in this field and the lack of regulations regarding it. Based on conversations with a number of architects, engineers, contractors and project managers, foreign consultants are hired to participate in tendering and planning for all types of buildings where an expert opinion in acoustics is required. In addition to that, the awareness on noise related issues is arid among them and especially amongst the population. From the reasons stated it can be presumed that the area of acoustics is one which requires cultivation and formation in the legislative aspects.

All codes and legislations need to pass through a series of technical and administrative associations, ministries and authorities before they are established and passed to the working sector.

Some guidelines by the Palestine Engineers Association are established on sound insulation in residential and educational buildings in the "Green Buildings Guideline - State of Palestine" booklet, which specifies the allowed limits of the sound transmission class for exterior and interior walls and floors. The guideline allows a minimum of 50 dB STC for both exterior and interior walls and floors, in addition to a minimum impact insulation class (IIC) of 56 dB. The guideline recommends that measurement results should be presented along with the tender, or if not possible, the detailed plans of such partitions with the indication of their insulation classes [PEA, 2013]. This guideline is the corner stone for establishing a Palestinian building code, and has not been made into a regulation yet, but the Association is working together with the Ministry of Local Government and the Ministry of Public Works on the legislation of those recommendations.

According to the Palestine Standards Institution, almost all standards, specifically the ones concerning acoustics, are adapted from the ISO standards. It is noted that both American and International standards are referred to in the different organizations, which means that the guidelines need further revision by the respective parties.

3. Materials

3.1. Typical Building Materials

3.1.1. Concrete

Concrete is a cement based material, mixed with water, aggregates, sand and other components in known and predefined proportions which can be poured into molds to solidify in shape, or poured on site. Other forms of concrete are prefabricated and purchased for large scale projects.

Concrete forms the basic component in structural building for its malleability, compression strength and other geophysical properties that optimizes it for load bearing in multiple story buildings.

As already mentioned, the cement supplies are completely imported and the majority of it is from Israel (80% from Israel while the rest is between Jordan, Europe and Egypt [ECB, 2002]). Some issues concerning the unreliability of the product rose throughout the years, mentioning a few of them here. As mentioned the majority of cement is imported from Israel, with a trade flow and prices which tend to have impulsive changes caused by prioritizing the Israeli market [MA'AN, 2014-01]. There are 65 factories in the West Bank specialized in the manufacture of concrete mix, only 20 of which have quality certificates [WAFA, 2014]. Some concrete is mixed and blended on site, and some contractors claim that the proportions are made in such a way to save cement. Other problems arise in Palestine such as the reduced weight of cement per bag which arrives to the Palestinian market; some news agencies reported the deficiency of 3 kg of cement of originally taxed 50 kg [MA'AN, 2014-04].

These facts, to a certain extent jeopardize the concrete quality in Palestinian buildings and makes the evaluation process more precarious for other post-construction testing, one of which is acoustics.

3.1.2. Hollow Concrete Block

Abbreviated as HCB, this type of block is the most commonly used in Palestinian constructions especially for its cost efficiency. It is made from concrete in addition to some gravel or other types of aggregates or air-entraining agents.

There are several thicknesses for the 40x20 cm mold in which hollow concrete block is produced, the most common thicknesses are 7, 10, 15 and 20 cm. The percentage of

openings in the brick are also variable depending on the production factory. Some of the main types are shown in Table 3.1, and in Figure 3.1.

Table 3.1.: Common Hollow Concrete Block Dimensions, Densities and Air Space [ECB, 2002]

Dimension 40x20xd [cm]	7	7	10	15	20	20	20
Density [kg/m^3]	1607	1428	1375	667	875	1125	1350
Air Space [%]	40.1	40.1	40.2	46.9	47.8	47.8	47.8



Figure 3.1.: Different types of Hollow Concrete Blocks

Plaster

Plaster is used to coat the wall of blocks, which is the intermediate layer between the blocks and the paint. In most circumstances the thickness of the plaster varies between 8 and 10 mm, however larger thicknesses are often encountered. It is ofter based on cement or gypsum, unless lime or mud are used as an alternative. Physical properties of typical plaster can be found and summarized in Table 3.2 below.

Table 3.2.: Typical Plaster Densities [ECB, 2002]

Material	**Density** [kg/m^3]
Cement-based plaster	1850
	1570
Gypsum-based plaster	1280
	1120

3.2. Alternative Building Materials

Since a Palestinian cement factory has not been established to guarantee the continuous flow of cement into the Palestinian market without the high dependence on Israel, an alternative to cement given the situation of today is to profit from what's available of natural resources from the earth and build using clay and mud.

In addition to the economic and political advantage of building with alternative materials, this method is highly sustainable and almost completely recyclable, it inherently reduces the carbon footprint on the planet, with other virtues such as thermal insulation and flexibility in design and functions.

3.2.1. Compressed Earth Block

Abbreviated as CEB, this type of block is the daughter masonry element of adobe, born as a result of the industrial revolution. The advantage of CEB is that it can be used as a substitute for imported materials thanks to the repeatability in its production and the stability of its properties, rendering it suitable for standardized building requirements [Rigassi, 1985]. This means that it can be used in a large array of occupancies.

The soil suited for building is usually in the bed-rock of the earth due to the small quantity of organic material in its composition. This part of the earth contains mixed gravel, sand, silts and clay, the latter not being very suitable in the production of CEB. Gravel and sand are the most stable, exhibiting least alteration to weather impacts such as humidity or dryness, with a major difference that sand displays cohesion when wet. Silts combine mechanical properties of both sand and clay, mainly due to having particle size which mediates between the two. It is still usable for producing CEB despite the fact that it changes slightly in volume due to weather exposure.

After careful examination of the soils in the ground where the brick is to be created from, and the evaluation of their properties and suitability, the earth elements are combined and mixed with stabilizers and water in predefined proportions and compressed using manual or automatic press machines and left to dry without the use of fire.

Stabilizers are either cement or lime based, and since lime is naturally found in the earth's crust in the Palestinian region, the CEB's used in this context are largely lime-based, even though it takes a longer time to bind with respect to cement.

Geo-technical and material properties obtained from test results made on CEBs used in this study - which include absorption and bulk specific gravity, compressive strength, modulus of rupture, liquid limit, plastic limit, plasticity index of soils, and particle size analysis of soils - suggest that it is possible to compare them with other materials, and it is possible to make a basic theoretical prediction for sound insulation.

3.2.2. Adobe Brick

The building tradition with Adobe blocks dates back to thousands of years, and as primitive and basic as it sounds, it is still in use until today in many places around the world, especially in dry climates. The technique is based on mixing soil with water and other elements such as straw and pouring them in molds, pressing them and leaving them to dry in the sun. The blocks examined in this study were two types, the new block which is pressed using a locally-made hydraulic press machine, and the old block which was most probably not pressed, as shall be seen based on measurements in later chapters.

Jericho and the surrounding areas are known for the arid climate and they are suitable for adobe brick building. For the purpose of this study, the adobe blocks from the neighboring hamlet of Jericho, Fasayel, were examined; they are made by combining known proportions of soil, aggregates, straw and water with occasional (experimental) addition of cement as a stabilizer. Even though the proportions are "known" it is still difficult to obtain consistent properties of the final product. The reason for this is that the mixing is done by hand, where the margin of error is relatively high, in addition to that, the workers who are getting those jobs are usually unskilled despite the fact that they are given some training. An image of adobe blocks from Fasayel area can be seen in Figure 3.2.



Figure 3.2.: Adobe Blocks from Fasayel Area

4. Theory

Sound is transmitted in buildings through two main paths, the sound transmitted through air and the sound transmitted through direct or indirect structural vibrations. The first one is called Airborne Sound transmission and the latter is called Impact Sound transmission. The focus in this report is going to be on the airborne sound transmission.

4.1. Sound Waves in Solids

Even though this research paper is focused on airborne sound, the propagation of sound in solids, the transformation of wave types around edges and corners causing radiation, and the reduction principles of structure borne sound, will be briefly presented.

Sound propagation in solids includes many wave types, such as longitudinal, quasi-longitudinal, torsional, transverse, shear and bending waves. Not all these wave types will be discussed in this chapter it is just worthy of mentioning that behavior of sound is dependent on the type of wave, but shear and bending waves are the most significant for this study and will be discussed below.

Speed of sound in solids, especially when bending waves are considered, is frequency dependent. This phenomena can be analyzed by the wavenumber solution for bending waves in Equation 4.1:

$$k_B = \sqrt[4]{\frac{\omega^2 m''}{B'}} \tag{4.1}$$

where k_B is the wavenumber of the bending wave (ω / c_B), ω is the angular frequency, c_B is the phase velocity, m'' is the mass per unit area, and B' is the bending stiffness per unit length. The wavenumber is hence proportional to the square root of the frequency, and consequently the speed of sound (or more precisely the phase and group velocities) as well. Having a frequency dependent speed of sound in solids due to bending waves will be useful information to keep in mind in Section 4.2 when the phenomenon of the critical frequency will be introduced.

4.2. Sound Insulation

For walls that are consisting of a single leaf, the most important factors in determining the sound insulation properties are the mass per unit area, the bending stiffness, and the loss factor of the wall material [Kleiner, 2012].

The general behavior of the reduction index (transmission loss) in single panel partitions varies along the frequency spectrum, where at the lowest frequencies the panel is behaving like a spring dominated by the stiffness factor. It is followed by a region overshadowed by resonances with relatively steep dips and peaks depending on the amount of damping included in the system. The increase in transmission loss is thereafter steady in what is called the "mass law" region until the appearance of the critical frequency characterized by a noticeable drop followed by a steep and steady increase in transmission loss for higher frequencies. See Figure 4.1 for an illustration.

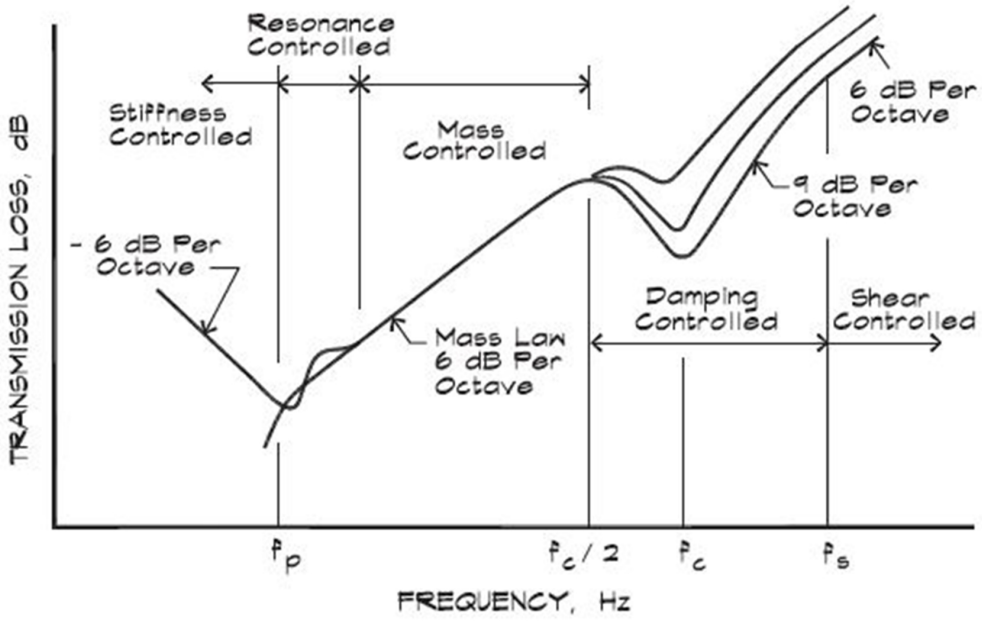


Figure 4.1.: Transmission loss behavior for a single panel wall [Long, 2006]

Not all parameters found in this illustration will be discussed, but it's worthy of knowing that f_P is the fundamental panel mode, $f_c/2$ is half the critical frequency, f_c is the critical frequency, and f_s is the shear limiting frequency.

The mass law is the primary and most used law for the approximation of the reduction index below the critical frequency, but before presenting it, the transmission of the incident wave through a wall will be briefly explained, starting with the absorption factor seen at the boundary of the wall by the normal incident wave, which is calculated

as in Equation 4.2 below

$$\alpha = \frac{4Re\left\{\frac{Z_g}{Z_0}\right\}}{\left\|\frac{Z_g}{Z_0}\right\|^2 + 2\Re\left\{\frac{Z_g}{Z_0}\right\} + 1} \tag{4.2}$$

where, Z_0 is the characteristic impedance of the air behind the partition ($\rho_0 c_0$), and Z_g is the resulting input impedance ($Z_0 + j\omega m$).

Assuming no internal energy losses, the transmission loss factor (transmission coefficient) τ would be calculated according to Equation 4.3

$$\tau = \frac{1}{1 + \left(\frac{\omega m''}{2Z_0}\right)^2} \tag{4.3}$$

where ω is the angular frequency and m'' is the mass per unit area. Therefore the reduction index in dB would be as per Equation 4.4

$$R_0 = 10\log\frac{1}{\tau} = 10\log\left[1 + \left(\frac{\omega m''}{2Z_0}\right)^2\right] \approx 20\log\left(\frac{\pi f m''}{Z_0}\right) \tag{4.4}$$

giving the simpler form (Eq. 4.5)

$$R_0 = 20\log(m'' f) - 42.5 \tag{4.5}$$

which is approximated by using the characteristic impedance (Z_0) of air at 20°C. This yields a reduction index which is dependent on both the mass per unit area and the frequency. The answer exhibits a 6 dB increase per octave or for every doubling of mass per unit area of the reduction index[Vigran, 2008].

It is more practical to view the reduction index for a diffuse field incidence rather than a normal incidence because it is closer to reality, since sound in general purpose rooms is diffuse (of course it is not ideal, but for the purpose of simplifying the math it is assumed to be so). Therefore the approximation for the diffuse field situation which yields better coherence with measurements at low frequencies, assuming even distribution of incidence angles and random phase (which defines a diffuse field), is given by Equation 4.6

$$R_d = R_0 - 5dB \approx 20log(fm'') - 47dB \tag{4.6}$$

where d stands for "diffuse field". That is an equation which will be encountered again in this report.

Most heavy and medium building partitions such as concrete and lightweight porous concrete walls have a critical frequency at around 500 Hz or below, which means that

the transmission loss behavior is typical of the steady increase in the post-coincidence plateau region, which will be explained after the understanding of the critical frequency (see "damping controlled area" in Figure 4.1).

To know the critical frequency of a partition, it is necessary to keep in mind the relation between the speed of sound in air and the speed of sound in the solid medium where bending waves are dominant. Remembering that that the speed of sound in solids is frequency dependent, there is one frequency where the two aforementioned speeds (phase and group velocities) are identical which is called the critical frequency and it is obtained by Equation 4.7

$$f_c = \frac{c_0^2}{2\pi}\sqrt{\frac{m''}{B'}} \tag{4.7}$$

where m'' is the mass per unit area of the material, and B' is the bending stiffness per unit length, see Equation 4.8 below to solve for the bending stiffness. It is therefore drawn that the critical frequency decreases with increasing bending stiffness.

$$B' = \frac{Eh^3}{12(1-v^2)} \tag{4.8}$$

where E is the Young's modulus, and v is the Poisson ratio, assumed to be 0.3.

The critical frequency is characterized by "acoustic transparency" meaning that the reduction index tends to be very low, depending on the angle of incidence. It can be approximated as in Equation 4.9 below

$$R_{d,fc} = R_d + 10log(\eta) + 8 \tag{4.9}$$

where η is the loss factor of the material, usually found for many common materials in tables [Kleiner, 2012].

The coincidence plateau seen in Figure 4.1 therefore is the set of frequencies arriving at different angles, at and around the critical frequency, which is characterized by a low reduction index.

In the frequencies above the coincidence region, the reduction index tends to have a steeper increase per octave. Measured data yield an increase by 9 dB per octave, and according to that, Cremer (1942) had derived an empirical approximation for the reduction index in that region, as can be seen in Equation 4.10:

$$R_{d,f>f_c} \simeq 20\log\left(\frac{\omega m_s}{2\rho_0 c_0}\right) + 10\log\left\{\frac{2\eta}{f_c}\left(\frac{f}{f_c}-1\right)\right\} \tag{4.10}$$

So in summary, the reduction index for single panel homogeneous walls, approximated for a diffuse field for the entire frequency range of interest is found in the set of equations 4.11:

$$R = \begin{cases} 20\log m'' + 20\log f - 47dB & f < f_c \\ R_d + 10\log\eta + 8dB & f = f_c \\ R_0 + 10\log(\frac{f}{f_c} - 1) + 10\log_{10}\eta - 2dB & f > f_c \end{cases} \quad (4.11)$$

Another wave type to keep into consideration especially for thick and heavy walls is the shear wave. There is a point at which the wavelengths in the wall start to fit in the thickness of that wall, and it can occur at low frequencies, and sometimes below the critical frequency. This results in a lower reduction index that what is expected by the mass-law. The theory behind this will not be shown here, but it is worthy of mentioning that the reduction index is expected to be around 6 dB lower in the region where shear waves are dominant [Long, 2006].

The frequencies considered in sound insulation of building elements are usually from 100 to 3150 Hz, less often from 50 to 5000 Hz. The reason why low frequencies (below 100 Hz) are not included in standard measurements is because the calculation is based on one important assumption that the sound field in the rooms is diffuse, and usually rooms exhibit a low modal density in frequencies with wavelengths that are comparable to the rooms' sizes which inherently means they are not diffuse at low frequencies.

4.2.1. Flanking Transmission

To start with, the method adapted in this research paper is based on field measurements which vary from laboratory measurements such that they do not solely represent direct energy transmitted by the test wall as lab measurements would do, they rather include energy that manages to find its way through to the receiving room by paths of flanking or leaks. As long as field measurements are within 3 to 5 dB of laboratory tests, the results are considered compliant [Long, 2006].

Several reasons cause flanking in buildings like structural connections between walls and floors or ceilings, electric sockets or studs in multiple panel partitions, ducts etc. which need to be cured in such a way that minimizes their readiness to transmit energy.

Despite the fact that the eventual flanking transmissions are caused by a combination of both airborne and structure-borne transmission, for the case of airborne sound insulation specified in this report, the notion of *Intensity* shall be introduced to exemplify the determination of flanking [EN 12354-1, 2000].

It is important to note that if there was one building element in the tested system with a low reduction index, it will be the dominating contributor of bad insulation, and will in turn determine the final value of the reduction index. This can be seen from the apparent sound reduction index for a system composed of several building elements (Equation 4.12):

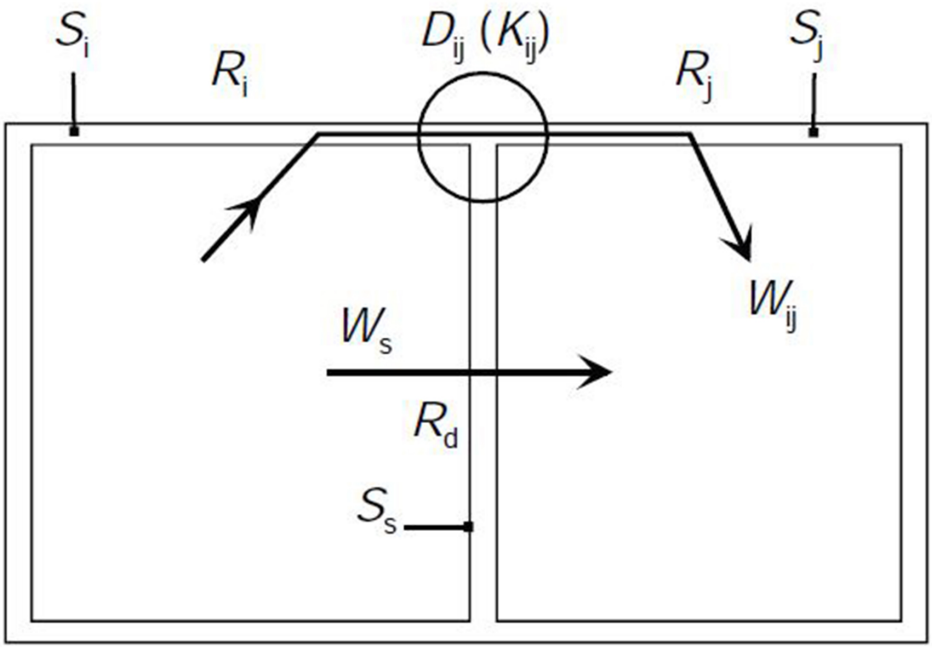


Figure 4.2.: Direct and Indirect transmission paths between two rooms [Vigran, 2008]

$$R' = -10 \log \left[10^{\frac{-R_d}{10}} + \sum 10^{\frac{R_f}{10}} \right] \tag{4.12}$$

where R_d is the reduction index of the separating wall, and the sum of R_f the sum of the reduction index associated with all flanking elements. Seeing that it is a logarithmic equation, then as stated, any single element with a bad reduction index will influence the final value.

In Figure 4.2 above, the transmitted sound power is classified in the direct path (W_s) and by first order flanking transmissions (W_{ij}). S_s is the surface area of the wall separating the rooms, S_j is the surface area of flanking element j with associated reduction index R_j and similarly S_i is the surface area of flanking element i with associated reduction index R_i. D_{ij} and K_{ij} are the velocity level difference and the vibration index for the junction ij, respectively. These values will not be discussed in detail, but it is worthy of seeing some of the flanking paths and how the sound power can be transfered from one room to another.

4.3. Airborne Sound Insulation Measurements

Sound insulation of building elements is not intuitive and requires some understanding of the energy transfer within the considered spaces. An overview of the energy flow will be shown below and that will aid in understanding the standardized measurements procedures.

4.3.1. ISO 140 - 4: Field Measurements of Airborne Sound Insulation Between Rooms

Assuming an omni-directional sound source in the sending room is emitting power W_i which is incident on the wall separating the two rooms, some of it is transmitted into the receiving room W_t. The ratio of the transmitted power to the incident power is called the transmission factor, τ, which was encountered in section 4.2, and can be seen in Equation 4.13

$$\tau = \frac{W_t}{W_i} \tag{4.13}$$

which is directly correlated with the reduction index (transmission loss) in the relation as seen in Equation 4.14:

$$R = 10 \log\left(\frac{1}{\tau}\right) \tag{4.14}$$

Always assuming a diffuse field in both rooms and considering the RMS sound pressure in the sending room $\tilde{p}_S$, and that in the receiving room $\tilde{p}_R$, the intensity on the wall caused by the sound source would be calculated by Equation 4.15

$$I_i = \frac{\tilde{p}_S^2}{4\rho_0 c_0} \tag{4.15}$$

and the transmitted power in the receiving room would be as in Equation 4.16

$$W_t = I_t \cdot S = \frac{\tilde{p}_R^2}{4\rho_0 c_0} \cdot A_R \tag{4.16}$$

where A_R is the total absorption area which can be obtained using reverberation time (T) measurements and the Sabine equation (equation 4.17).

$$T = \frac{0.16V}{A_R} \tag{4.17}$$

where V is the volume of the room.

The transmission factor can now be interpreted according to Equation 4.18 using the above introduced energy relations and relevant areas

$$\tau = \frac{I_t S}{I_i S} = \frac{\tilde{p}_R^2 A_R}{\tilde{p}_S^2 S} \tag{4.18}$$

which brings back to a neat representation of the reduction index which shows up in the measurements standard and is the most significant for this study (Eq. 4.19)

$$R = 20 \log \left(\frac{\tilde{p}_S}{\tilde{p}_R} \right) + 10 \log \frac{S}{A_R} = L_S - L_R + 10 \log \frac{S}{A_R} \tag{4.19}$$

In reality this index does not necessarily identify with the wall per se, rather includes all other flanking paths which could exist in the structure, which is why the standard specifies a second method more focused on the element under investigation itself using the intensity method. Via this method, the reduction index for a part of the wall may be obtained, or for other elements or corners to investigate the source of flanking and its respective transmission. Since flanking will not be measured in this study, it is sufficient to know that it is possible to measure it, if intensity measurement tools are available.

4.3.2. ISO 170 - 1: Rating of [Airborne] Sound Insulation in Buildings and of Building Elements

In order to have a simple figure with which a building element can be described for its reduction index, which was obtained in the section above for a whole set of frequencies, a method is agreed upon to summarize the sound reduction behavior of the element in one single value.

A reference curve is provided by the standard which guides till the achievement of the single unit value R'_w.

The set of values comprising the reference curve is given in octave bands and third octave bands which inherently suggests that the reduction index obtained from ISO standard 140-4 should be filtered in the same way.

If third-octave band filtering is used then the method would be to "shift the reference curve in steps of 1 dB towards the measured [reduction index] curve until the sum of unfavorable deviations is as large as possible but not more than 32.0 dB" [ISO 170-1, 1996], which means that "high insulation data in the higher frequency range does not compensate for bad insulation at low frequencies" [Vigran, 2008]. After that, the value of the *reference curve* at 500 Hz is considered to be the single unit value intended.

4.4. Relation between Compressive Strength and Modulus of Elasticity

The Modulus of Elasticity (Young's modulus) is a vital property in the determination of the sound insulation behavior of a material, and especially for the caluclation of its critical frequency. In this section the relation between the modulus of Elasticity and compressive strength (which is sometimes more readily attainable for the materials at hand than the modulus of Elasticity) will be briefly introduced.

According to the Comité Euro-International di Béton and the Fédération Internationale de la Précontrainte (CEB-FIP) Model Code, the relation between the modulus of Elasticity and compressive strength is as Equation 4.20:

$$E = 22000\left(\frac{\sigma_B}{10}\right)^{\frac{1}{3}} \tag{4.20}$$

where E is the modulus of Elasticity and σ_B is the compressive strength, both in MPa.

This formula is based on empirical theories, mainly for normal strength and high strength concrete [ACI, 2009].

4.5. Simulation Theory

The theoretical calculations were obtained by a simulation created with Insul, which is a software specified in predicting sound insulation of building elements. This version can predict Rw and STC values of single panels in addition to multiple-panel partitions and other elements and systems, filtered in third octave bands.

Single, uniform panels are modeled quite well using the mass law up until half the critical frequency. In that case only the density and the thickness of the panel are required. The equation used to determine the transmission loss up till the critical frequency is

$$TL = 20\log(f.m'') - 48dB \tag{4.21}$$

It shows an increase by 6 dB per doubling octave or doubling mass per unit area. This equation is closely related to equation 4.6 with the correction for diffuse sound fields.

The critical frequency is calculated using Youngs modulus (Modulus of Elasticity) and the mass per unit area. From this information it can be assumed that the equations used to obtain the critical frequency are parallel to the ones mentioned earlier (equation 4.7 and 4.8).

Above the critical frequency the transmission loss is increasing by 12 dB per octave. In addition to that the option of editing the damping factor (loss factor) is available so

that if the data is known it can be inserted for the simulation at and above the critical frequency.

Shear waves become more significant for heavy and thick walls (ex. concrete $>$ 100 mm) where the transmission loss is expected to be lower than that predicted by the mass law. This is accounted for in Insul for the high frequencies, where the transmission loss increases by only 6 dB per octave.

Software limitations

Insul software predicts Rw/STC values up to an accuracy of 3 dB and decreases for increasing numbers of panels and layers, and when there are resonance frequencies near the edge of the Rw/STC criteria curve [Insul, 2013]. It is also discussed among users of Insul on blogs and forums that the tendency of this program is to overestimate the reduction index, and some claim that the estimation is noticed to be higher (+5 dB) in some situations.

The frequency range covered in this software is 50 to 5000 Hz, however only frequencies from 100 to 3150 Hz will be considered in this study.

5. Method

The methodology followed to carry this report is based on field measurements adapted from ISO 140 - 4: *Acoustics - Measurements of sound insulation in buildings and of building elements - Field measurements of airborne sound insulation between two rooms*. Several projects were chosen to conduct this study, some of them are built using typical building materials used in Palestine such as hollow concrete blocks of several thicknesses. Other projects are built using alternative materials of variable types. The reduction index of the partition as part of the building system (R') will be measured, and the single unit value (R'_w) will be calculated following ISO 170 - 1: *Acoustics - Rating of sound insulation in buildings and of building elements - Airborne sound insulation. The results will be later compared and analyzed*.

The major guidelines in the standard were followed, some deviations were necessary though, which will be discussed separately in the Results section.

5.1. Equipment

The same equipment was used for all measurements except the ones in Gaza, which had to be performed using available equipment from there.

Loudspeaker: Cromo 8 by dB Technologies L382003697
Microphone: Type 2 Mic 300 condenser microphone Nr. 918 RCM akustik (Specifications in Appendix A)
Computer: SONY Vaio model VGN - NS21S, serial number 5003005
Software for measurements: ARTA version 1.8.3 by ARTALABS
Software for simulation: Insul version 7.0.4 (2013) by Marshall Day Acoustics, serial number 3706
Sound Card: Lexicon Lambda model LEXLAMBDAV, serial number 00000083347
Cables: XLR, 1/4" balanced Jack $>$ 1/8" balanced Jack, USB 2.0 A $>$ B

5.1.1. Gaza

Loudspeaker: Behringer Eurolive B315D
Microphone: Type 2 Digital sound level meter WS1361 (Specification in Appendix B)
Computer: Lenovo ideapad S410p

Software: Audacity 2.0.6
Cables: RCL, 1/8” balanced Jack

5.2. Setup

The standard recommends a test arrangement such that the sending and the receiving rooms are of identical dimensions and with diffusing elements such as furniture or building boards etc. It was possible for some projects to fulfill this recommendation but not all; some projects had one room larger than the other, which is still workable according to ISO 140 - 4, and others were a little more special such as staggered rooms. This will be discussed separately also in the Results section.

5.2.1. Test Procedure

A single loudspeaker was placed in two corners opposite the test wall in the source room (Room 1) and three microphone positions were allocated to each loudspeaker position, so in total 6 measurements were taken from the source room. When the rooms are of different volumes the loudspeaker was placed in the larger one, as specified by the standard. Sound pressure level measurements of a high quality white noise audio wave file were taken while continuously oscillating the microphone in a figure of ”8”. The duration of each measurement was approximately 15 seconds.

Maintaining the loudspeaker positions in the source room, six more sound pressure level measurements were taken in the same manner as above in the receiving room (Room 2).

Four background noise measurements were taken in the receiving room also using moving microphone positions. Finally, the loudspeaker is placed in a corner in the receiving room and five - six impulse response measurements were taken in fixed microphone positions around the ”diffuse field” of the room.

5.2.2. Data acquisition

The data was recorded using ARTA software which offers the possibility to measure time-averaged sound pressure level and to calculate impulse responses by generating a sine sweep signal. Energy decay curves were calculated from the previously recorded impulse responses where it is possible to obtain the reverberation time using the same software.

All the data was averaged according to its dedicated purpose, that is, the six measurements of the source room, the six measurements of the receiving room, the four measurements of the background noise, and finally the six measurements of reverberation time, in third octave bands. The reduction index was obtained according to Equa-

tion 4.19 and the single unit value was calculated according to specifications mentioned in Section 4.3.2.

Gaza

Due to political and geographical restrictions, the measurements had to be carried out in Gaza by a third party, and due to lack of experts in building acoustics the instructions on how to perform the test with what was available had to be personalized. It is possible to find the instructions document in Appendix C.

The reverberation time was done according to the interrupted noise method, and the measurements including sound pressure levels were recorded on Audacity as uncompressed wave files using a simple sound pressure level meter and then sent by email.

Inaccuracies - Gaza

The level range control switch on the sound level meter was not set according to specification (in Appendix C), it was rather set as the following:

- Step 1 (SPL/Sending): 30 – 130 dB, [range 100 dB]
- Step 2 (SPL/Receiving): 80 – 130 dB, [range 50 dB]
- Step 3 (Background noise/Receiving): 80 – 130 dB, [range 50 dB]
- Step 4 (Interrupted noise/Receiving): 30 – 130 dB, [range 100 dB]

showing that the range span was different for step 2 and 3, which means that the relative magnitude spectra had to be corrected to get relevant values. 50 dB were subtracted from the receiving room values (Step 2) and the background noise values (Step 3). In addition, the achieved sound pressure levels of step 2 and 3 were on average $\sim$55 and $\sim$40 dB respectively, and this shows that the chosen ranges were too high for the expected sound and therefore they are not very reliable, however due to the great value of having results from Gaza, the measurements were still considered for this study.

Data Acquisition - Gaza

The third-octave band magnitude spectrum for the sound pressure levels was retrieved later on from the audio files using ARTA software, and the reverberation time was obtained also using ARTA which calculated the energy decay curve of the edited "interrupted noise" audio file (see Figure 5.1). This audio file was trimmed using Audacity to the smallest possible fraction with significant data, that is, the first instance of interruption and some background noise after it. The T20 extrapolation of the reverberation

time was used rather than T30 due to the insufficient energy loss in the received files caused by the high noise in the background.

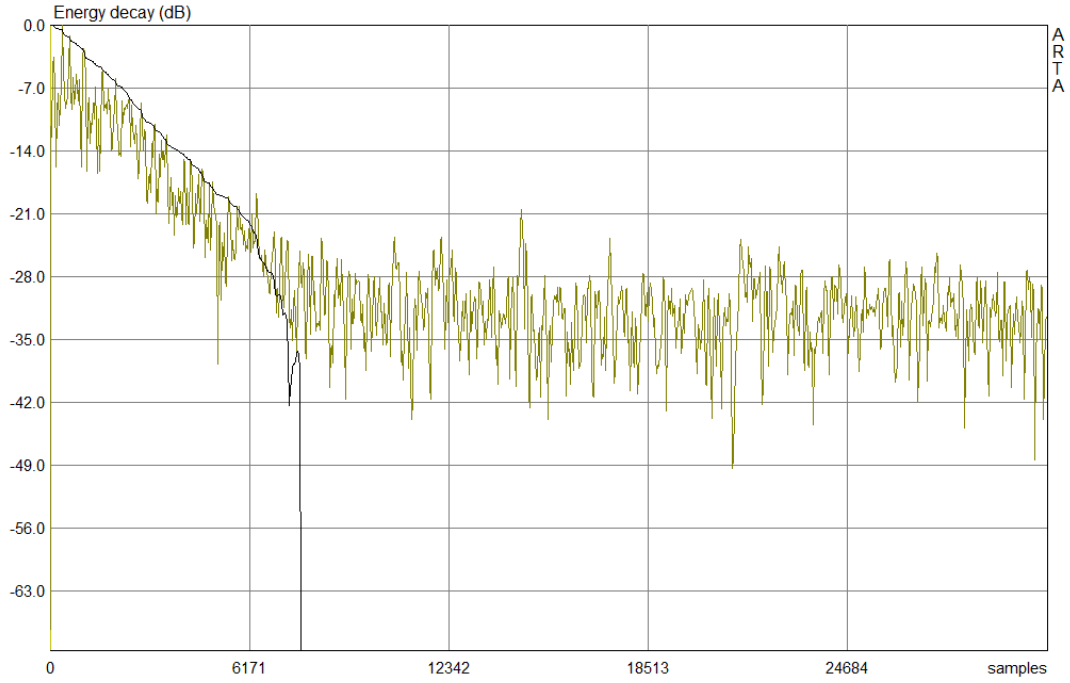


Figure 5.1.: Energy decay curve showing ≈20 dB drop (ARTA)

5.3. Comparativeness

The measurements on field work are comparable as long as they are performed in accordance with the standard, which means that they can be repeated and the same results will be obtained. However, these measurements do not describe the test specimen as an individual element because on field measurements it is rather inseparable from its surroundings and therefore the results give information about the building system as a whole which includes flanking. In order to make the results more relevant to the building element itself, a theoretical calculation based on the type and material of the partition is juxtaposed with the measured results opening a window for analysis and discussion.

5.4. Materials

The *typical* materials used in the test are Hollow Concrete Blocks of thicknesses 10, 15, 20 cm. The *alternative* materials used in the tests are Compressed Earth Block and adobe

block.

Two types of CEB are used in this study, the Jericho (with test results obtained from Geotechnical and Material Testing Center in Ramallah) and the Gaza-based soil bricks (according to the data received from Eng. Khaldi). The most relevant data obtained from accredited tests is the measured maximum dry density:

- Jericho CEB: 1919 kg/m^3
- Gaza CEB: 1750 kg/m^3

In addition to that, the compressive strength for the Jericho CEB was also measured by accredited test, and it was given as

- Jericho CEB: 11.3 MPa

Given the accredited data of the compressive strength for CEB - Jericho, it can be assumed that CEB - Gaza is similar.

Turning to adobe, two samples of blocks were taken from the site that pertain to the two measured projects, the ”new block” and the ”old block”. The samples were weighed and their volume was measured, and the obtained densities are as follows:

- Old Adobe: 983 kg/m^3
- New Adobe: 1418 kg/m^3

Compressive strength for this type of material is low in comparison to CEB. Even though no test data is attained for the adobe blocks studied in this report, other results about an adobe block of the Mediterranean area suggest that compressive strength varies between 0.5 and 5 MPa [de Almeida, 2012].

The compressive strength will be used to obtain an approximation of the Young's modulus following Equation 4.20.

5.4.1. Simulated Materials

Some materials from the Insul database was used as a starting point for the simulation (see Table 5.1). Some of it was fully considered and some was partially considered. Each test in Chapter 6 will describe how the material properties were chosen, but it is worthy of stating that the simulation was made after the field measurements and they were therefore tuned-in according to the obtained results.

The loss factor η was assumed to be 0.01 for all materials in the simulation due to the impossibility of obtaining their real values.

Frequency Range of Interest

All the measurements were taken in 1/3 octave bands from 100 to 3150 Hz.

Table 5.1.: Material Database from Insul

Material	**Density** $[kg/m^3]$	Young's Modulus [GPa]
HCB	760	1.804
HCB	900	2.367
HCB	1157	3.366
HCB	1220	3.773
HCB	1250	4.058
HCB	1428	6.328
HCB	1600	5.976
HCB	1800	7.294
Lightweight Concrete	1300	3.697

6. Tests: Results and Analysis

The description and the drawings showing the annotated plan, sections and wall detail will be presented for each test, giving the reader an idea about the space and the dimensions. The letters "S" and "R" refer to Source and Receiver room respectively. Some of the tests are supported with a photograph, particularly the ones with a special situation in the field or which are necessary to have a better understanding.

Each description is followed by a reduction index graph showing the **measured** results in a **thick** black line and the simulated results in a dotted line. All the plots include the ISO 170-1 reference curve for the measured result in a dashed line. The single unit value result (R'_w) can be retrieved from the Reduction Index value at 500 Hz of the *reference curve*, whereas the (R_w), which is the value obtained by simulation, will be given in the description of the results.

6.1. Typical Materials

6.1.1. Hollow concrete block

Birzeit University Chemistry Laboratory – Ramallah

This construction is part of the Birzeit University and it represents two staggered rooms with different dimensions. The sending room which is the larger one is a Chemistry laboratory and the receiving room is a multipurpose lecture room. The wall is a typical 10 cm thick hollow concrete block. During the measurements it was not possible to place the sound source in two different angles, it was rather placed in one corner for all the measurements, which is the one at the upper-left corner in the plan 6.1.

Results

With the knowledge that the partition was 10 cm thick, the density was assumed to be 1375 kg/m^3 in the simulation, referenced from Table 3.1, and the Young's modulus was obtained by approximating it from Table 5.1: "Material Database from Insul" and the total simulation is shown in Table 6.1.

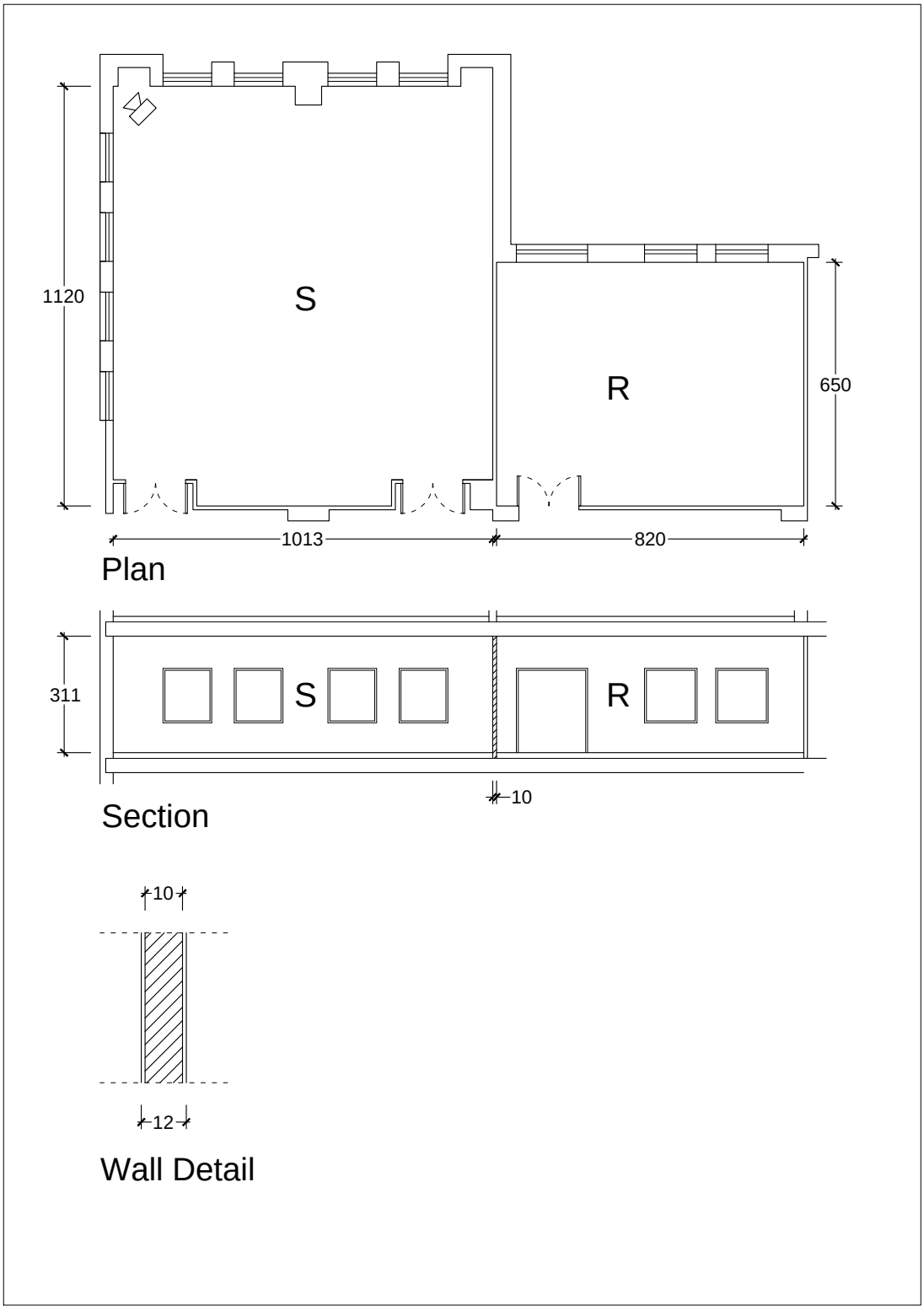


Figure 6.1.: Birzeit University Chemistry Lab - Plan and Section

Table 6.1.: Birzeit University Chemistry Laboratory - Simulation details

Material	**Thickness**	ρ [kg/m^3]	**E** [GPa]	η	f_c [Hz]
HCB	10 cm	1375	5.058	0.01	338
Gypsum plaster	1 cm	1280	4.67	0.01	3396

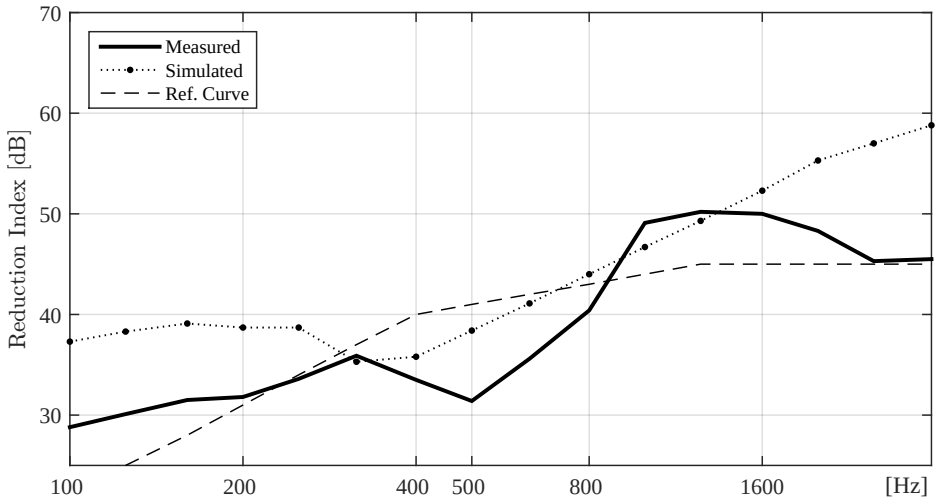


Figure 6.2.: Birzeit Chemistry Laboratory - Measured and simulated reduction index

Based on the results from Figure 6.2 The R'w index is **41 dB** for the measured, and the Rw index is **45 dB** for the calculated graphs.

A dip at 500 Hz can be seen in the measured graph, whereas it is found between 300 and 400 Hz in the simulated graph. If the range 500 to 2000 Hz is compared, the increase in reduction index is 17 dB for both the measurements and the simulation, if the range 2000 till 3150 Hz is compared, then the increase in reduction index is - 3 dB for the measurements and + 3 dB for the simulation. Finally, it can be seen that the reduction index is much better in the simulation in the low ($<$ 250 Hz) and high frequencies ($>$ 1600 Hz).

Analysis

Referring to Figure 6.2, the increase in reduction index between 500 and 2000 Hz can be summarized as 8.5 dB per octave, which means that the panel is behaving as predicted by the post-critical-frequency mass-law. It can be seen that shear waves start to dominate in the simulation at 2000 Hz, where the increase in reduction index can be summarized as 5.5 dB per octave, which is what is expected. In the measurements it

can be seen that this value is negative, which suggests that the construction lacks some stiffness. The difference between the measured and simulated results in the high frequency range (1.6 kHz 3.15 kHz) is also caused by leakage from the outdoor windows and possibly the doors as well, while the differences at the lower end of the spectrum (100 - 250 Hz) are likely caused by a fault in the measurements: In addition to the fact that only one source position was chosen for the measurement, the placement of the sound source might not have been suitable for this type of staggered rooms.

Tantour Office – Jerusalem

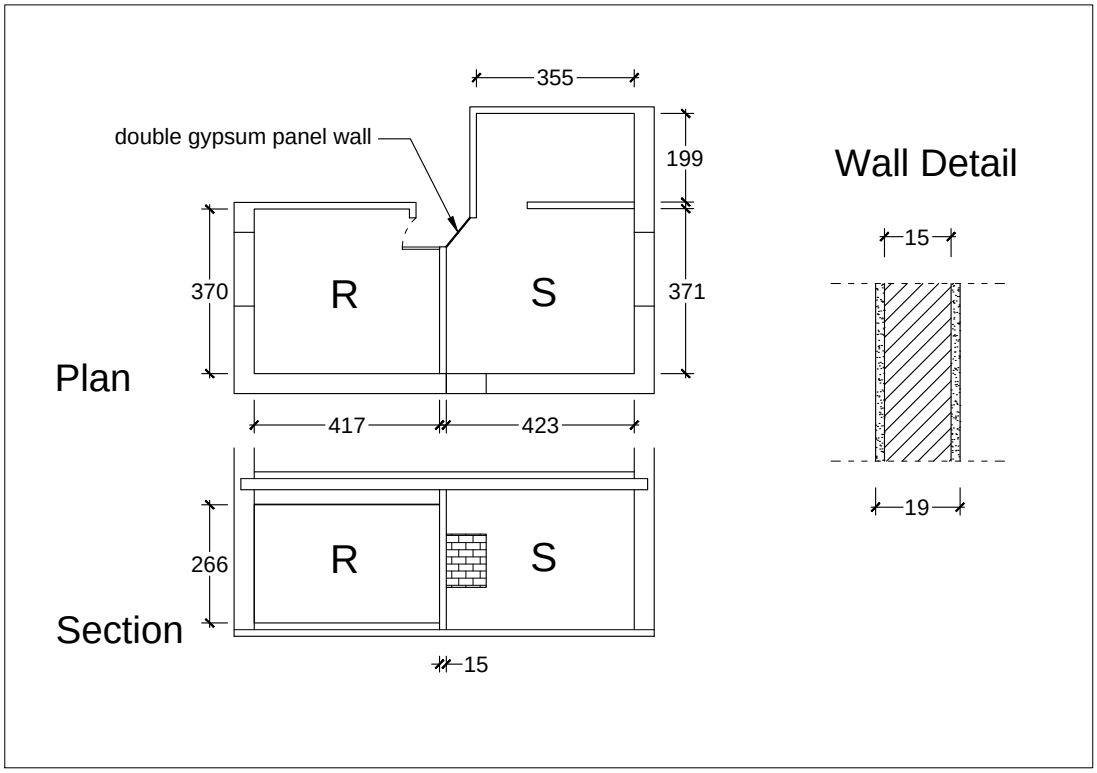


Figure 6.3.: Tantour Office - Plan and Section

The construction was built in the 70's and it is now under renovation. The two offices are separated by a 15 cm hollow concrete block wall, with a measured density of 1638 kg/m^3. The wall is covered with a 2 cm thick layer of plaster on both sides in addition to the paint, the density for which was 1222 kg/m^3 (measured). See Figure 6.4 for a cross section of the wall showing the block anatomy followed by a layer of plaster and white paint. The door of the sending room (from the corridor) was replaced by

two layers of gypsum board and sealed well from all edges. In addition to that, the tiles were completely removed and it was left with only the lower strata of sand and aggregates, and the window was blocked with hollow concrete blocks, as can be seen in Figure 6.5.



Figure 6.4.: Cross section of the wall showing composition and anatomy of block



Figure 6.5.: Sending Room - showing removed tiles, blocked door and blocked window

Results

Figure 6.6 shows the reduction index for the aforementioned partition. The theoretical result was obtained by simulating a 15 cm hollow concrete block (1638 kg/m^3), and 2 cm of gypsum-based plaster on the source side (1222 kg/m^3). Only the density was measured, whereas the Young's modulus was adopted from similar materials of the templates provided by Insul (Check Table 5.1).

Table 6.2.: Tantour Office - Simulation details

Material	**Thickness**	ρ [kg/m^3]	**E** [GPa]	η	f_c [Hz]
HCB	15 cm	1638	5.976	0.01	226
Gypsum Plaster	2 cm	1222	4.67	0.01	1659

Based on the results from Figure 6.6 The R'w index is **48 dB** for the measured, and the Rw index is **51 dB** for the calculated graphs.

Looking at Figure 6.6, the simulated plot shows a dip at 250 Hz band which doesn't appear in the measured plot. It can be seen that both indices are identical from 315 till 500 Hz, and any deviation within 3 dB is an indication that the results are reliable. The difference starts to get larger than 3 dB below 125 Hz and above 1000 Hz.

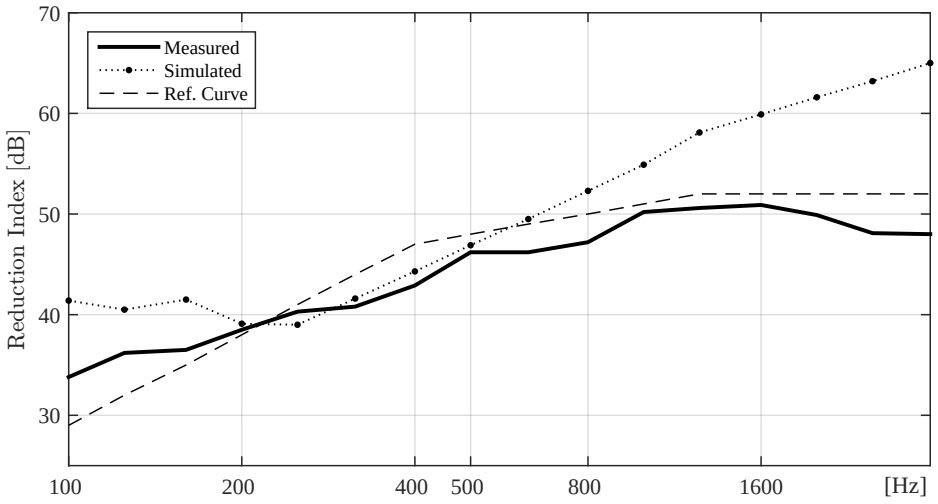


Figure 6.6.: Tantour - Measured and simulated reduction index

Analysis

As could be seen from Figure 6.4 the anatomy of the block is showing a dual air space per depth, which means that there is more concrete in this block compared to the ones with only one air space per depth. More concrete means more mass per unit area and therefore a better performance in sound reduction overall. In addition to that, the figure shows that the mechanical connections that separate the air gaps from each other are a bit staggered. This might play a role in the increase of overall sound reduction.

The critical frequency was noticed to be in the 250 Hz third octave band for the simulated results, while it is not clear if it's the same or not in the measured, but from the way the reduction index is increasing, the critical frequency of the measured results is expected to be lower than 100 Hz. This might be attributed to the wrong assumption of the Young's modulus. The higher E the lower f_c, and therefore the real block might have had a lower E. The other possibility would be, if the Young's modulus estimation is correct, that the critical frequency is the same and the values between 100 and 200 are indicating the resonances of the system or the effect of a low shear limiting frequency.

Above 1000 Hz it could be seen that the measured and simulated results deviate by more than 3 dB, which indicates that the structure is possibly leaking some high frequency sound from the places not well sealed. Judging by the site, this could be linked with the blocked window, which was not tightly sealed, in addition to the balcony doors which don't insulate well, as well as the removed tiles, resulting in a structurally connected junction and therefore a definite flanking path.

Beit Hanina School – Jerusalem

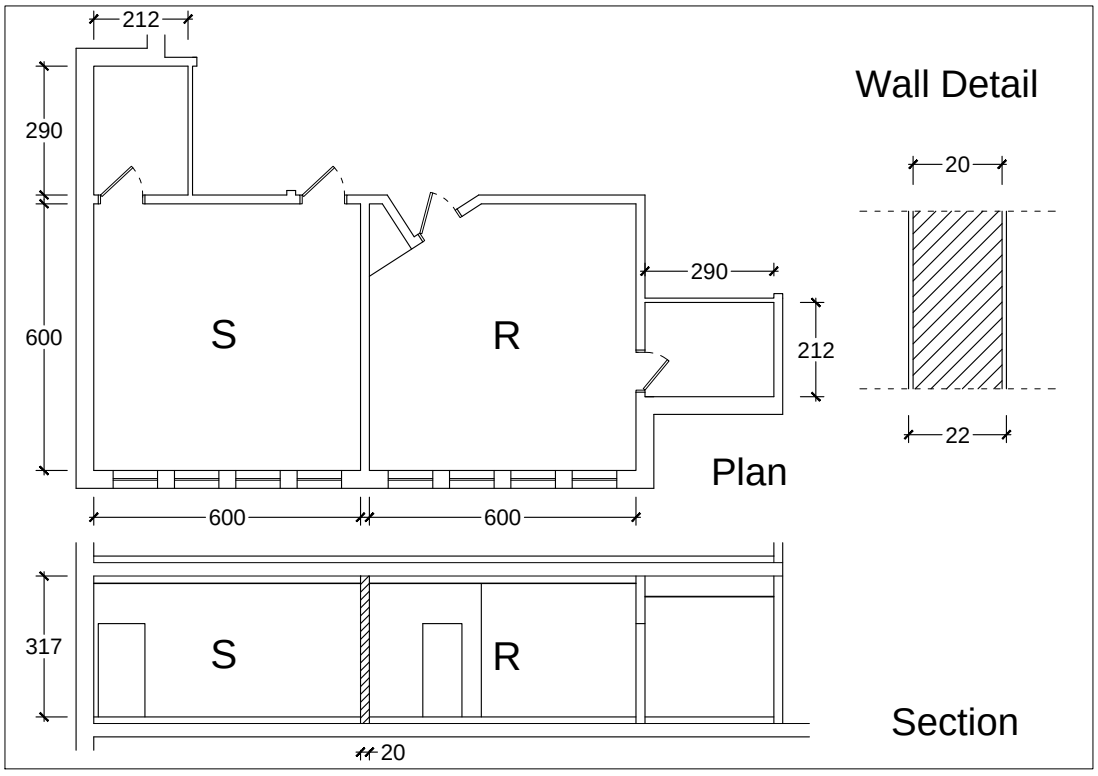


Figure 6.7.: Beit Hanina School - Plan and Section

Beit Hanina School is a newly constructed building in Jerusalem, built with norms and materials typically used in Israel. The classrooms are identical and the partition is made of 20 cm thick hollow concrete block with 1 cm of plaster on both sides. The density of the block was not measured. It is important to note that there were grille openings above all the doors, which had the same width of the door (95 cm) and a hight of 50 cm.

The material used to simulate the wall is 20 cm hollow concrete block with 1 cm layer of plaster on the source side. The density of the block was assumed to be 875 kg/m^3 (from Table 3.1) with a critical frequency of 173 Hz which falls within the same third octave band as the measured result.

Results

Table 6.3.: Beit Hanina School - Simulation details

Material	**Thickness**	ρ [kg/m^3]	**E** [GPa]	η	f_c [Hz]
HCB	20 cm	875	2.2	0.01	205
Gypsum Plaster	1 cm	1280	4.67	0.01	3396

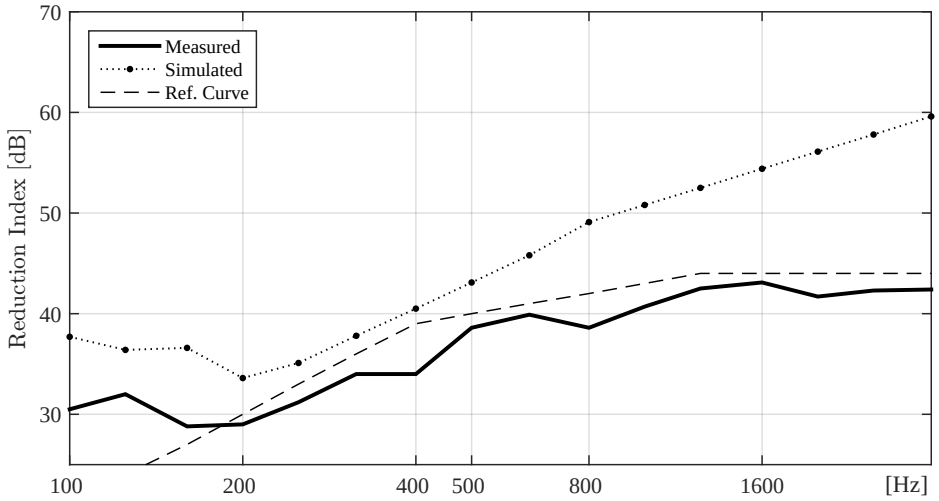


Figure 6.8.: Beit Hanina School - Measured and simulated reduction index

Based on the results from Figure 6.8 The R'w index is **40 dB** for the measured, and the Rw index is **47 dB** for the calculated graphs.

It can be seen in Figure 6.8 that the theoretical index is higher than the measured index on all frequency bands. Both results show a dip at 200 Hz, and after that the simulated result is increasing with a bigger step (15 dB) in the region from 200 - 800 Hz, as opposed to the measured result which is only increasing by 10 dB overall. From 800 to 3150 Hz, which is where shear waves seem to be dominant, the increase for the simulation is by 10 dB whereas for the measured is 4 dB.

Analysis

Hollow Concrete Block was assumed to be 875 kg/m^3 because it matched measured result. Whether this is true or not needs to be verified, but it could be assumed by the knowledge of typical 20 cm HCB from Table 3.1 that the densities associated with 20-cm

thick HCB are either 1350, 1125 or 875 kg/m^3 and by trial and error, the lighter block with a relevant Young's modulus of 2.2 GPa was the most suitable.

During the measurements significant sound could be heard through open grilles above the doors, and some via the HVAC grilles. This fact reduces the reduction index for the mid and high frequencies, especially due to the openings above the doors which are 95 cm wide and about 50 cm long, allowing frequencies of around 360 Hz and higher to pass, which explains the lower reduction index in those frequencies as higher when compared to the simulation.

6.2. Alternative Materials

6.2.1. Compressed Earth Block

Al Dyouk Restaurant – Jericho

The room is built using compressed earth block for the most part of it. The construction is joined with load baring concrete blocks in some areas, however the test partition is entirely made of CEB and it is 10 cm thick. The density was reported as 1919 kg/m^3 and the compressive strength was reported as 11.3 MPa. The sending room is open to the rest of the space, as can be see from the plan in Figure 6.9.

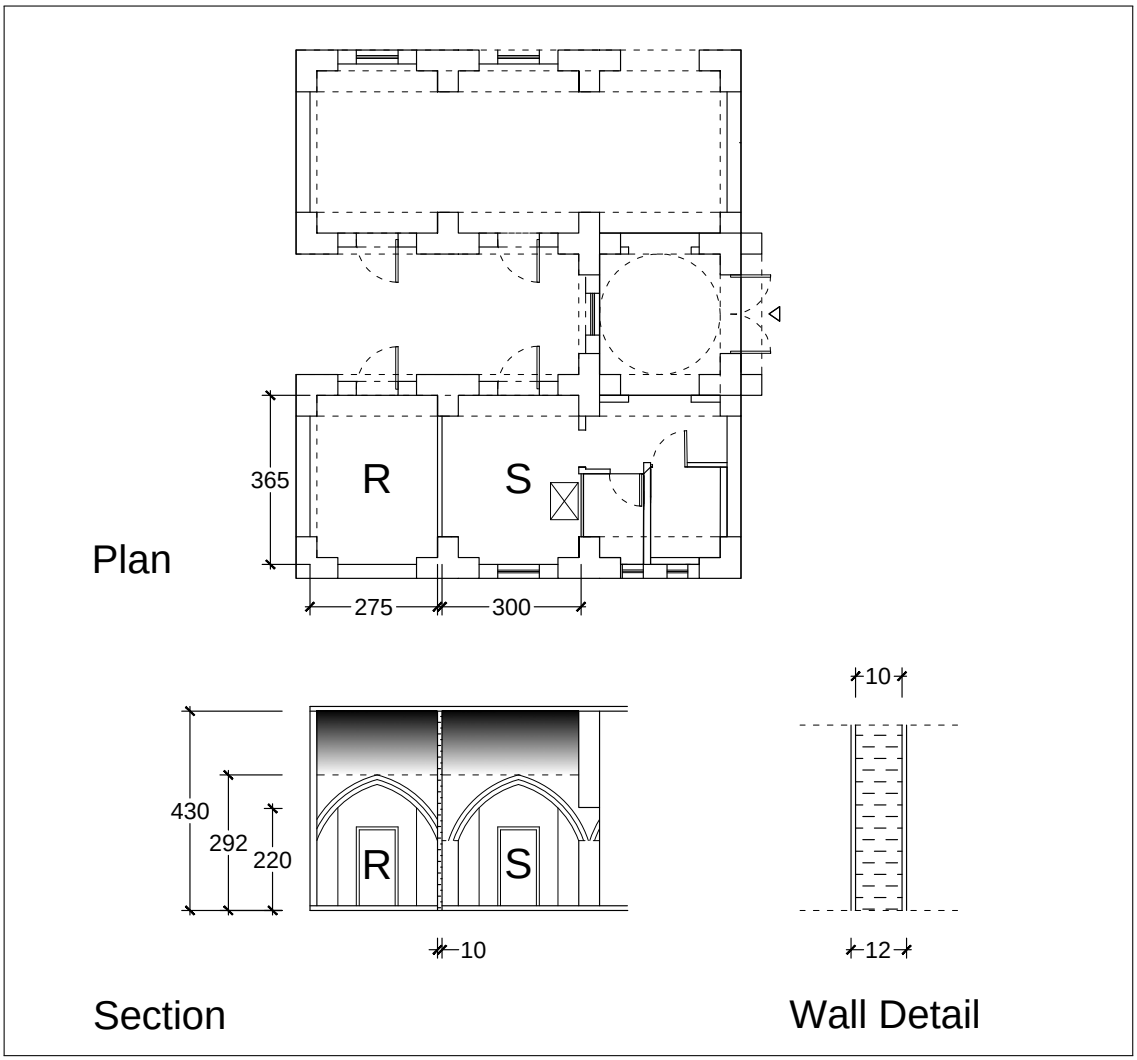


Figure 6.9.: Al Dyouk Restaurant - Plan and Section

Results

The calculation is made by simulating a 10 cm CEB block of the aforementioned density, using a Young's modulus of 22.9 GPa. This value was obtained from the compressive strength according to the Equation 4.20. Check Table 6.4 for the whole simulation data.

Table 6.4.: Al Dyouk Restaurant - Simulation details

Material	**Thickness**	ρ [kg/m^3]	**E** [GPa]	η	f_c [Hz]
CEB Jericho	10 cm	1919	22.91	0.01	260
Gypsum plaster	1 cm	1280	4.67	0.01	3396

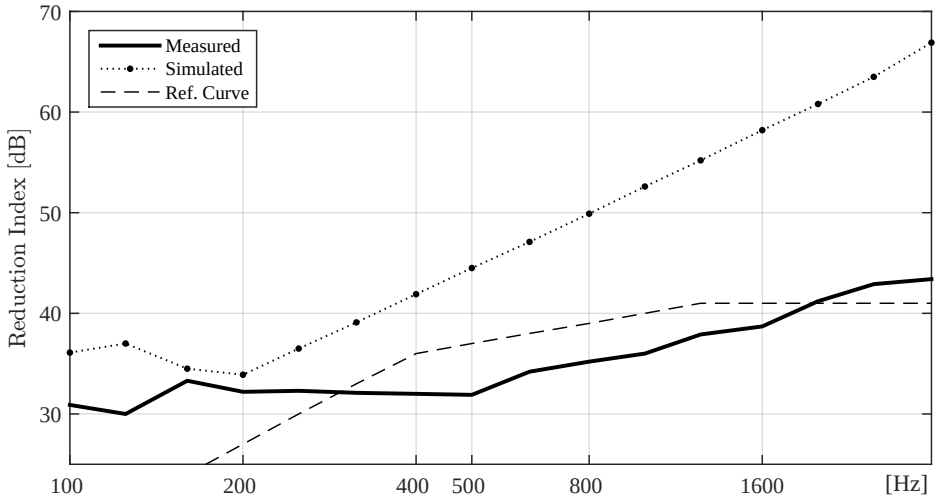


Figure 6.10.: Al Dyouk Restaurant - Measured and simulated reduction index

Based on the results from Figure 6.10 The R'w index is **37 dB** for the measured, and the Rw index is **48 dB** for the calculated graphs.

It can be seen that the critical frequencies for both graphs are within the 200 Hz third octave band, and both their reduction indices are within less than 3 dB (32 dB - measured, 34 dB simulated) at that frequency, however the deterioration in reduction index in the measured values is very large in comparison with the simulated values in the lower and higher frequencies. There is a 11 dB difference between R'_w and R_w values.

Analysis

One of the reasons causing the low transmission loss in the high frequencies as could be seen in Figure 6.10 is a crack in the wall where most of the high frequencies could be heard (see Figure 6.11 below). Another reason is the door of the receiving room which was not sealed properly.



Figure 6.11.: Al Dyouk Restaurant - Crack

It is also possible to notice that the peaks and dips below the critical frequency (200 Hz) are shifted to the left in the simulation. The reason behind this could be the fact that the binding material or the mortar was not taken into consideration in the total estimation of the wall's properties, therefore it could be that the Young's modulus was wrongly estimated.

It is interesting to note that the measurements were carried out without stable electricity, and the power to feed the speaker and the computer was borrowed from a small generator attached to the car battery, using long, unbalanced cables. Even though these are uncalibrated measurements, it is hard to determine whether the conditions throughout the whole experiment were stable, which might have affected the results.

UNRWA Prototype House – Gaza

The studied rooms in Gaza are part of an UNRWA funded project, designed and supervised by Eng. Emad Khaldi. The purpose of this house is to host war victims whose homes were partially or completely destroyed. The idea behind this type of construction is to be built within a short time and with an equivalent cost of normal constructions, possibly lower, especially within the limitations on construction materials in Gaza, as mentioned in Chapter 2.3.3.

The shelter is built with 45 cm cross-shaped pillars and the connecting walls are 30 cm, in particular the partition between the two studied rooms, all of that is built with compressed earth block from Gaza. The area of the partition taken into account in the calculations does not include the pillars. The material has a reported density of $1750\,\mathrm{kg/m^3}$.

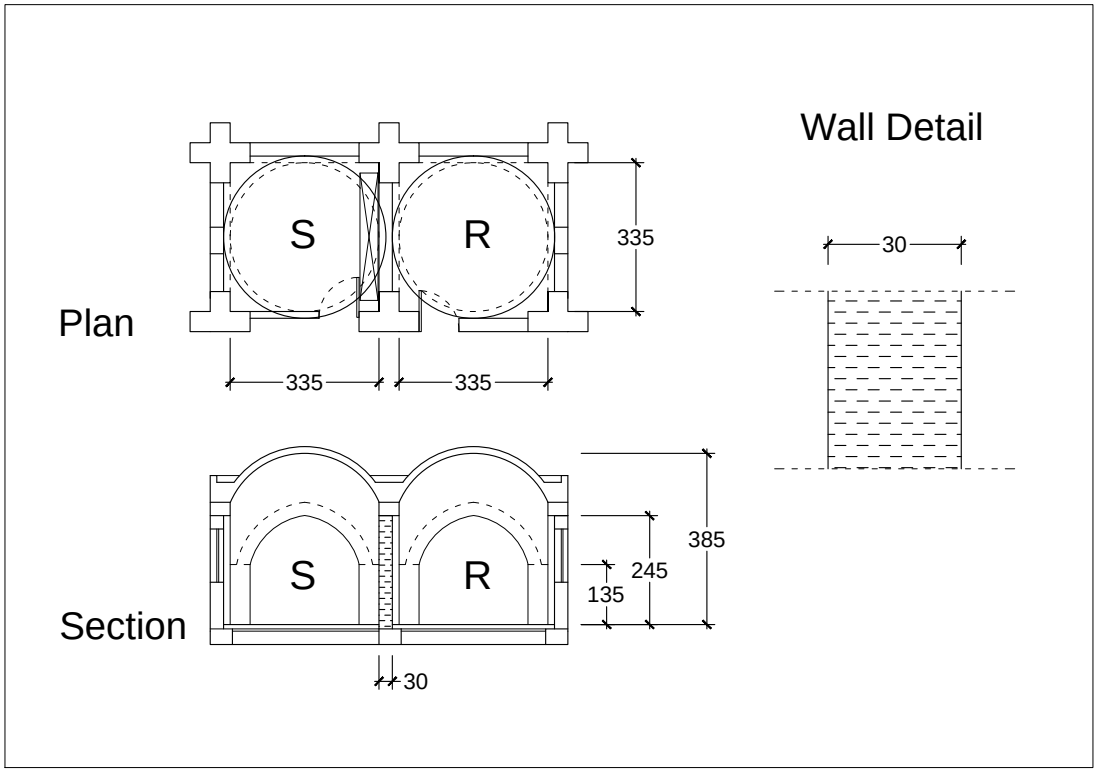


Figure 6.12.: UNRWA Prototype House - Plan and Section

As can be seen from the plan, a large wardrobe is standing right in front of the test partition and this might overestimate the reduction in the results.

A note to keep in mind is that in all measurements three persons were always present except for the reverberation time measurement where four people were present. This



Figure 6.13.: Prototype House showing part of the receiving room

means that the room is slightly damper than how it is supposed to be which might overestimate the reduction by a small amount.

Results

The simulation was made using CEB Gaza with a density of 1750 kg/m^3 and thickness of 30 cm. The Young's modulus was 20.13 GPa, which was approximated from CEB Jericho, but since the density is smaller, the Young's modulus was also assumed to be smaller. The simulation data can be found in Table 6.5.

Table 6.5.: UNRWA Prototype House - Simulation details

Material	**Thickness**	ρ [kg/m^3]	**E** [GPa]	η	f_c [Hz]
CEB Gaza	30 cm	1750	20.13	0.01	64

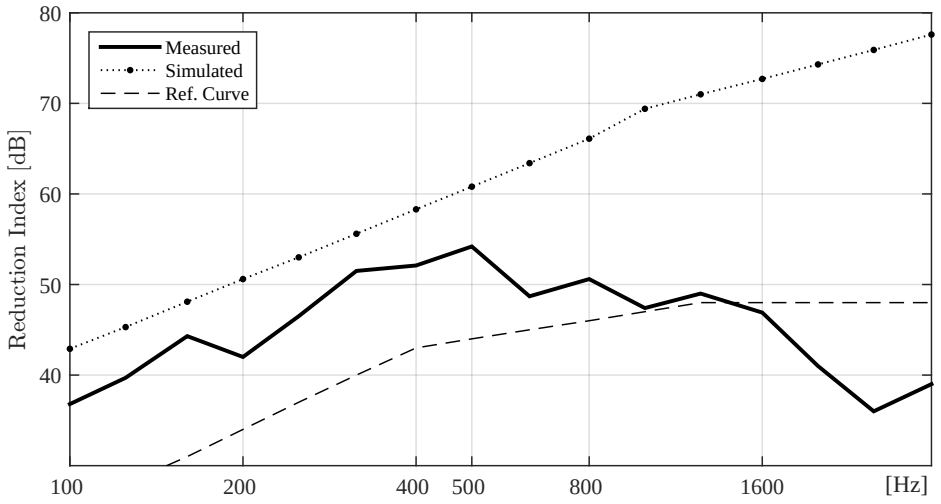


Figure 6.14.: UNRWA Prototype House - Measured and simulated reduction index

Based on the results from Figure 6.14 The R'w index is **44 dB** for the measured, and the Rw index is **64 dB** for the calculated graphs.

Despite the fact that the Gaza measurements are not 100% reliable for the reasons stated in the measurements section 5.2.2, it can be seen quite vividly how the reduction index of the measurement is increasing in the region between 100 and 500 Hz in the same ratio as the theoretical values (13 dB for both) until a serious decrease in the measured results is observed in the frequencies above 500 Hz.

Analysis

The results in this section had been obtained with some risk due to the different equipment used during the test and the fact that it had been conducted by a third party unspecialized in building acoustics. The results are still considered due to their great value for this research.

There are several reasons that could lead to the deterioration of sound reduction in the frequencies above 500 Hz in Figure 6.14, and one of them is the leakage through cracks caused by heavy bombing in the surrounding areas. One of those cracks can be seen in Figure 6.15 below. Another reason is due to the expected low insulation values

of the doors and windows which by default causes some flanking sound associated with high frequencies. This was also testified by Eng. Khaldi on a phone call when he described the situation.

The critical frequency is lower than the frequency range studied (64 Hz), as can be seen from Table 6.5.



Figure 6.15.: UNRWA Prototype House - Crack

6.2.2. Adobe Brick

Fasayel Center Guest Room – Fasayel

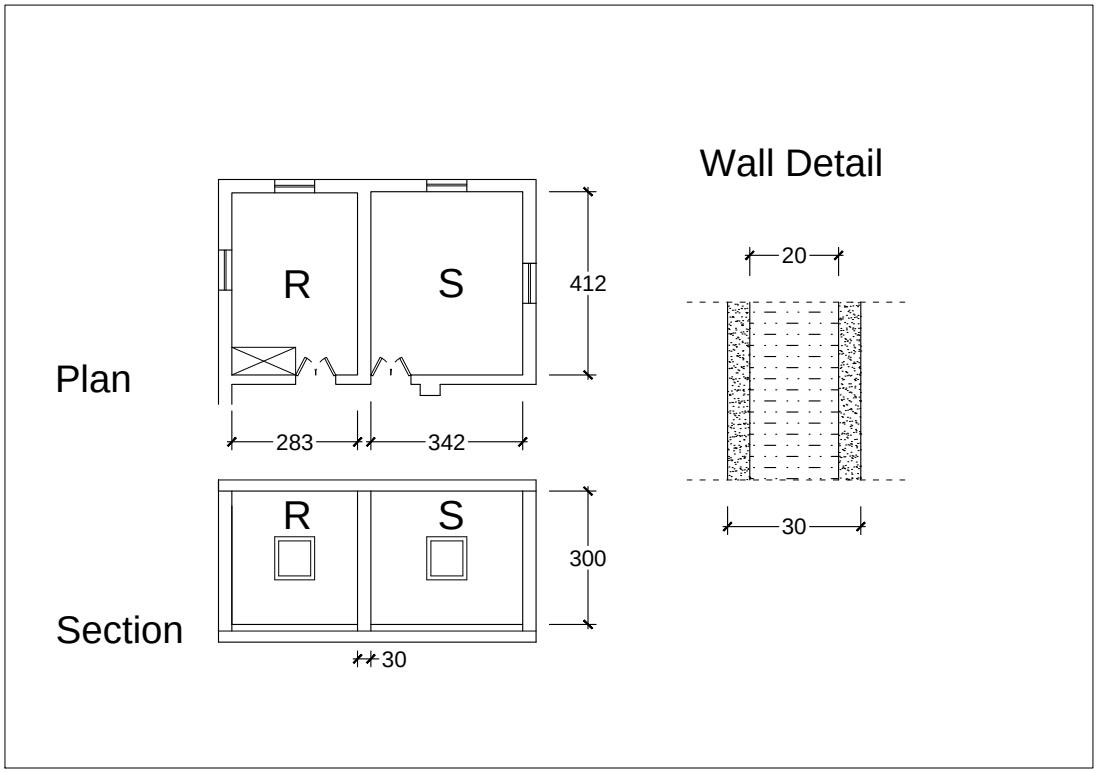


Figure 6.16.: Fasayel Center Guest Rooms - Plan and Section

This is one of the buildings where adobe brick is used for construction. It was built over 80 years ago (the exact year is not known) and unfortunately it was in a bad condition due to low maintenance, see Figure 6.18. Weather was an active factor in the degradation of the walls due to rain which had been falling above average predictions in Fasayel area, which is considered to have an arid climate throughout the year. The density of the wall is measured to be around 983 kg/m^3 and the thickness of the wall is assumed to be 30 cm, composed of 20 cm adobe block and around 5 cm plaster on each side.

Results

Calculations were made according to the composition, thicknesses and densities mentioned above, and the Young's modulus was assumed to be 1.13 GPa based on similar adobe materials [de Almeida, 2012]. The simulation data can be found in Table 6.6.

Table 6.6.: Fasayel Center - Simulation details

Material	**Thickness**	ρ [kg/m^3]	**E** [GPa]	η	f_c [Hz]
Adobe Old	20 cm	983	1.13	0.01	302
Gypsum Plaster	5 cm	1280	4.67	0.01	679

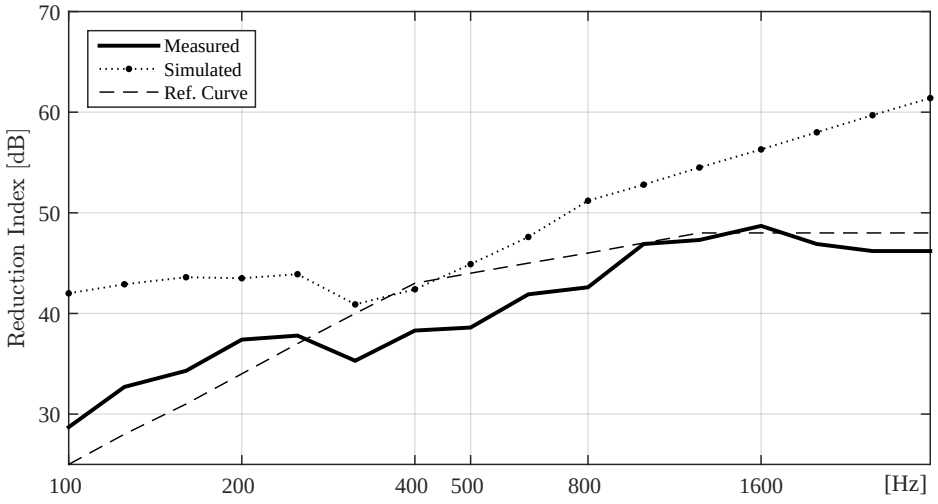


Figure 6.17.: Fasayel Center - Measured and simulated reduction index

Based on the results from Figure 6.17 The R'w index is **44 dB** for the measured, and the Rw index is **51 dB** for the calculated graphs.

The simulated figure indicates that the wall is behaving very similarly to the prediction especially around the critical frequency (315 Hz). The reduction in the lower frequencies is not quite close to the prediction but it can be seen in the higher frequencies that the reduction is increasing by 7 dB per octave for the measured values and 10 dB for the predicted values especially between 315 and 800 Hz, which is not a big difference. Above 1000 Hz the measured reduction starts to deteriorate in comparison with predictions.

Analysis

It is important to note that the doors of these test rooms were not well isolated and it was possible to hear a lot of transmission through that path, which explains why the higher frequencies don't match in Figure 6.17. In addition to that, the cracks in the wall as seen in Figure 6.18 are likely to cause flanking. Apart from that, the wall seems to be behaving very similarly according to predictions, and this means that the assumption



Figure 6.18.: Part of the lobby showing the status of the construction with the two rooms in the front

for the Young's modulus and the composition of the wall was close to reality. The only other difference between the measured and predicted values is that the latter were higher by 6-7 dB overall. This might be attributed to the fact that Insul overestimates reduction index.

Talib House – Fasayel

This test also demonstrates an adobe block construction, built a few years ago in Fasayel, near Jericho. The construction was probably built by untrained workers due to the asymmetries in the space and the loose angles around the doors and windows. The roof was made with corrugated zinc plates topped with earth and mortar. Two illustrative figures can be seen 6.20 and 6.21.

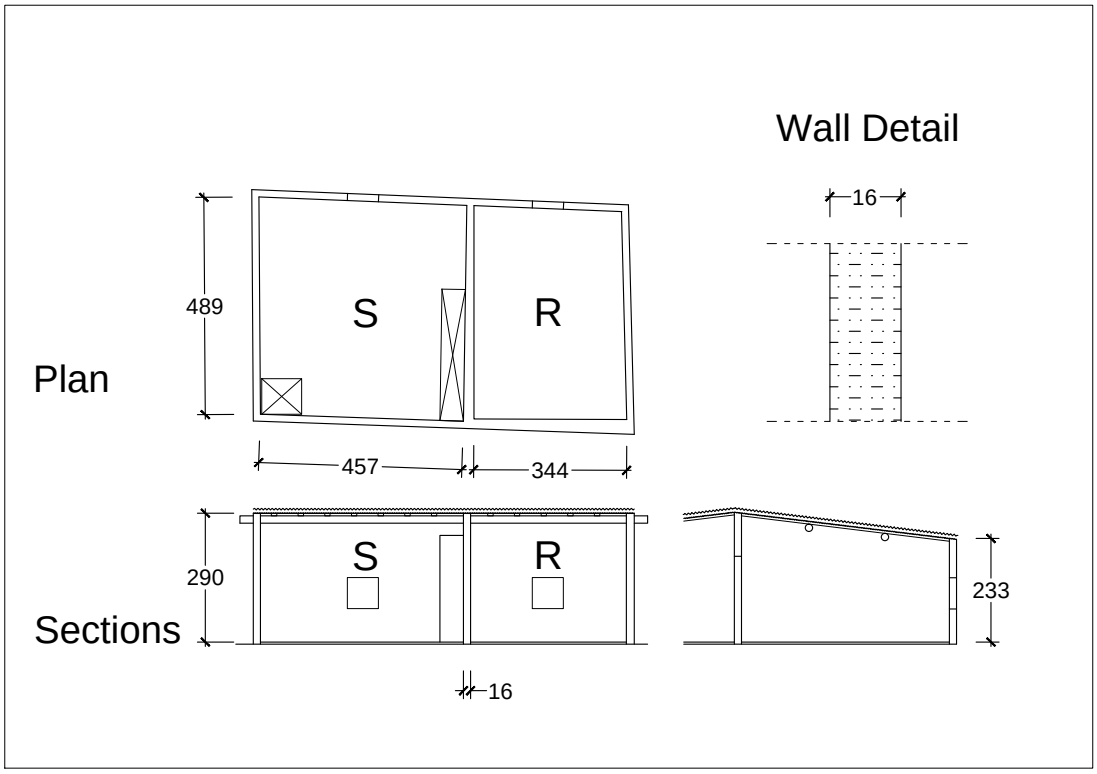


Figure 6.19.: Talib House - Plan and Section

The two rooms are connected by a 16 cm thick adobe brick partition and the measured density of the block is around 1418 kg/m^3.

Results

The simulation was made according to the measured thickness of the wall, the measured density and the assumed Young's modulus from similar adobe materials [de Almeida, 2012] but considering that it is denser than Adobe Old, the Young's modulus is expected to be higher.



Figure 6.20.: An image of Talib House showing the status of the building and the ceiling



Figure 6.21.: Room showing openings around obtuse edges around the door

Table 6.7.: Talib House - Simulation details

Material	**Thickness**	ρ[kg/m^3]	**E** [GPa]	η	f_c [Hz]
Adobe New	16 cm	1418	2.69	0.01	294

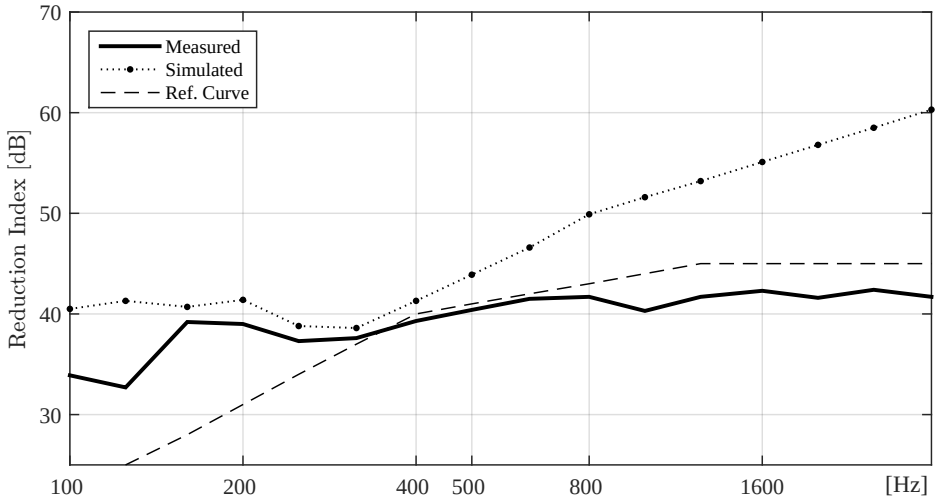


Figure 6.22.: Talib House - Measured and simulated reduction index

Based on the results from Figure 6.22 The R'w index is **41 dB** for the measured, and the Rw index is **49 dB** for the calculated graphs.

Low reduction index is found in the higher parts of the spectrum (above 315 Hz) as opposed to the predicted values. The critical frequency looks exactly the same for both graphs (at 315 Hz) and below that the measured graph shows a dip at 125 Hz which doesn't appear in the predictions.

Analysis

The deterioration of the transmission loss in the high octaves (Figure 6.22) is a result of badly insulated doors primarily, in addition to the obvious cracks in the walls (refer to Figure 6.23). The match between the measured and simulated results at and around the critical frequency (315 Hz) suggests that the physical properties of the simulation are close to reality. The dip at 125 Hz in the measured plot could be caused by resonances in the system.



Figure 6.23.: Talib House - Cracks in the wall near the window

6.3. Synopsis of Results

The results of the previous tests will be shown below in such a way to be able to compare typical and alternative materials according to their properties. The unit "mass/unit area" is the quantity chosen to represent the relation between density and thickness, where $(m'' = \rho \cdot d)$ given that ρ is the density in kg/m^3 and d is the depth of the material in meters, and therefore the unit addressed will be kg/m^2. In some cases the mass/unit area is a combination of two materials, like the block and the plaster, in such a case the result would be $(m''_1 + m''_2)$ where 1 stands for the block layer and 2 stands for the plaster layer. In addition to that the Young's modulus chosen for the simulation will also be presented together with the measured and the simulated Reduction Index values. Hollow Concrete Blocks will be expressed according to their thickness d.

It can be noticed from Table 6.8 that the estimation of the Young's modulus (E) for the compressed earth block is much higher than the rest of the simulations. The equation used to obtain E from the compressive strength is empirically derived from medium and high strength concrete, which could possibly be not the most suitable for the tested materials. Knowing that if the Young's modulus is lower the critical frequency is higher, then the results for both CEB tests will indicate a higher critical frequency, however after testing, the resulting single unit value was not affected by much. The conclusion will be based on the shown results.

Finally, as the theory says, the larger the mass per unit area the larger the reduction index, and this can be seen from the obtained simulated results. It is of more value for this research to observe the *reasons* causing a deviation from the predictions, which can be found in the next section.

Table 6.8.: Synopsis of Results

Typical Mat.	**Test**	**m"** [kg/m^2]	**E** [GPa]	R'_w [dB]	R_w [dB]
HCB (10)	BZU-Chemistry Lab	150	5.058	41	45
HCB (15)	Tantour Office	270	5.976	48	51
HCB (20)	Beit Hanina School	188	2.2	40	47
Alternative Mat.					
CEB (Jericho)	Al Dyouk Restaurant	205	22.91	37	48
CEB (Gaza)	UNRWA Prototype	538	20.13	44	64
Adobe (Old)	Fasayel Center	260.6	1.13	44	51
Adobe (New)	Talib House	227	2.69	41	49

6.4. Concluding remarks

It is possible to summarize the test results and outcome by relating the difference between measured and predicted values ($R_w - R'_w$) with the aspects causing those differences, if any.

Table 6.9.: Sum up of observations

Typical Mat.	**Test**	$R_w - R'_w$	**Comments**
HCB (10)	BZU-Chemistry Lab	4 dB	Acceptable
HCB (15)	Tantour Office	3 dB	Good relation between measurements and predictions
HCB (20)	Beit Hanina School	7 dB	Airborne sound leakage through openings
Alternative Mat.			
CEB (Jericho)	Al Dyouk Restaurant	11 dB	Leakage from cracks
CEB (Gaza)	UNRWA Prototype	20 dB	Leakage from cracks
Adobe (Old)	Fasayel Center	7 dB	Leakage from cracks and loose doors
Adobe (New)	Talib House	8 dB	Leakage from cracks and loose doors and windows

7. Discussion

It has been known since the inceptive papers on building acoustics that the traditional, thick and heavy partitions insulate sound better than the trending light-weight and space-saving partitions. However, as could be seen from the examples in this report, the purpose of saving space was not a design strategy where the alternative materials had been used, and it is possible to come across thick walls (ex. 16 - 30 cm like Talib House and UNRWA Prototype House), which means that suggesting thicker layers or coats would not cause design conflicts.

It was noticed that all the projects built with alternative materials result in a much lower reduction value than the prediction as opposed to the typical materials (refer to Table 6.9). A common aspect in those buildings is settling cracks and other leaks which were either formed with time or were formed during the construction phase. Even though it's possible to see a large difference between measured and calculated values in the typical materials (especially Beit Hanina School) but the reason is caused by an intended architectural design concerning the grille openings over the doors.

In addition to that, it was noticed that the construction precision was not encountered in the tested projects, for example all the "alternative" tests showed "weak" doors and/or windows especially in Talib House and Fasayel Center. It is worthy of noting that these buildings are in Area C, and the zone is inhabited by Bedouins whom in general have a different life style compared to what is referred to as a "modern" living standard, and therefore the purpose of having doors that don't close completely could be attributed to other functions such as ventilation.

The Young's modulus of blocks was approximated from tables of similar materials or from templates offered by Insul, which then affected the overall estimation of reduction index in the simulation and especially the prediction of the critical frequency. The mortar used in the construction also plays an important role in the determination of the total compressive strength of the structure, which in turn affects the Young's modulus. This data was not known for all the tests and therefore the simulated plots are reliable only to a certain extent. For the purpose of this study, it would be more beneficial to obtain data about the elasticity of the materials of interest to get a deeper analysis level on how they behave acoustically, and furthermore, to be able to design materials which would perform better in reducing noise and in other aspects as well.

8. Conclusion

The value in substituting cement with alternative materials is rewarding in the context of political and economic instability, and it paves the way for a more sustainable and greener building industry also from the energy perspective since these materials are completely recyclable and have a low carbon footprint. Those materials, however still need further development before they can qualify for the minimum sound insulation requirements of green building in Palestine.

Cost of production, shape (surface, texture, appearance), thermal insulation, durability, practicality, sustainability and maintenance are all factors that need to be part of the comprehensive study of alternative materials.

For a good noise protected climate it is recommended to keep the cracks under frequent control by filling them up with resilient material or by plastering and trim with attention on filling up the air gaps. During the curing phase of a mud-and-straw-based construction it is possible to follow up and mend the cracks that start to appear by rubbing over them with a sponge [Snell, Callahan, 2005]. In addition to that, if the sound insulation is considered to be a goal, then the choice of doors and windows and their framing should be part of the architectural design.

If alternative materials such as Compressed Earth Block and Adobe block will shape the future of the building industry in Palestine, more focus should be placed on the material design and building technique, as all the materials studied in this report showed a weak endurance against settling cracks and climate issues, and none of the case studies complied with minimum requirements of sound insulation for green buildings in Palestine. Nevertheless, even for the thin walls (10 cm), simulations showed a good reduction index, and with just moderately extra work on insulation (probably a thicker or denser coat of plaster) it is possible to achieve the minimum requirements given the above recommendations.

In order to be able to get reliable test results and arrive to a critical understanding of the sound behavior, it is very important to visit the site, listen and see, and form an educated impression about the space. In addition to that, the equipment used in the test should be carefully selected, unless more information can be obtained about them.

Finally, for better sheltering, it is advised that the material design be optimized in such a way to have a higher resistance to bombardment, meaning higher strength and supported with more reinforcements, if available.

8.1. Further Research

Since the results are based on a limited number of case studies, a statistical analysis was not possible and conclusions were based on observing tendencies in the results. The results would have probably been more inclusive if more tests were made, enough to make a statistical approach. Otherwise, it would be interesting to make the research with only few case studies given the knowledge of all the necessary physical properties of the materials, and the details of construction, or perhaps by making laboratory tests given the possibility to transport the materials. This would be good if archival data is required.

There are countries where building with adobe or compressed earth block is regulated, which would be interesting to compare with the results obtained from this study. Apart from the final sound insulation results of those cases, it would be more engaging to observe building techniques implemented in the decision making in their design.

Airborne sound insulation is not enough to understand the acoustical nature of a material. It would be necessary for building purposes to have impact sound insulation measurements for a better understanding on the behavior against vibrations.

During the tests, it was noticed that the sound in the rooms made with alternative materials was soft and decently damped, which signifies that the walls are microperforated and have a good absorption characteristic. It would be interesting to make a study on the room acoustical properties of those materials to discover whether they can be used in room acoustic design, and how to improve them.

8.2. Summary

The occupation in Palestine is causing a severe impediment in the natural development of economy, the building industry and even legislation. This results in a nation incapable of supporting itself, its population and their needs. Part of the problem is the construction materials which are denied entry in some places, the home demolitions and threatenings in other places, the difficulty in obtaining building permits and overpopulation. Despite all that, the construction sector is one of the largest industries in Palestine and 80% of the building materials, especially cement, are bought from Israel.

Two alternatives to cement are seen in today's Palestinian market, building with compressed earth block and going back to traditional adobe brick. Dedicated engineers are investing time and resources into the development and improvement of the aforementioned blocks to devise parallel quality of cement or at least achieve minimum requirements in building codes. Acoustical analysis has never been made on such materials or building systems using those materials, which is why this paper comes at a great value.

Airborne sound insulation measurements were made on three cases of constructions made with typical materials, precisely hollow concrete block, and four cases of constructions made with alternative materials, precisely compressed earth block and adobe block. Each measurement was compared to its parallel theoretical prediction, then the measurements were compared to each other.

Results showed an acceptable similarity between predicted and measured values of the typical materials, whereas this similarity was minimal for the alternative materials. In addition to that, the causes of bad insulation in the typical materials was noticed to be part of the architectural design or caused by leakage through doors and windows, whereas the alternative materials exhibited cracks causing a significant leakage of sound, which are not supposed to be intended.

Finally, if alternative materials will shape part of the future, sustainable building in Palestine, maintenance should be persistent and extra care should be taken during the curing and construction phases of a project. If those are kept constant, it is possible to achieve minimum requirements of sound isolation even with thin walls of alternative, earth-based materials.

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A. RCM Akustik - Mic 300, Specifications

CONDENSER MICROPHONE

The Mic 300 is a condenser microphone which has been developed specifically for the purposes of sound ranging.

Specifications:

Frequency response: 20 – 20.000 Hz
Directional characteristic: omni-directional
Sensitivity with field idling at 1 kHz: 6 + 1,5 dB mV/Pa
Electrical impedance: 500 Ω
Nominal load impedance: $\geq$ 2000 Ω
Signal-to-noise ratio: 64 dB
Maximum sound pressure for 0.5% distortion factor at 1 kΩ: 120 dB
Phantom power: 10 – 48 V
Feed current: 5,5 mA

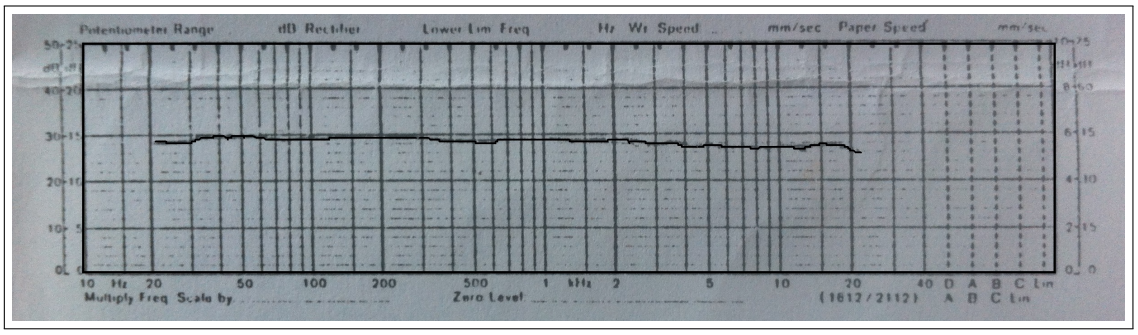


Figure A.1.: Frequency response

B. Wensn - Digital Sound Level Meter, Specifications

WENSN Digital Sound Level Meter (WS1361)

Accuracy: +1,5 dB
Measuring range: 30 - 130 dBA or 35 - 130 dBC
Frequency weighting: A and C
Time weighting: Fast & Slow
Level range control switch: 30–80 dB, 40–90 dB, 50–100 dB, 60–110 dB, 70–120 dB, 80–130 dB, 30–130 dB
Electret Condenser Microphone
Frequency response: Not available
Directional characteristic: Not available
Sensitivity: Not available
Signal-to-noise ratio: Not available

C. Measurements Procedure - Gaza

Airborne Sound Insulation Measurements Procedure (adapted from ISO 140 - 4: Measurement of Sound Insulation in Buildings and of Building Elements, Part 4: Field measurements of airborne sound insulation between rooms) – INSTRUCTIONS DOCUMENT

Background

This document is part of a study conducted by May Hanna for her Master's Thesis with preliminary title "Quiet and Alternative Building Materials from Palestine" where a comparative analysis will be made on several building systems; each made using a different building material made in Palestine. The methodology selected for this thesis is field measurements which requires following a standard during the performance of those measurements to obtain comparable results. Due to difficulties in transporting the desired building material from Gaza, where it is produced, to Jerusalem, where the measurements will be taken, in addition to the difficulty to get access into Gaza, the alternative chosen is to have the measurements carried out by a third party. This document specifies the guidelines on the procedure of measuring airborne sound insulation properties of a wall made of limestone brick so that the results are comparable. It is to be used by Eng. Emad Khalidi and Dr. Husammeddin M. Dawoud for the purpose of this study. Please read thoroughly before initiation of measurements, and keep a copy of the instructions available during measurements.

Both Dr. Husameddin Dawoud who is conducting the measurements, and Eng. Emad Khalidi who is involved in the production and development of the aforementioned brick, are greatly thanked for their support and collaboration. The results of this study will be offered to both.

Equipment

- Loudspeaker with sufficiently high sound power (approx. SPL 110 dB)
  Example: Cromo 8 by dB Technologies
- Sound Level Meter
- Computer

- Audacity
- ”White Noise” sound file (attached)
- Laptop/ipad/smartphone with white noise file
- Necessary cables
- Hearing protection

Setup

- The measurements shall be carried out in a (prototype) house in Gaza built using the limestone/mud brick. It requires the availability of electricity and two (furnished) rooms of similar volumes separated by a wall.
- If the rooms are not of similar volumes, loudspeaker should be placed in the larger room.
- Loudspeaker should always be placed in a corner facing the wall as in the picture attached.
- Loudspeaker positions: in the two corners on the other side of the room from the test wall. If two loudspeaker locations are not possible, use one corner and eventually 6 microphone positions instead of 3.
- Microphone positions: at least half a meter away from any surface, and sufficiently away from the loudspeaker (1 meter)- i.e. in the ”diffuse field”, and at least 0.7 meter away from one position to the other.
- Windows and doors should be firmly closed during measurements.
- Sound Level Meter should be set to NO WEIGHTING [dB] if available, otherwise please choose A-weighting [dBA], not C-weighting [dBC] and indicate it in the report.
- White Noise file should be accessible from smartphone/ipad/laptop.
- Sound files should be saved in .WAV format with names indicated in the next chapter.
- A plan showing the two rooms indicating rough positions of loudspeaker and microphone is required. Any ventilation ducts, false ceilings, openings or cracks should be indicated as well.

- Pictures of the four corners and any other interesting details in both rooms should be taken.

Measurements

Sound Pressure Level Measurements (SPL)

STEP 1:- Room 1: Sending Room (where loudspeaker is placed):

- Make sure the ”level range control switch” on the sound level meter is on 70-120 dB.
- Connect Loudspeaker to electricity
- Place it in one of the two corners farther away from the test wall
- Connect smart phone/ipad etc. to Loudspeaker via appropriate cable
- Connect Sound Level Meter to Laptop via AC output
- Open Audacity and make sure Setup>Audio Devices to be correct
- Wear hearing protection
- Loudspeaker and smartphone/ipad gain should be set to the maximum possible without distortion (approx. 110 dB)
- Play continuous White noise (on repeat)
- Take three recordings, in three different positions in the room, with length not less than 15 seconds each.
- Sound level meter should be moving slowly in a figure of ”8” for at least 15 seconds during each measurement.
- Place loudspeaker in opposite corner
- Take three more recordings in the same manner as above
- Audio files should be named as:

o $SPL_L1_1.1$
o $SPL_L1_1.2$
o $SPL_L1_1.3$
o $SPL_L1_2.1$
o $SPL_L1_2.2$

o *SPL_L*1_2.3
where the numbers 1.1 etc. refer to the loudspeaker position.microphone position.

STEP 2:- Room 2: Receiving Room:

- Keep the loudspeaker ON in Room 1, do NOT change gain settings.
- Move Laptop and Sound Level Meter to Room 2
- Make sure the ”level range control switch” on the sound level meter is on 30-80 dB.
- Take three recordings in the same manner as above
- Sound level meter should be moving slowly in a figure of ”8” for at least 15 seconds for each measurement.
- Place Loudspeaker in Room 1 in opposite corner
- Take three more recordings in Room 2 in the same manner
- Microphone positions and loudspeaker positions should be roughly indicated on a plan.
- Audio files should be named as:

o *SPL_L*2_1.1
o *SPL_L*2_1.2
o *SPL_L*2_1.3
o *SPL_L*2_2.1
o *SPL_L*2_2.2
o *SPL_L*2_2.3

STEP 3:-
Background Noise Measurements (BN)

- Turn off loudspeaker.
- Make sure the ”level range control switch” on the sound level meter is on 30-80 dB.
- Take four recordings of the background noise in the receiving room (Room 2).

- Sound level meter should be moving slowly in a figure of ”8” for at least 15 seconds for each measurement.
- Audio files should be named as:

o *SPL_B*2_1
o *SPL_B*2_2
o *SPL_B*2_3
o *SPL_B*2_4

STEP 4:-
Reverberation Time Measurements (RT60) - ”interrupted noise method”

- Take loudspeaker to Room 2.
- Lower Loudspeaker gain till three-quarters
- Make sure the ”level range control switch” on the sound level meter is on 50-100 dB.
- Wear hearing protection and PLAY white noise on loudspeaker.
- Using fixed microphone position: Start recording, wait for 10 seconds, PAUSE white noise, wait for 5-6 seconds, stop recording.
- Repeat for 2 more microphone positions.
- Place loudspeaker in the other corner. Do NOT change gain settings.
- PLAY white noise.
- Using fixed microphone position: Start recording, wait for 10 seconds, PAUSE white noise, wait for 5-6 seconds, stop recording.
- Repeat for 2 more microphone positions.
- Audio files should be named as:

o *RT*60_*Room*2_1.1
o *RT*60_*Room*2_1.2
o *RT*60_*Room*2_1.3
o *RT*60_*Room*2_2.1
o *RT*60_*Room*2_2.2
o *RT*60_*Room*2_2.3

STEP 5:- *Architectural Measurements*
Indicate on the plan: length, width, height of both rooms including positions and dimensions of doors and windows, with a note on the thickness of the separating wall and the material it is made with.

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