

**ASSESSMENT OF MOISTURE RELATED DEFECTS IN MASONRY
WALLS**

BY

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APPROVAL

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DECLARATION

I **Mr Elem Joel** have conducted this original study, as an individual, under the supervision of DR Kyakula Michael, and Dr Bulolo Sam, for the purpose of achieving an award of a master of science degree in structural engineering under directorate of research and graduate training of Kyambogo University. No part of this work, or material has ever been published, or written by any other persons, nor has been submitted elsewhere, to any organisation, or institution, in any form. No part of this work should be used elsewhere for any purpose, except; with the express authority, and permission that shall be granted by the researcher, cited, or acknowledgement in the; literature, text or referencing;

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DEDICATION

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LIST OF ACRONYMS / SYMBOLS

ADRI	Africa Resources & Research Institute Journal
AGWA	Australian Glass & Window Association
APA	American Psychological Association
ASHRAE	American Society of Heating & Air Conditioning Engineers
ASTM	American Society of Testing and Materials
BASE	Building Assessment & Survey
BCA	Building Association of Austria
BE	Structural Engineers
BRE	Building Research Establishment
BRRI	Building & Road Research Institute
C/S	Cement sand mix ratio
CBE	Civil and Building Engineering
Co	Company
CRST	Certified Surveyor in Remedial Treatments
CSIR	Council for Scientific and Industrial Research
DFP	Differing Vapour Pressure
DPC	Damp Proof Course
EPA	Environment Protection Agency
Eqn	Equation
ETIC	External walls Insulation Fixings
EWI	Engineering Works Instructions
EWI	External Wall Insulation
Exp	Experiment
FGD	Focus group Discussion
IBPC	International Building Physics Conference
Lab	Laboratory
LIPID	Laboratory of Integrated performance in Design
Ltd	Limited
MC or m.c	Moisture Content

Mi	Miles
Mpa	Megapascal
OFWAT	Office of the Water Service
PCA	Property Care Association
PPDA	Public Procurement and Disposal of Public Assets
PVC	Polyvinyl Chloride
RECCCE	Reconnaissance
SABS	South Africa Bureau of Standards
SI	Standard International Unit
SMC	Surface Matrix Crack
U. K	United Kingdom
U. S	United States of America
UBOS	Uganda Bureau of Statistic

ABSTRACT

Moisture intrusion into walls continues to be one of the top challenges in the building construction industry in Uganda. The study assessed and investigated moisture related defects in masonry walls, materials and construction methods to mitigate moisture rise and related defects in masonry.

This study made an assessment on moisture related defects in masonry walls, together with; carrying out a baseline survey on the building industry practice to find the cement to sand mix commonly used, and to assess prevalence of capillary water rise in buildings, determining the height of water rise by capillarity in masonry walls from damp proof course level, and finding out the materials and construction methods that can be used to mitigate moisture rise and related defects in masonry walls, as the specific objectives.

Experimental masonry wall models measuring; 1.6m wide x 1.9m height x 230mm thick for the study. The models were built of ordinary clay bricks, well plastered and built with cement sand mortar / plaster of mix ratios; 1:1, 1:2, 1:3, & 1:4. Selected vertical points on the wall surface were cored and tested for moisture content. It was found that the masonry walls were susceptible to moisture rise, and it was also observed that; the stronger the mortar mix, the less the capillary rise of moisture in the wall.

The height of water / dampness is highest at the bottom, just above the damp proof course levels, and moisture rise ranged between 0 – 0.6m above dpc levels. The study further investigated the efficiency of various water proofing materials that can be applied on the external walls to minimise capillary rise. The percentage reduction in moisture content was as follows; overlapping dpc 95, stone slates 94.1, glazed tiles 82.3, cement sand mortar in plaster with 4% clay giving 66.8, bituminous paint 44, facing bricks 43.7, and finally weep holes in plaster 30.5.

All the three objectives were observed to be realistic, and true. And the study therefore concluded that water proofing treatment of masonry walls should be done to heights of not less than 0.70m above DPC level to improve durability of masonry walls against related effects. This provides knowledge, and innovation to the construction industry. And this study also recommends; the use of overlapping of damp proof course, together with slates, as some of the best water proofing materials. There is also need for conducting more research on the areas of; variation of strength of building units with moisture content, and failure mechanism of most water proofing materials.

Key words; models, moisture content, capillarity, masonry, dampness and water proofing.

CHAPTER ONE - INTRODUCTION

1.0 Introduction

This report gives a concise information, as a result of a study that was undertaken by the researcher, concerning “**Assessment of moisture related defect in masonry walls**”. The order of documentation in this chapter are; background of the study, statement of the problem, the main objective of the study, specific objective, research questions, research justification, study’s significance, conceptual framework, and research scope.

1.1 Background.

Moisture related defects in masonry walls occurs in most buildings in the world today (Olawaju, Rashid & Aziz, 2015). Numerous researches have been conducted, regarding rising dampness in buildings (Muhwezi, Twinamatsiko and Acai, 2020), their treatments and solution to their impact on buildings (Trotman, 2007). There is a big engineering challenge concerning moisture related defects in walls, and research shows that this is a global challenge, to an extent that so many scholars have been trying to address the subject (Adrian & Neil, 2018) (Laldintluanga, Ramhmachluani and Ramthlangliani, 2020).

1.1.1 A Worldwide Perspective

Research demonstrates that, water enters structures by capillarity, and masonry defects in walls due to moisture rise has been so rampant worldwide (Sayed, Miklewski, Kahangi and Shareza, 2021). Research reveals that, molecular affinity between water and the nearby absorbing material determines how much water is absorbed. (Hall & Hoff, 2007).

Water moves slowly through building units, influenced by, cohesiveness, interpreted as the bond holding water molecules to one another (Nunziante, 2021). It also plays a role in moisture caused defects. Particular reference has been observed within the years 1994 to 1998, in a study carried out by the United States Environmental Protection Agency (Persily, Gorfainl, & Brunner, 2022). This study was conducted in more than 100 randomly selected private & public buildings, and the study revealed that; 85% of the buildings had been badly damaged by water, 45% had leaks. This shows that moisture causes terrible problems to buildings.

According to a study conducted in Norway by Tore Kvande involving 302 masonry defects in a span of 20 years from 1983 to 2002, masonry defects in structures accounted for 2% yearly maintenance cost in the construction industry (Tore & Kim, 2009). Also, moisture attack on buildings leads to severe exposure that results in a great amount of water absorption by bricks.

When the water in the bricks cools, it's volume expands by 9%, this results in; spalling, flaking off, crumbling of the bricks and plaster / finishes (Designing Buildings Wiki, 2021).

Problems resulting from water penetration can be avoided by undertaking procedures that are backed by knowledge about water behaviour in buildings. This provides good research on water defects in masonry walls (Maysum, 2022). And according to reports from the United Kingdom, structural dampness is associated with moisture. The shape and porosity of the construction materials through which capillary penetration takes place determine rising damp. Higher levels of humidity are to be blamed for the majority of structural wetness, regardless of the means by which it occurs (Adrian & Neil, 2018).

The majority of inhabitants in various Australian states, were exposed to fungus spores, which can lead to asthma and other respiratory-related illnesses, posing health dangers (Chudley & Greeno, 2004). Also, building construction of Australia observed that, many buildings had numerous stalactites in basements. Water damage, decaying carpets, respiratory illnesses brought on by water damage, mold and mildew are just a few of the issues involved in litigation (Kim, 2013).

1.1.2 African perspective

In Ghana, dampness was a highly widespread problem in both public and private structures. There has been a lot of worry expressed about the issue of dampness in residential buildings in Ghana for a long time, with a serious need to get a solution to wall defects associated with moisture rise in masonry walls (Agyekum, Ayardwa and Kofi, 2014).

The above study that was done by Kofi Agyekum, evaluated the responses to a questionnaire given to 247 construction professionals (architects, quantity surveyors, and site engineers) in Ghana to determine their perceptions of the causes and signs of dampness in most residential buildings. Widespread rising wetness, floods, and leaks were also shown by the studies. Water penetration and construction water are the major causes of dampness in residential buildings in Ghana (Agyekum, Ayardwa and Kofi, 2014). Also, it was further observed that; surface efflorescence just above skirting, stains especially in horizontal band, dampness at the base of walls up to 1.5m in horizontal band, softening / deterioration of plaster, and blistering / flaking of paints, are the major symptoms associated with dampness. The study recommends that, the actual laboratory tests, and further analysis on samples from those affected buildings should be done, to have a clear

understanding of how to address the problem of dampness. This was related to the choice of using bricks as a building unit (Dalkilic & Nabikoglu, 2017).

The National Building Institute, the Portland Cement Institute, and the South African Bureau of Standards came to the conclusion that SABS 1090 compliant sands will always result in mortars with good rain resistance (Walker, & Kearns, 2005). The universal reason for rain infiltration in brickwork structures was an incomplete filling of perpendicular joints. Therefore, filling of mortar joints should be considered in brickwork design (Graham, Ballin & Kazirukanyo, 2019).

Rising moisture was one of the issues that buildings are sadly increasingly experiencing as a result of improper construction techniques (Straube, 2002). The above research by Straube further observed that, 78 randomly selected building environment specialists in Kumasi and Ejisu who had encountered moisture rise in buildings, were collected using snowball sampling and purposive sampling procedures. The study confirmed that dampness was associated with; lack of use of a damp proof barrier, high groundwater, porosity in the masonry / concrete, and sand flooding. Making repairs to plumbing leaks, using certified waterproof chemical injection, and applying admixtures were some of the key precautions advised to prevent growing dampness, it has been noticed (Oduru & Ankrah, 2017).

1.1.3 A National View

A number of scholars have conducted research on dampness in structures. Notable among these was Bakashaba and Zzigwa (2021), whose work revealed that there have been many cases of dampness in structures in Uganda, with the cause being attributed to mainly capillarity, with credible sources that include water leakages in structures (Eno, 2022). It was also observed that leakages slowly weaken the strength of structures progressively.

This same research concluded that the use of waste motor oil reduces dampness levels in sundried bricks from 18.25 to 11.2% (Bakashaba & Zzigwa, 2021). Research done on a majority of modern buildings reveals that, structural dampness is unwelcome in building structures. It was always as a result of moisture infiltration or condensation in buildings (Chew, 2021). And condensation and rain penetration are elements reliant on the ambient environment that contribute significantly to damp problems in buildings (Trotman, 2007).

1.2 A statement of the Problem

Water intrusion into buildings continues to be one of the top challenges in Building construction in Uganda, and current building codes (Statutory Instruments Supplement No 2, 2020), and rules that are related to the construction industry (National Building Standards Code, 2019), have not been able to provide a remedy.



Figure 1.1: Defects in masonry walls

The majority of buildings, built lately as shown in Figure 1.1 above, had widespread flaws that are envisioned in terms of; peeling paint and plaster, colored stains (insoluble salts generated) on wall surfaces, and loss of aesthetic among others, which poses a big problem (Ercio & Hipolito, 2014). This is connected to water infiltration and can be linked to capillary rise, seepage through the materials, inadequate construction techniques, poor quality of materials used in construction (Maysum, 2022). Buildings constructed in the 1960s and 1970s, never experienced as much of this observation of water penetration (Brown & Williams, 1996). A systematic illustration of buildings affected by water penetration into buildings in Northern Uganda are as shown in Table 1.1 below;

Table 1.1. Sample buildings affected by water penetration into buildings in Northern Uganda
(Source: Author)

Building	Location	Defect
Lira District Local Government Headquarters Works Department	Lira Town	Peeling of plaster, fading of paint, & staining of wall
Abim Hospital	Abim Town	Stains on walls, peeling of plaster
Abim District Headquarters	Abuk Town	Peeling of plaster, staining of walls
Amolatar District Headquarters	Amolatar Town	Flaking of walls, peeling of Plaster, & staining of walls

An example of buildings constructed long ago, but still having walls free from water defect is Lira District Local Government Headquarters a three level structure located in Lira Town shown in Figure 1.2 below;



Figure 1.2: Photo of Lira District Local Government Headquarters built in the 60's, & 70's showing no wall defects

To discover a long term solution to this problem, the building industry was forced to adopt a requirement for scientific approach and conduct experimental research, particularly on materials (Graham, Ballin & Kazirukanyo, 2019). Therefore, by assessing the material quality and modeling water penetration through building components, the aim of this study was to identify a long term solution to the previously mentioned problem.

1.3 Main Objective of the study

The main objective of the study was to “improve durability of masonry walls against moisture related effects”

1.4 Specific Objective of the study

The specific objective of the research was;

- a) To carry out a baseline survey on the building industrial practice to find out the cement to sand mix commonly used, and to assess incidence of capillary water rise in buildings.
- b) To determine the height of water, rise by capillarity in masonry walls from damp proof course level
- c) To find out the materials and construction methods that can be used to mitigate moisture rise and related defects in masonry walls

1.5 Research Hypotheses or Questions

- a) What is the common cement to sand mix used in the building industry, and to what extent are the incidences of capillary water rise in buildings?
- b) What is the height of water rise by capillarity in masonry walls from damp proof course level
- c) What are the materials and construction methods that can be used to mitigate moisture rise and related defects in masonry walls

1.6 Justification

Dampness, and water infiltration into buildings continues to be one of Uganda's construction industry's challenges. And current building codes and rules that are related to the construction industry have not been able to provide a remedy (National Building Standards Code, 2019). Even though there are many active engineers in the nation, the issue of water intrusion into buildings has persisted, impairing a number of structures in Uganda (Olaewaju, Rashid, & Aziz, 2015), even those owned by the government and engineers themselves. Therefore, the goal of this research study was to find a remedy to this problem.

Rising damp has been very common, and the Building Research establishment (BRE) says in its evaluation (Agyekum, Ayardwa and Kofi, 2014). As a result, there was evidence that the assessment of moisture related defects in masonry walls was a researchable study, making it legitimate.

1.7 The study's significance

When this research is completed, it will therefore restore engineers' hopes for finding a solution to the problem of water penetration into buildings, which was a challenge to society. It will also help to improve existing structures that have been severely damaged by water penetration resulting in their structural failures and collapse (Assingwire, Muhwezi, & Ssenkozi, 2021).

Modern structures that are intended to withstand water penetration would advance the construction industry and be a guiding concept for controlling new projects in the country, and perhaps elsewhere if it could be embraced worldwide, by adopting practical solutions to masonry defects in walls associated with moisture (Austin, Robins, & Godier, 2002). As a model intervention in the construction industry with widespread acclaim, this would enhance the academic excellence of Kyambogo University.

1.8 Study's scope

In this area, the study was evaluated using three criteria: content, geography, and time frames.

1.8.1 Time scope

From December 2021 to June 2022, this significant investigation was carried out in the districts of: Dokolo, Lira Abim, Moyo, & Kampala.

1.8.2 Content scope

The study examined moisture-related flaws in masonry walls, particularly in the Dokolo District. The analysis of masonry defects brought about by water infiltration through mortars, plaster, and finishes constituted the main focus of the content. Actual models were constructed for experiments used in the study. Cracks and colored stains on the walls are some of these flaws. The study was limited to the followings;

- i. Carrying out a baseline survey cement : sand ratio commonly used in Uganda
- ii. Determining the effects of mortar / plaster on capillary rise
- iii. Determining the height of capillary rise in masonry walls
- iv. Determining the effect of wall finishes on capillary rise

1.8.3 Geographical scope

The Dokolo area in northern Uganda was used for literature review & problem statement, and also served as the study's base of operations. There are 209,800 inhabitants there, and the area is 1,073 km². Lira, Moyo & Abim District Headquarters was another important research hub for inspecting buildings that has been severely impacted by moisture. The study was carried out in Northern Uganda, more specifically in the districts of Lira, Abim, and Dokolo. It is found in Northern Uganda in East Africa, above the Equator. It has the Eastings 3310 and Northings 0115 coordinates, natural vegetation, wide land, and a few hills. The temperature ranges from 33 0 C at its highest point to 19 0 C at its lowest point. Tropical weather prevails there.

Dokolo district lies between Lira and Soroti on the main highway. Dokolo District has got 5 Sub-counties covering Dokolo, Agwata, Batta, Ngai & Kwera. This is shown in Figure 1.3 below;



Figure 1.3: Map of Dokolo District, Source: Google Map

1.9 Conceptual framework

1.9.1 Introduction

A conceptual framework used in this was a collection of overarching concepts and guiding ideas drawn from pertinent disciplines of study and used to organise subsequent presentation. It was a diagrammatic representation that illustrates the link between dependent and independent variables (Young, 2009).

According to Mugenda (2008), a conceptual framework refers to a brief description of the phenomenon being studied that includes visual or graphical representation of the key study variables. The main factors in the study were divided into independent, moderator, and dependent variables. According to Mugenda (2008), the dependent variable, also known as the criterion variable, were influenced by the independent variables and was known as predictor variables because it predicts the amount of variation that happens in another variable.

This notion aims to illustrate how the researcher synthesized the available material to describe the topic in his research on the assessment of moisture-related faults in masonry walls. Given the information of the observations on the research topic, diagram Figure 1.1, illustrates procedures and sequence that were taken during the investigation. This was by describing the differences and arrangement of the various variables used to depict the modeling of water penetration into masonry walls.

1.9.2 Interrelation of the different variables

The interrelation between the variables were as shown in Figure 1.4 below;

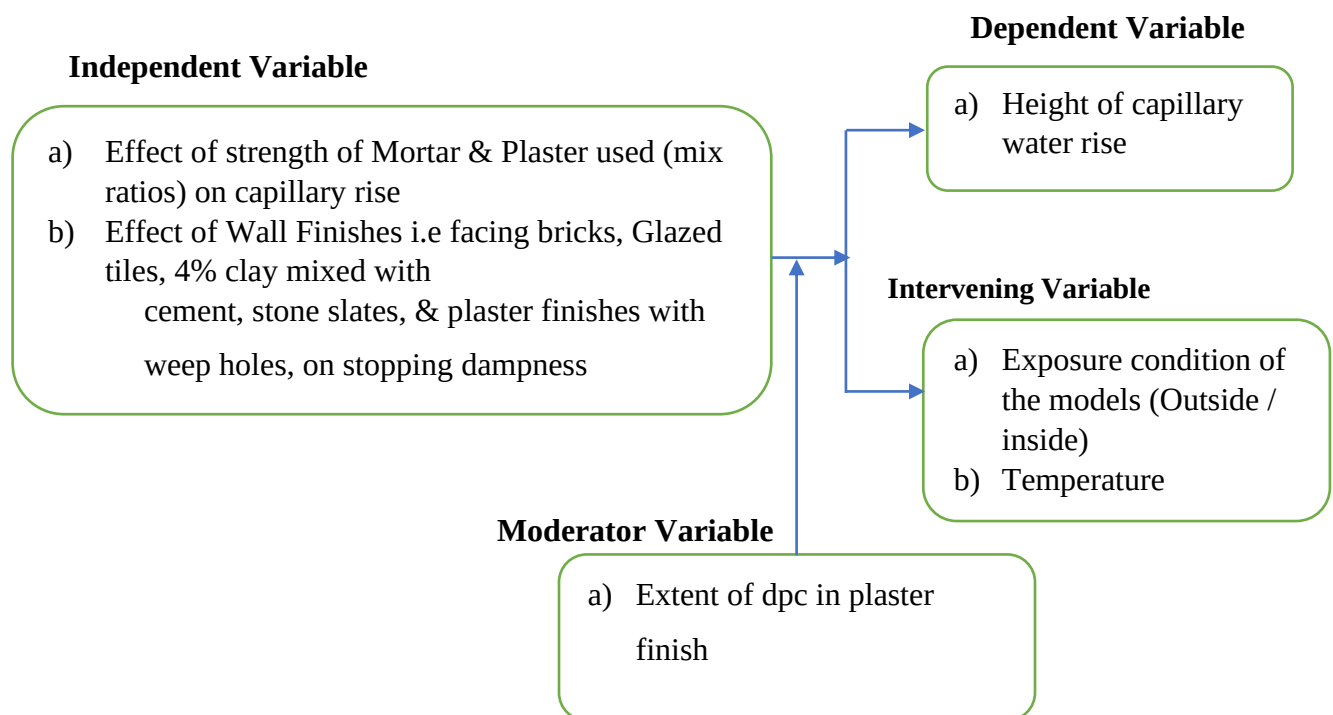


Figure 1.4: The detail of the variables for the study

CHAPTER TWO - LITERATURE REVIEW

2.0 Introduction

The content used in this comprehensive chapter, in relation to assessment of moisture related defects in walls was by referring to secondary informations, to aid the researcher in developing a through primary information. The method of citation, and referencing used in this chapter that applies to the study, was APA sixth edition. In accordance with recent studies on the assessment of moisture related defects in masonry walls, and generally rising dampness or water penetration into structures, the literature was evaluated with a focus on defects in walls connected to moisture (Eno, 2022). This was intended to improve durability of masonry walls against related effects.

This structure had been used to support the theory of “assessment of moisture related defects in masonry walls”. It also gives an account that; describes the theory of assessment of moisture defects in walls, explains why the research problem existed, and this gave proof of the study. It was used to explain; phenomena, make predictions, and conclusion, with a sole objective of guiding the research (Vinz, 2002).

Much as the construction industry in Uganda is growing very fast, one of its challenges had remained capillary rise into masonry walls, with its associated defects. The construction industry had no choice but to adopt a need for scientific approach by conducting experimental research especially on materials, to find a long-lasting solution to this issue (Graham, Ballin & Kazirukanyo, 2019). This study provides a long-term solution to the aforementioned issue by examining the material quality, simulating water penetration through building components.

2.1 A review of the theory

2.1.1 Historical background of rising damp

Since the beginning of time, increasing damp has been a challenge in masonry walls. According to the British Medical Journal of May 25, 1872, dampness in structures have been so much wide spread globally, causing tremendous challenge to the construction industry, and there had been so much intervention by a number of stakeholders in addressing the issue (Lesslie, 2017). Also, the Roman architect Vitruvius studied the issue of dampness climbing up walls with great curiosity and provided advice on how to create structures to avoid the issue known as wet dwellings.

Interestingly, though, there were no traces of damp proof courses or gratings to demonstrate that ventilation to the ground floor joists had not been overlooked. The effects of the flaws are more evident in the house as it currently stands in the damp and green stains that can be observed everywhere from the ground level to a great height up the wall (Burdett, 1885). In the United Kingdom's Public Health Act of 1875, prevention of pollution & flood control was emphasised seriously (Department of Environment Food & Rural Affairs, 2005), and it's important to note that, there was now an established requirement for a damp proof course in walls to prevent rising dampness, and rising dampness has been frequently discussed.

Rising wetness was described in an article from 1872 in the British Medical Journal. It will be discovered that this was put in the wall as well, close to the ground line, so that the heavy rain strikes the ground and splashes above it, even though the rising dampness is stopped by what was formally referred to as an impenetrable damp proof course (Burdett, 1885).

Wet walls absorb much more heat than dry ones, which was something to keep in mind, and they frequently contribute to the development of rheumatism, kidney disease, and colds. Simple methods can be used to stop rising damp from the earth (Eric & Zhongy, 2010). Good Portland cement concrete should be placed six inches thick throughout the entire building site. And all walls should be supported by concrete that was at least nine inches thick. The entire system of foundations should be cut off from the superstructure by a damp course (Lesslie, 2017). A double layer of thick slates embedded in cement, blocks of stoneware with patent perforations, or three-quarters of an inch of the best asphalt can all be used as preventative measure. The investor and philanthropist Henry Burdett outlines the need for an effective damp-proof course to protect against rising moisture in his book (Burdett, 1885), damp-course ceramics made of vitiated stone.

We must now focus on the walls, which are similarly important to protect from rising damp, after making sure that air and moisture have no opportunity of rising into the home from the ground beneath the floor (Adrian & Neil, 2018). Research reveals that; stone wall on soil that has the ability to store moisture, the moisture will surely follow the law of capillary attraction and climb the wall unless you take steps to stop it (Austin, Robins, & Godier, 2002). The best way to avoid this was to place something impervious between two courses of brickwork bars that was above the floor level but below the ground. Examples include a course of intentionally vitrified stoneware, two layers of

slates laid in cement, or another impervious material that was equally effective (Designing Buildings Wiki, 2021).

According to the eminent scholar Sir Henry Burdett (1885), page 124, there are spaces between damp courses that allow moisture to rise in jerry built homes. Henry Burdett warned prospective home purchasers to be extremely vigilant and check houses for the presence of a damp-proof course and to ensure that it was of high quality because he was so genuinely concerned about the quality of the structures in Victorian England (Burdett, 1885).

In a variety of earlier works on the subject, structural dampness was defined as the presence of unwelcome moisture in a building's structure, whether as the result of direct infiltration from the outside or general condensation from within (Persilyl, Gorfainl, & Brunner, 2022). Condensation and rain penetration, which are dependent on the ambient environment, account for a significant share of damp issues in structures. Rising Damp was the term for the evaporation-limited capillary penetration of fluid through concrete or masonry from the ground up (OlaREWaju, Rashid, & Aziz, 2015). It was controlled by the shape and porosity of the construction materials.

Higher humidity levels worsen structural damp regardless of the processes via which it occurs. Buildings must be constructed to resist rising damp, penetrating damp, and condensation, under Section 5.2 of The Building Regulations 2010 Approved Document C, "Site preparation and resistance to pollutants and moisture," which is part of the UK's building regulations (UK Statutory Instrument, The Building Regulation 2010 of the UK, 2010). It states that, walls ought to;

- a) Prevent moisture from the ground from penetrating the building's interior.
- b) If the wall was an external wall, it should not be harmed by moisture from the ground or carry moisture from the ground to any portion which would be harmed by it.
- c) Prevent rain from penetrating structural elements that might be harmed by moisture; and
- d) Prevent precipitation from penetrating the building's interior; and
- e) Be created and built in a way that prevents interstitial condensation from impairing their structural and thermal performance, given appropriate occupancy conditions
- f) Not encourage surface condensation or mold growth.

This body of literature demonstrates how pre planning measures were used to guarantee that new constructions wouldn't be harmed by water or dampness. Structures are still being impacted by

moisture, though, and this necessitates more investigation into the issue. According to the UK's Homes Act 2018, private landlords in England and Wales are required to make sure that the homes they rent are "free from damp," and this identification includes using a variety of tools and techniques to look into the presence of moisture in building materials (UK Statutory Instrument, Homes (fitness for human habitation) Act , 2018).

When properly applied, they can be a useful tool for research. According to Kim Longrove, the skill and knowledge of the person doing the treatment, and the importance of his or her inquiries frequently outweighs the kit they are carrying. A correct or wrong diagnosis of damp depends on the experience and qualifications of the surveyor. Condensation, for instance, may occasionally be mistaken as another type of wetness, leading to the inappropriate type of treatment being recommended (Kim, 2013). However, their reports frequently recommend that dampness problems be addressed by a specialist damp and timber surveyor with a CSRT qualification.

Chartered building surveyors are typically adept in recognizing dampness issues. BRE Digest 245 outlines the procedures for assessing growing damp in buildings (Agyekum, Ayardwa and Kofi, 2014). The amount of the height of the increase in wall wetness was not mentioned in this investigation, which was carried out during those years in the UK. This suggests that additional study might be beneficial in developing a mathematical representation for increased dampness in structures. Additionally, there were techniques for both preventing and treating moisture in buildings.

Additionally, creative building design and meticulous construction might mostly minimize dampness (Designing Buildings Wiki, 2021). In order to operate as a barrier that prevents water from passing through, well-built modern homes in the UK contain damp proofing in the form of a synthetic damp-proof course (DPC), around **15 cm** above ground level. For the first few courses above ground level, slate or "engineering bricks" with a low porosity were frequently employed, and they can assist minimize the issue.

Treatment options for moisture in older buildings are numerous (Nishant, 2022). Research shows that correctly identifying the forms of moisture affecting a building was essential to choosing an effective cure. First, the source of the dampness must be removed, either by improving drainage or repairing leaky pipes. In essence, BRE Digest 245 provides a number of ways to treat rising damp,

including the installation of physical and chemical DPCs as well as the utilization of land-drains. Before rebuilding the plaster and repainting, any significantly damaged plaster or mortar must first be removed, and the wall must then receive special care.

There were other treatments for humidity. Building-related factors contribute to humidity in enclosed spaces. Building leaks, rising wet, and porous walls all contribute to structural dampness brought on by high humidity levels (Ercio & Hipolito, 2014). The building's construction can also contribute to indoor humidity and unwelcome moisture. For up to the second year of occupancy in the building, wet materials, such as lumber stored exposed outdoors before construction, might result in increased inside humidity. Elevated relative humidity was most frequently caused by inadequate drainage systems in homes. This causes substructures like crawl spaces and basements to get moist. The wetness causes vaporization, which transmits water vapor into the inside of the building.

The building can be exposed to water vapor through supply air pipes in building slabs and moved by warm forced air. Leaky return air ducts in houses with crawlspaces can also allow water vapor to enter a building (Adrian & Neil, 2018). The presence of people significantly raises the interior humidity level. Simple human functions like breathing and sweating cause an indoor environment to become damp. Cooking and taking a shower increase interior humidity levels, which have a direct impact on a home's structural wetness.

Home features can also raise a room's humidity level. Hot tubs, indoor swimming pools, aquariums, and even indoor plants all increase the humidity of a room. All of these characteristics have the potential to raise a home's humidity level above the ideal range of thirty to fifty percent. Based on the season and temperature, humidity levels in an interior setting must be taken into consideration (Brown & Williams, 1996).

Both structural dampness and an increase in the health concerns related to moisture damage are likely to happen. Furthermore, there were also prevention and care for moisture in buildings. By using vapor retarders and other strong portland cement (Walker, & Kearns, 2005), a structure can avoid structural moisture or stop it from getting worse. Also, altering occupant activities and indoor mechanics is one method for lowering humidity levels in an indoor setting. Bathrooms and kitchens must each have their own vents (Persily, Gorfainl, & Brunner, 2022). Furthermore, washing

machines must be vented outside. Both of these are crucial in order to reduce indoor moisture brought on by the activities that take place in these interior spaces, which produce humidity. When not in use, moisture sources like hot tubs and indoor pools should be sealed off with airtight lids to keep indoor humidity levels low.

Previous investigations conducted in the UK indicated that rain penetration was a frequent cause of water intrusion into structures. A typical type of moisture in structures was rain penetration, commonly referred to as "penetrating damp". It can happen through openings, walls, or roofs (e.g. window reveals). Water frequently seeps through a building's exterior and appears inside (Lesslie, 2017). Defects in masonry walls includes;

- 1) Roof flaws include defective flashing, broken or missing slates or tiles are examples of common flaws.
- 2) Masonry or brick defects, such as missing or broken pointing. stones or bricks with pores.
- 3) Inadequate or missing caulk around windows and doors.
- 4) Unable to weep holes.
- 5) Trays that are missing or broken in cavity walls.

Rain penetration was most frequently linked to single-skin walls in Walls, but it can also happen via cavity walls, for instance by tracking through wall connections. Since single skin brick walls of normal thickness (9 inches) have long been thought to offer insufficient protection against rain penetration (Adrian & Neil, 2018), cavity wall construction has been the norm in the UK. That was noted in the 1944 Housing Manual that was produced by the Ministries of Works and Health.

"When built correctly, with attention to detail at the heads and joints of apertures, an 11 inch brick cavity wall should provide a minimum level of resistance to rain penetration. Unrendered 9 inch walls are seen as being below par." Although renders are frequently used in an effort to prevent rain from penetrating a building, they must be kept in good condition in order to perform this role (Persilyl, Gorfainl, & Brunner, 2022). Rainwater can seep through relatively minor render fractures and into the underlying masonry. Hugh Braun noted issues with specific render types that were frequently utilized in the late eighteenth century and during the Victorian era in his 1954 book "The Restoration of Old Houses."

A variety of patent water-repellent cements started to appear on the market by the end of the eighteenth century, the most well-known of which, roman cement, remained in widespread use throughout the Victorian era; many old buildings were rendered with this substance (Walker, & Kearns, 2005). Its adherence was weak; as a result, it frequently separates from the walling across sizable areas and can be removed in bulky sheets. Additionally, the main causes were;

- 1) Cracks
- 2) Porous masonry (underfired bricks, porous stone, or porous mortar)
- 3) Defective pointing
- 4) Unfilled joints and perpend
- 5) Poor sealing around doors and windows
- 6) Wall openings where cables or pipes emerge Poorly applied render

Exacerbators of rain penetration were also present (Adrian & Neil, 2018). When a wall has one or more of the aforementioned basic causes of rain penetration, one of the exacerbators of rain penetration listed below can exacerbate the issue;

- 1) Faulty rainwater goods Moss growth on roof tiles (which prevents rainwater goods from working properly)
- 2) Faulty or missing window sills (causing high concentrations of rainwater to bear on section of wall below window)
- 3) Location/aspect of wall, such as how walls facing prevailing wind are more susceptible to rain penetration issues
- 4) Non breathable coatings, such as acrylic masonry paints, particularly when applied to a poorly prepared masonry substrate (see BS8104)
- 5) Extreme rainfall events during times of heavy
- 6) Prolonged rainfall, walls that are typically thick enough to keep rain from reaching the inner face may become insufficient.

Most often, changes to a building made with impermeable materials can make rain penetration worse by retaining moisture. With regard to the installation of retrofit external wall insulation, this can be a special issue (EWI). It's important to note that rising damp or water infiltration into structures were widespread (Borri, Corradi, & De Maria, 2020). The term "rising damp" refers to the capillary action that causes water to be absorbed in the lower portions of walls and other ground-

supported structures (Lesslie, 2017). Although rising damp as high as around 5 meters has been seen, the average rise height is substantially smaller and rarely exceeds 1.5 meters. There have been numerous reports of rising damp for at least 200 years.

Rising damp is a phenomenon that happens when ground water rises through porous construction materials like brick, sandstone, or mortar, much like how oil rises through a lamp's wick (Eric & Zhongy, 2010). Placing a piece of porous brick, stone, or mortar in a shallow tray of water will demonstrate the impact by showing how the water is absorbed by the porous material and moved above the water line. A distinctive "tide mark" on the lowest portion of the afflicted walls can be used to identify rising wetness (Agyekum, Ayardwa and Kofi, 2014). Solvable salts in the groundwater, especially nitrates and chlorides, are to blame for this tide mark. These salts gather at the "peak" of the increasing water because of evaporation's effects. These salts build up at the "peak" of the increasing damp due to the effects of evaporation.

It was uncommon to discover rising damp on levels above ground level because it was frequently brought on by moisture from wet ground (Eno, 2022). Research reveals that, the passages mentioned above, which are a collection of secondary data from earlier studies, provide enough details about the basis for water penetration into buildings, the primary focus of my research issue (Eric & Zhongy, 2010). The actual mathematical solution to the size of the water surge inside buildings has, however, been seriously lacking. And in order to break the deadlock, more research is required.

2.1.2 African architectural history of water infiltration

A number of African researchers have studied rising damp / water infiltration into buildings (Straube, 2002). One of which was a recent study from Kumasi, Ghana, in both public and private structures in Ghana, the issue of dampness has long since grown alarmingly severe. An investigation was done on a three-bedroom residential bungalow owned by the department of urban roads in Kumasi (Oduru & Ankrah, 2017), which has experienced dampness issues for the past four years since it was built and occupied. Also, a study was done using a two stage damp investigation technique to determine the places in the walls that were significantly affected by moisture. This approach took a comprehensive view of dampness in buildings (Agyekum, Ayardwa and Kofi, 2014). But modelling of moisture penetration was not handled. This becomes a research gap.

Visual survey (site inspection) findings revealed signs such as; blistering of paint, flaking of mortar, wet patches in horizontal bands, surface efflorescence, and occasionally mold growth to be connected to the walls (Ercio & Hipolito, 2014). The research revealed that the building's wetness may have been brought on by a mixture of plumbing leaks, rainwater splash back, lateral penetration, and growing dampness. The living room, bedrooms, and bathrooms all had greater moisture contents, according to the results of the nondestructive testing.

A thorough investigation indicated that plumbing leakage was a contributing problem, particularly in the interior walls, since it was unusually higher in the bathrooms than in the other rooms (Olawajun, Rashid, & Aziz, 2015). Although the study identified plumbing leaks and water penetration as contributing factors to the dampness experienced in the walls of the bathrooms, additional destructive tests are advised to confirm the true source(s) of dampness in the walls of the bedrooms and living room. This will greatly aid in identifying the correct remediation to manage or cure the issue. The height of the increase in dampness was not addressed by this study, so additional research is required to provide a solution to the problem of rising moisture in structures.

2.1.3 How to prevent growing damp

According to Jurin's law, which states that the greatest height of increase is inversely related to the capillary radius, an observation was to be made by making a keen observation (Loannou & Andreou, 2008). Jurin's Law would predict an astounding maximum rise of about 15 m, based on a good observation of the typical pore radius for most building materials of 1 m, but in practice, because of the effects of evaporation, the rise would actually be much lower, and this also varies from one building to another. There was a lot of fact that arose from the earlier work of scientists like; Eric and Zhongy, where they observed that; rising dampness is always associated with capillarity effects, absorption of moisture, evaporation and then formation of salts (Eric & Zhongy, 2010). The basis of their research work evolves around the study of rising dampness by carrying experiments on different mortar samples, and observations were compared with theoretical models. Results of these magnificent studies reveals very significant relation between mortar and height of rising dampness in structures or masonry walls. This was explained by the theories surrounding “the sharp front models”. This was further explained by the research performed by “Hall and Holf” in 20002, that gave the approximation and simplified modelling of unsaturated capillary transport, without complicated numerical and computational analysis. It was also highly observed that rising

dampness was associated with underground water, and the water passes through the pores of the building units. Building units like fired bricks are from fired silicate structure which contain pores which was a result evaporated water at manufacturing stage (Loannou & Andreou, 2008). Mortar also contains pores, and the network of these pores provide the pass way for rising dampness. Water has high affinity with capillarity, quite related to the diameter of the pores. Where it was found out that the pore size was inversely proportional to the height of the rise in moisture, this was termed Jurin's law, given by the expression in equation 1 below;

$$h = \frac{2\gamma \cos\theta}{r\rho g} \dots\dots\dots \text{Eqn (1)}$$

The symbols above mean;

γ = surface tension

θ = contact angle

r = capillary radius

ρ = liquid density

g = gravity

The magnitude of height h called rising dampness was inversely proportional to pore size r , for instance; when $r = 0.1\text{mm}$, $h = 14\text{cm}$, and when $r = 0.01\text{mm}$, $h = 1.4\text{m}$.

As the moisture rise up in masonry walls, its effect is counteracted by viscous forces, hence evaporation was determined by; temperature, humidity, air movement and surface condition. According to Hall & Holf, the interaction the boundary between wet and dry surfaces of the wall, was sharp, and this provides the concept of evaporation (Loannou & Andreou, 2008), and this was given by the expression in equation 2 below;

$$H = S \left[\frac{b}{2e\theta} \right]^{1/2} \dots\dots\dots \text{Eqn (2)}$$

Where;

H = height of the rising damp front,

S = sorptivity (the suction of water into the mortar),

b = wall thickness,

e = rate of evaporation per unit area of the wetted surface,

θ = moisture content of the wetted surface

The rising dampness causes dissolution of the salts in bricks and mortar, redistributing the salts, and to a great extent, this phenomenon has re directed the argument on moisture content, & rising dampness.

In their recent research study titled "Rising damp or capillary rise dynamics in walls," Christopher Hall and William D. Hoff established a physical sample model of rising damp. The approach is firmly grounded in the physics of observed evaporation from building surfaces and empirically validated studied features of porous building materials. The model can be used to forecast the height to which wetness will increase in a specific wall, according to scientific observation (Hall & Hoff, 2007).

The wall thickness, sorptivity of the wall structure, and rate of evaporation from the walls are the main factors influencing the observed height of rise. BRE Digest 245 lists a number of scientific experimental factors that can, in most cases, influence the height of the rise, including rate of evaporation from the wall, pore sizes of the masonry, salt content of the materials and the soil, groundwater and degree of saturation, and use of heating within the property. Additional work has also confirmed experimentally the importance of mortar properties in determining the height to which dampness will rise in most walls (Chudley & Greeno, 2004). Comprehensive descriptions have also been given of how documented seasonal fluctuations in evaporation rate affect the height of moisture increases.

Rising damp has been a long-standing and pervasive problem, according to a review of the data and scientific publication commissioned by the Property Care Association and expertly completed by the University of Portsmouth. Additionally, it stated that "This occurrence has been documented and described since very ancient times (Property Care Association, 2017). In the latter half of the 19th century, the majority of building researchers recognized it as a problem for public health "As demonstrated in the classic review, which examined rising dampness data and studies from a number of nations, including the United Kingdom, Portugal, Germany, Denmark, the Netherlands, Greece, Australia, and Malaysia, rising dampness data were examined in the review.

The presence of various types of undesired moisture in buildings causes a gradual loss in the strength of the majority of structural elements, bad living circumstances for people, and health issues for the inhabitants (Property Care Association, 2017). The bulk of residential buildings in India are typically made of stone masonry and are not typically engineered. Additionally, based on the items that are now on the market and their own assessments of the situation, the inhabitants have devised the usage of a number of moisture-preventing methods. This study was a step toward analysing the effectiveness of such resident-used wall remediation procedures in a scientific way. In order to assess the current quality of the majority of residential buildings and the level of engineering knowledge of the locals (Nishant, 2022), and a study was also carried out in the Chandkheda neighborhood of Ahmedabad, India.

2.1.4 Bricks used in construction

Bricks were initially discovered in southern Turkey (Schmandt, 1977), and the great discovery in the areas of Jericho approximately 7000 BC (Dalkilic & Nabikoglu, 2017), making them one of the oldest building materials ever discovered. He continued by pointing out that the first bricks were mud bricks that had been sun dried, per literature on world discovery and civilization. Mud bricks would not have been adequate for use in permanent buildings because it was discovered that fired bricks are more resistant to harsher weather conditions.

Bricks are particularly popular because they are readily available, affordable, robust, durable, and dependable. The Great Wall of China was constructed using both burnt and sun dried bricks. Other than wood, bricks are the material that was utilized in building construction the most. Brick and terracotta architecture dominates its industry, and a significant business has grown and invested in the production of a wide variety of bricks in all sizes, forms, and colors. Brick production has significantly increased in productivity and efficiency because to new technology, earth moving equipment, strong electric motors, and modern tunnel kilns. The most popular material for making bricks was clay, but other options include calcium silicate and concrete. Due to their increased popularity, clay bricks are now made using three different processes: soft mud, dry press, and extrusion. The novel "fly ash" brick was also developed in 2007 utilizing coal power plant wastes.

The most popular material for making bricks was clay, but other options include calcium silicate and concrete. Due to their increased popularity, clay bricks are now made using three different

processes: soft mud, dry press, and extrusion. The novel "fly ash" brick was also developed in 2007 utilizing coal power plant wastes. Bricks are consistently employed as a construction material in the modern world due to its widespread use, accessibility, affordability, strength, and capability for sound and heat insulation (Schmandt, 1977). However, when exposed to moisture, the weight of water absorbed by bricks should be less than 15% for first-class bricks and 25% for second-class bricks. Additionally, white salt deposits should not be visible on brick exposed to dampness. This explains why walls seem stained after being exposed to moisture. hence, the wall fault. This literature therefore provide evidence for the need for a research study on masonry defect in walls (Sayed, Miklewski, Kahangi and Shareza, 2021).

2.1.5 Failures in structural aesthetics

In structures, durability failure brought on by water intrusion was the primary cause of structural failure and degradation (Newman, & Ban, 2003). It's important to analyse this aesthetic problem, because some consumers find widespread efflorescence or bloom to be wholly unpleasant, thus the materials and design should take this into consideration.

The former UK Code (BSI 1973) advised that "newly installed brickwork (for brickwork one may read masonry) shall be covered at the end of each working day or when it rains off." This piece of advice was succinct and pertinent. It was obvious that failing to cover newly constructed brickwork will leave it susceptible to saturation, perhaps leading to issues with durability as well as disfiguring discoloration (Makul & Sualan, 2017). A calcareous solution, primarily in the form of dissolved calcium hydroxide, has the ability to leach from hydrated portland cement when the material is saturated. As a result of a reaction with ambient carbon dioxide or with dissolved species in rainwater, solid material, typically in the form of calcium carbonate, may be deposited on the surface of the joint or unit when water from this solution evaporates.

Inadequate protection of newly constructed work frequently results in the typical horizontal line of white discoloration that occurs from this process of solution leaching (Walker & Kearns, 2005). A related type of white staining may happen when poor detailing or poor workmanship causes a localized stain to spread over time. Unfilled or inadequately filled vertical joints create reservoirs for water to collect in below a flaw in a coping or in a free-standing wall, where it may leak out.

2.1.6 Failures of Building Envelopes

It has been noted that the influence of most building facades in relation to space design, always have a bearing on aesthetic, and it was highly associated with design flaws that leads to building failures (Luisa & Marilyne, 2022). Facades might give off the desired visual impressions, but they might not be the ideal option for their intended purposes. Because mistakes happen, architects occasionally produce plans that call for the wrong materials. When building materials don't account for local thermal motions, mistakes like this frequently happen. Architects might overlook the fact that Mother Nature is always in charge.

Temperature variations inevitably cause cracks and loosen joints in constructions, whether they are made of stone or masonry. Water penetration, resistance, and structural capacity can potentially lead to design flaws. Building materials warp as water enters the building envelope and becomes trapped. Additionally, this produces the ideal environment for mold to flourish, posing a fresh issue. Which are; Siding and other elements of the envelope do not last forever; occasionally, it was better to replace them rather than spend a lot of money on repairs (Straube, 2002).

Be Structural stresses that it was always prepared to share cost-cutting advice and has experience mitigating building envelope challenges (Danna, 2020). This also pave the way for a research failure on aesthetic features associated with moisture rise in masonry units, that always affect beauty, hence research on assessment of moisture related defect in masonry structure. Challenges associated with water intrusion into structures includes; repair cost will continue to rise.

Problematic transitions and joint seals are inextricably linked to delayed maintenance and subpar repairs. Imagine that a homeowner chooses to replace a gutter expansion junction rather than repair it. When it rains hard, water flows in all directions and overflows the capacity of the gutters (Persilyl, Gorfainl, & Brunner, 2022). By allowing more water to enter the building, that example of inadequate maintenance weakens the building envelope.

If a structure's deterioration was not tracked and maintained, it can quickly lead to dangerous living conditions. Additionally, the cost of repairing and improving deteriorated conditions was astronomical. Property owners can avoid unneeded emergencies by being proactive and doing routine inspections, repairs, and upkeep (OlaREWaju, Rashid, & Aziz, 2015). Before water and moisture create substantial and expensive damage to structures, structural experts are pleased to

check and identify problem areas (Danna, 2020). It went to suggest observed engineering mitigating measures that include;

- 1) A building envelope that has been properly built and developed to adhere to all relevant codes and standards.
- 2) Choosing the right building supplies.
- 3) Including the aforementioned two elements in the design-build process early on to avoid serviceability problems and failures in the future. For the structure to be weatherproof and have a solid structural foundation, every component must be kept in good condition.
- 4) Regularity in building envelope inspections and upkeep. Thermal imagers are used by BE Structural to find building envelope problems and moisture penetration.

2.1.7 The wet method of treating wall defects

Sand / cement renders and plasters, which are typically 10 to 20 mm thick, are traditionally applied using wet-spraying in continental Europe (Austin, Robins, & Godier, 2002). This research project went on to note that, despite limited activity in the UK, it has become the accepted way for applying plaster in a number of European nations. In certain nations, such as Norway and Sweden, where wet processes account for the majority of work, and in the USA, where the two techniques have always been utilized for repair. Even while the amount of wet sprayed concrete was growing in the UK (Brown & Williams, 1996), other nations like Germany are primarily focused on the dry procedure.

These variations highlight the significance of the two processes, namely the wet mix for high output applications like tunneling and the dry mix for low to medium output applications like repair or scenarios requiring longer transport distances and greater flexibility, like mining. Quantitative information on wet process sprayed concrete repair was not readily available, most scholarly works reveals that there are already a vast number of methods available, where mortar or concrete was usually applied through a hose pipe onto the required surface or point under a high pressure, or velocity, in a nozzle (Austin, Robins, & Godier, 2002).

In conclusion, the study sources mentioned above show that a lot of past works had been done to address wall defects related to water penetration throughout the world, which was also generally applicable to engineering problems in Africa, East Africa, and Uganda in particular (Assingwire,

Muhwezi, & Ssengozi, 2021), with regard to wall defects, and structural failures in general. Since these circumstances have continued to occur, additional study was required to find a more scientifically sound answer to the issue. Hence the study was conducted, to provide additional solution to the problem.

2.1.8 Walls' reduced strength and safety as a result of increased damp/efflorescence damage

This essay examines the reasons behind the damage to retaining walls made of bricks, soft tuff blocks, or porous stones (Nunziante, 2021). He continued by stating that the damage results in the outward face being affected and that the disintegration of the capillarity, which causes moisture from the ground below to rise to a specific height within the wall constructed of porous, permeable material that contains voids, was the cause of the damage. In micrometric capillaries, rising water causes the dissolved salts and water molecules to evaporate under particular ventilation and sunlight circumstances, resulting in efflorescence on the exterior face of the wall (Mahdavinnejad, Javanroodi, Hashemirafsanjani, 2013).

When salts are dissolved in water, some water molecules are lost, causing normal efflorescence. This volume increase creates pressure inside the pores, which causes the material to disintegrate (Chudley & Greeno, 2004). The salts' crystalline phase, known as efflorescence, grows in volume and regulates the pressure inside the pores of masonry, which causes the structure to deteriorate and erode (Oluwaseun, 2017). The damage to the wall extends to significant depths in the order of decimeters, reducing its section and weakening it, causing cracks, and a general structural failure of the structure, and this study was done using questionnaires, but there was also need for scientific experiment (Eno, 2022), where this call for the current research study about assessment of moisture related defects in masonry walls. The damage lowers the wall's safety coefficient and exacerbates the stress state brought on by acting loads and the thrust of the soil.

Layers of the wall are lost, reducing the section and strength of the bottom portion of the wall and significantly lowering its safety. An analysis that is not linear can convey this (Chew, 2021). A nonlinear structural analysis, similar to those of a retaining wall, was the best tool for describing the stress distribution in lower portions of buildings that are being penetrated by water. Characteristics show that small reductions of about 10 to 20% in sections caused by capillarity

effect / efflorescence damage could cause stresses to increase by about 60% in most retaining wall, seriously jeopardizing its security.

It is further observed that when geofoam inclusion is used on a wall through material testing, the shear strength and interface between other materials having a ratio of wall thickness to height ratio of 0.065 reduces the lateral pressure behind the retaining wall by 28%, and this study involving geofoam inclusion, reduces pressure and zero pressure profile (Abdulsalam & Azzam, 2016). Structural elements need to be studied analytically in order to address the issue of water defect brought on by water penetration in structures. This therefore requires more research, hence the need for assessment of moisture related defects in masonry walls.

2.1.9 Assessment of structural failure related to moisture rise in structures in Uganda;

Recent studies reveal that there have been so many structural failures manifested in total collapse of structures in Uganda (Assingwire, Muhwezi & Ssenigozi, 2021), and this research which was about investigation of project implementation strategies in eliminating building collapse in Uganda, with a case study of the City of Kampala, reveals that, there has been quite a number of failures of masonry walls by disaggregation and the masonry quality index, in which it has been observed that, when acted upon by some external force, most masonry walls do fail (Borri, Corradi & De Maria, 2020).

Studies also observed that, most structural failures were attributed to; failures to have approval from relevant city authorities, poor planning, poor supervision by the technical people, lack of access to finance, and compromise arising from material quality, testing, and selection. Structural failures were also observed to be associated with; financial loss to the owners of the collapse structures, both public and private (Assingwire, Muhwezi, & Ssenigozi, 2021). It was also important to note that this study was conducted by method of case study design involving investigation of phenomenon using probability sampling, and a much better study by using scientific experiments should be conducted to analyse the real cause and getting the best solutions. This therefore calls for scientific modelling, hence the study of “assessment of moisture related defects in masonry walls. This is the subject of the study.

CHAPTER THREE - METHODOLOGY

3.1 Introduction

The method that was employed in this research include; a baseline study, and an experimental programme. In the baseline study of this chapter, the study; population, sample size, sampling techniques, data gathering structure, data collection tools, and data analysis, are explained.

The aim of the baseline study was to establish; the percentage, and classification of buildings that had been affected by dampness, and the number for both public and private structures. The baseline survey was also used to establish the mortar / plaster ratios commonly used in civil works in Uganda. The research relied heavily on experiments, that were used in conjunction with secondary data from identification of defects.

The establishment of scientific data regarding the capillary passage of water up constructed walls, and its effects that would cause varying degrees of water infiltration / ingress.

3.1.1 Research Strategy

This was used to provide an overall procedure of conducting the research. This involved quantitative and qualitative strategy. Baseline survey and experiments using models was used for conducting the study. This involved the use of a trajectory for the study.

The research plan was conducted as shown in the plan trajectory in Figure 3.1 below;

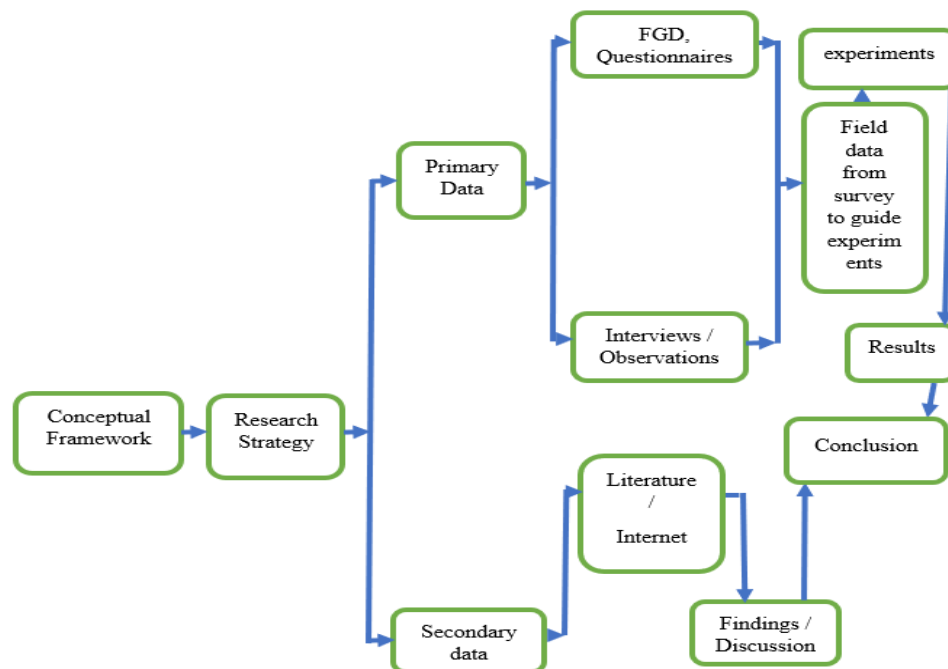


Figure 3.1: The plan trajectory for the study

3.1.2 Tools used for the experiments;

The tools used in the experiments were as follows;

- a) The cylindrical pipe 50mm diameter, 2mm thick, and 300mm length, plus a moisture can
- b) 10kg hammer, and spatula
- c) 440mm chrome chisel, and thermometer
- d) 300 x 300 x 10 mm wooden board, fix to the wall to receive the sample to be cored
- e) An oven for drying of sample
- f) Crucible, for heating the sample in an oven
- g) Analytical balances, for weighing the sample
- h) Compressive strength measuring equipments
- i) Rebound hammer
- j) Compressive Strength Measuring Machine. The compressive strength measuring machine, & sample ordinary clay bricks measuring; 230 x 110 x 70 mm, are shown in **Figure 3.2** below;



Figure 3.2: Compressive Strength Measuring Machine

3.1.3 Procedure for determining compressive strength

- i Ordinary clay brick was introduced into the above machine, lying by the small edge as shown above
- ii Each of the ordinary clay brick was compressed steadily, and the reading was noted
- iii The two procedures stated above was repeated for 4 additional ordinary clay bricks.
- iv The compressive strength is determined using the expression in equation 3 and 4 below;

$$F = \frac{P}{A} \dots \dots \dots \text{Eqn (3)}$$

where; -F is the compressive strength in **kN / m² or Mpa**

-P is the applied load in **kN**

-A is the area occupied by the sample as the load is applied in **m²**

Also,

$$\text{Average compressive strength} = \sum_{i=1}^n \frac{\sigma_i}{n} \dots \dots \dots \text{Eqn (4)}$$

Where; σ is the compressive force in Mpa

n = number of tests

v the results were calculated using Eqn 3 & 4 above;

3.1.4 Materials used for the experiments;

The materials that were used for the study included both industrial, and local materials as follows;

- a) Sand. This was a naturally occurring local material without any standard specification, tests, or checks.
- b) Ordinary portland cement **32.5N**. This was an industrial material that conforms to EN specification with; seven days compressive strength of 23 Mpa, and 28 days compressive strength of 42 Mpa.
- c) Burnt ordinary clay bricks. This was also one of the locally produced materials that does not have any special specification, but with the compressive strength that ranges between 2.5 to 3.7 Mpa. But average weight of 2.7Kg, and water absorption capacity of 10.

Samples of the ordinary clay bricks are shown in Figure 3.3

- d) Moisture rises reduction materials, and methods. This includes;
- i. Stone slates. This was a local material that conforms to the guides C1242, and C1528
 - ii. Facing bricks. This was a locally produced material with limited specification that conforms to ASTM C216, and BS EN 772
 - iii. Bituminous paint. This was an industrial material that conforms to BS 5439, and BS 6150. It was applied in 3 coats
 - iv. Glazed tiles. This was a locally produced material that met the quality of ASTM C-126
 - v. Weep holes cement sand mixed with 4% clay. The weep hole was made from PVC pipes of minimum diameter 1 inch
 - vi. Overlapping DPC, and lining fill with cement sand. The DPC material had the specification of BS 11785.

All these materials were bonded directly to the ordinary clay bricks using a cement sand mortar, whose strength corresponds to that of the mortar joint for uniformity. These materials were used as finishes as shown in **Figure 3.4, & A4.16**



Figure 3.3: Ordinary clay bricks

3.2 Data Collection Method

3.2.1 Introduction;

Questionnaires were used to carry out “a linear snowball sampling”, to obtain justification for the research, as represented in the problem statement. The baseline survey was conducted using questionnaires. The baseline survey involved a combination of 213 respondents drawn from the districts of; Dokolo, Lira, Abim, Gulu, Moyo, and Kampala, where the respondents included; contractors, District Engineers, and private property owners.

3.2.2 Baseline survey

A baseline survey was conducted on a population of 213 respondent. In Kampala, the population were drawn from Ministry of works register of contractors, that consist of grades; A, B, C, & D. Grade A and B were big contractors, mainly doing road works. They were not willing to participate in the survey, and their major business were not buildings, but roads, while grade C and D, were contractors mainly doing medium projects like buildings, and they were willing to participate in the survey. Other groups of respondents also included; contractors, superintendants of works (buildings), private property owners, and site engineers. The population and sampling of contractors were as shown **Table 3.1** below;

Table 3.1: Population sample of contractors in the selected districts for the baseline survey

District	Dokolo	Lira	Abim	Moyo	Kampala	Total
Population	12	18	15	10	22	77
Sample	9	12	8	6	20	55

The contractors in; Dokolo, Lira, Abim, Moyo and Kampala Districts were reached through the respective District procurement offices, and sampling was conducted as shown in **Table 3.2**.

A similar sampling of the population, and sample space was observed for; superintendant of works, property owners, and site Engineers. A snowball sampling was used for property owners because of the specificity of the traits. One property owner was always used to identify another property owner with a similar problem of; moisture rise in walls.

Table 3.2: Detail of population of respondents in the selected districts for the baseline survey

Detail of respondents						
Category of respondents	Districts					
	Dokolo	Lira	Abim	Moyo	Kampala	Total
Contractors	9	12	8	6	20	55
Superintendants of works (buildings)	1	2	1	1	4	9
Private property owners	12	18	10	8	28	76
Site Engineers	10	20	7	6	30	73
Total Number of respondents	32	52	26	21	82	213

And the following informations were to be justified, as the reason for conducting the baseline survey. These informations included;

- i. Identification of the cement sand mix ratios that are commonly used for plaster, as a wall finish in most public and private projects.
- ii. Percentage of structures affected by dampness
- iii. Identification of structures whose masonry walls were affected by capillary moisture rise.

3.2.3 Use of information from questionnaires;

Questionnaires was used, and find its sample attached in appendix **A1** and **A2**. The choice of the method of questionnaires was because, it's; easy to use, fast, accurate, and give a practical sample population, whose results gives a statistical figure that portray the exact situation in real life. From the baseline study, the ratio of plaster commonly used in Uganda were found to be 1:3, therefore, a mix of 1:3 was chosen for further experimental study. And in the experimental models used in the study, various materials for finishes were applied. These includes; facing brick, stone slates, glazed tiles, plaster containing 4% clay, bituminous paint, DPC overlapping the plaster finish, a layer of strong plaster finish externally applied as a seal on the DPC, and weep holes, in the plaster finish.

3.3 Physical Models for assessment of height of moisture rise in walls

There were 8 models measuring 1.9m high, 1.6m long, and 0.23m thick constructed of ordinary clay bricks, with the models fitted in a trough (timber box), double lined internally with black polythene gauge 1000. Allowance of 400mm working space was left all-round the base of the models. The models were constructed of cement: sand mortar / plaster mix ratios of; 1:1, 1:2, 1:3, and 1:4. Some of the models were left outdoor for determination of the effect of moisture infiltration on outdoor walls. Others were put indoor. The models were named as; Model 1 outdoor with cement sand ratio 1:1, Model 2 outdoor with cement sand ratio 1:2, Model 3 outdoor 1 with cement sand ratio 1:3, Model 4 outdoor with cement sand ratio 1:4, Model 5 No1 indoor with cement sand ratio 1:3, Model 6 indoor with cement sand ratio 1:2, Model 7 indoor with cement sand ratio 1:4, Model 8 outdoor 2 with cement sand ratio 1:3, Model 9 indoor 2 with cement sand ratio 1:2. The plaster used in each of the models had a constant thickness of 20mm.

The models were left exposed for a period of 3 months with the trough full of water. The water was replenished every day to just below DPC. The DPC was made of gauge 1000 black polythene. A typical sketch and photo of the wall (model) used to carry out the experiments used in the research at Kyambogo University soil laboratory, are as shown **Figure 3.4** and **Figure 3.5** below;

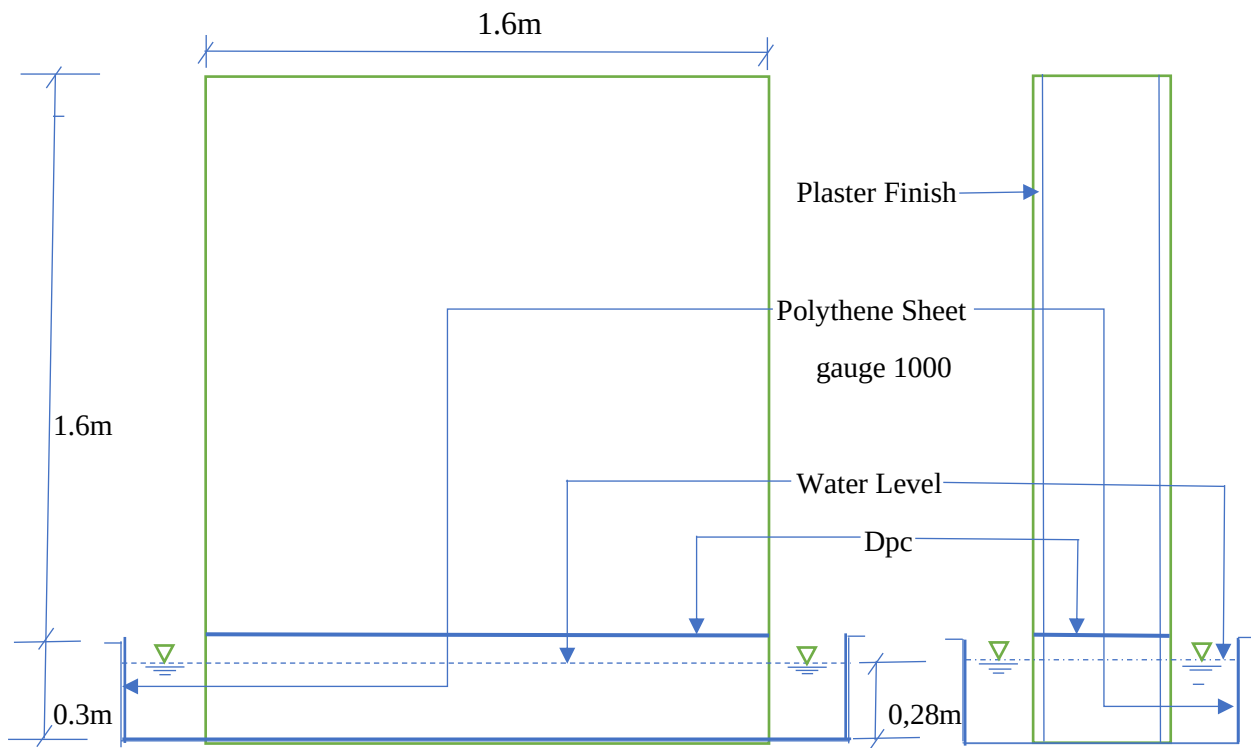


Figure 3.4: Sketch of the models for the experiments



Figure 3.5: Photo of Selected Models

The DPC was made to coincide with the brick wall thickness. The rise of water through the finishes was monitored, and moisture content determination was carried out from 7:00am to 8:00am on a daily basis. After 10 days, the moisture rise remained constant. After 3 months, when the rise had stabilised, final testing was done.

Selected points on the vertical surface of the models simulating masonry walls, shown in **Figure 3.7**, were cored using a 50mm diameter cylindrical pipe, 2mm thick, and measuring a length of 300mm. All tests were performed according to **BS 6576:2005** & according to BS 3921:1985, and moisture content in those selected points were tested. Samples were picked from brick & plaster, but not from the mortar joints. This was because the mortar joints had the same mix as the plaster. It was assumed that their moisture content was the same.

When quantifiable datas were obtained, microsoft excel software applications were used as an excellent tool for presentation, and analysis of data.

3.4 Determination of moisture content of mortar and the ordinary clay bricks, by dry oven testing;

These experiments were carried out in reference to standard laboratory test procedures for determination of water (moisture) content of soil and rock materials by mass often referred to as ASTM D2216, in line with ISO 638. Moisture content test was determined by using the procedure as follows;

- i Measuring a small sample of the dry mortar. Let its weight be a_1
- ii Putting the sample in an oven. Set the temperature in the oven to 100°C . Keep the sample in the oven for 24 hours. Remove the sample, cool it, and remeasure its weight. Note it as a_2
- iii Then moisture content was calculated by using the expression in equation 5 as shown below;

$$\mathbf{m. c} = \frac{a_1 - a_2}{a_1} \times 100\% \dots \dots \dots \text{Eqn (5)}$$

where;

$\mathbf{m. c}$ = moisture content

$\mathbf{a_1}$ weight of mortar or brick material immediately after extraction from model plus container

$\mathbf{a_2}$ weight of dry mortar or brick plus container after 24 hours in oven at 100°C

$\mathbf{100 \%}$ = The SI unit of moisture content

Using the procedure in Equation 1. Moisture content tests were carried out at different selected positions as marked by letters; A, B, C, D and E in Figures 3.6, 3.7, and 3.8 below;

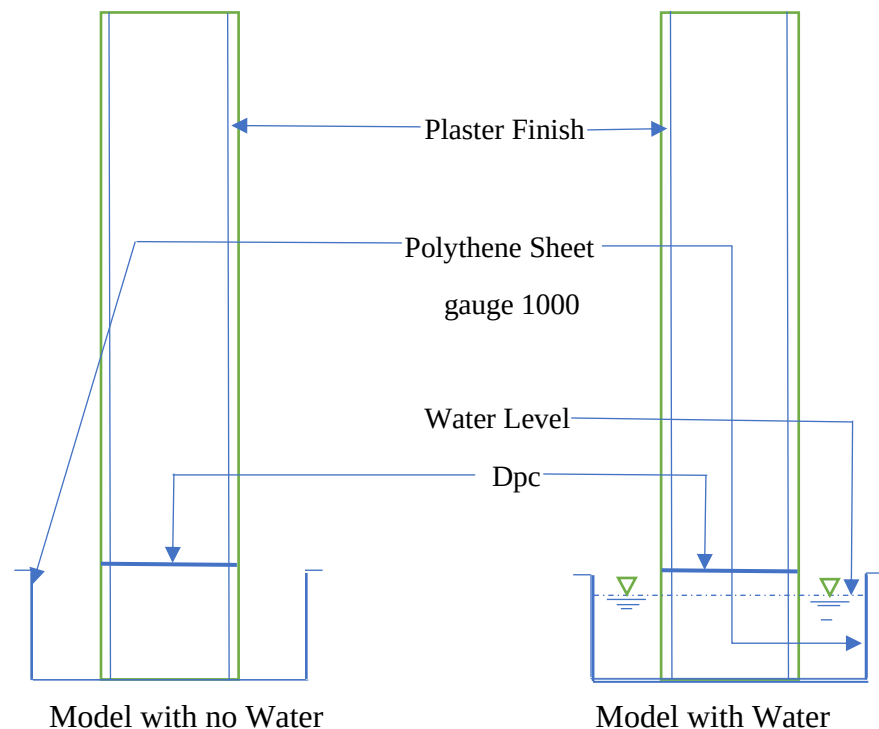


Figure 3.6: Sketch of models without, and with water



Figure 3.7: Selected points on the face of one of the models, without water



Figure 3.8: Selected points on the face of one of the models, with water

3.5 Physical Models for assessment of materials for reduction of moisture rise in walls

The tests were carried out according to; **BS 6576:2005** & according to BS 3921:1985. There were **8 models** measuring 1.9m high, 1.6m long, and 0.23m thick constructed of ordinary clay bricks,

with the models fitted in a trough (timber box), double lined internally with black polythene gauge 1000. Allowance of 400mm working space was left all-round the base of the models. The models were constructed of cement: sand mortar / plaster / finish mix ratios of 1:3. The models were named as; Model 9 outdoor F for facing bricks, Model 10 outdoor S for stone slates, Model 11 outdoor B for bituminous paint, Model 12 outdoor T for glazed tiles, Model 13 outdoor W for weep holes, Model 14 outdoor C for 4% clay mix with 1:3 cement sand ratio, Model 15 indoor K for overlapping DPC, Model 16 indoor F 2 with a cement sand fill. The plaster used in each of the models had a constant thickness of 20mm.

The models were left exposed for a period of 3 months with the trough full of water. The water was replenished every day to just below DPC. The DPC was made of gauge 1000 black polythene.

A typical sketch of the wall (model) showing finishing materials, are as shown **Figure 3.9 below;**

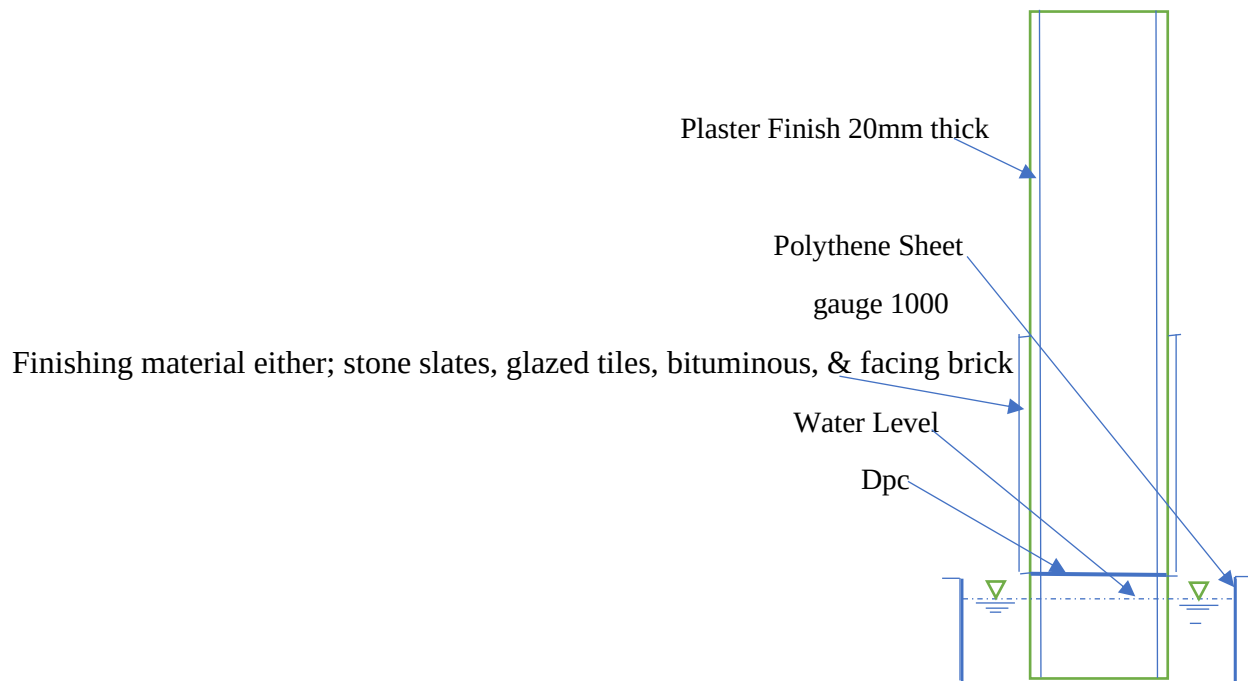


Figure 3.9: Sketch of model showing finishing material

CHAPTER FOUR – PRESENTATION AND DISCUSSION RESULTS

4.1 Introduction

This chapter contains; results and discussion of the baseline survey, and that of experiments. It gives thorough modalities that was used by the researcher to relate finding to facts, and generate an accurate assessment of the situation.

4.2 Baseline survey & General Experiments

4.2.1 Baseline survey

The baseline survey also shows that, there was always need for proper plumbing in structures, and leakages are common in structures constructed in wetland, and the study shows that those leakages are associated with materials which are not genuine. Those leakages do cause profound weakness in structures. That include; peeling of plaster, and loosening of walls. According to the baseline survey that was conducted, solution to moisture penetration into buildings include; use of genuine materials of good quality, water proofings and strong finishes.

In the local perspective, the baseline survey was conducted on 213 respondents in selected Districts in Dokolo, Lira, Abim, and Moyo Districts in Northern Uganda, and then Kampala. It revealed that most buildings look pretty nice when recently built, but loses the appearance within a very short time, where plaster begins to; peel off, and colour of the wall changes. This is greatly attributed to dampness that causes unwanted moisture in the building structure, and the categories of these moistures include; condensation dampness which was caused by condensing warm air that cools commonly in kitchens and bathrooms, rising dampness caused by underground water that enters through floors and walls, penetrating dampness that enters the structure through leakages in pipes and general drainages in the floors, walls and the roofs.

The baseline study also indicated that most notable causes of dampness include; poor type of construction, variable climatic conditions, variability of soil conditions, poor orientation of buildings, location or level of the site, entrapped moisture in walls and floors of structures during construction, and finally penetration of rain. And the most reliable solution is mostly the use of sheeting of damp proof course, that conventionally contain bituminous material. The study thus revealed that;

- i. 205 respondents out of 213, which is 96.2%, of visited structures in Dokolo, Lira, Abim, and Moyo Districts in Northern Uganda, and then Kampala District in general, were affected by capillary moisture rise
- ii. 197 respondents out of 213, which is 92.4%, of visited government and private projects in Dokolo and Northern Uganda, the most recommendable cement sand plaster mix ratios used was found to be 1:3.
- iii. The result of the sampling, as stated above, revealed that; a number of structures are affected by moisture rise in walls, and also the mix ratios for cement sand mortar / plaster finishes on most public and private structures was 1:3.

This is the justification for conducting the remaining experiments on moisture rise in masonry structures using the cement : sand ratio of 1:3.

4.3 Verification of moisture rise in masonry walls by capillarity;

4.3.1 Determination of moisture content at different points of the model

Two experiments were carried out using the equipments in section 3.1, and procedures stated briefly in section 3.2.3, on the vertical surface of the wall. One of the models was without water, and the other had water in the trough. Moisture content was measured at points; A, B, C, D and E, as shown in Figure 3.4, and 3.5, for models in both experiments. The value of moisture contents at the different points were calculated using Equation 5, and moisture content was calculated, the result is shown in; **Table 4.1, and 4.2**, justified by **Figure 4.1 and 4.2**;

a) Table of moisture content from selected points for trough without water;

Table 4.1: Results for moisture content tests on plaster taken from different spots on the face of Model R without water fed to the trough Figure 4.1

S/No & Points	Height (m)	M.C in %
1 at point A	0.1	2.231
2 at point B	0.3	2.214
3 at point C	0.5	2.225
4 at point D	0.8	2.228
5 at point E	1.0	2.231
6 above point A	Above 1.0	2.226



Figure 4.1: Sample plaster taken from different spots on the face of model 5 outdoor 1 cement sand ratio 1:3

b) Table of moisture content at selected points of model with water in the trough

Table 4.2: Results for moisture content for sample plaster taken from different spots on the face of model 5 outdoor 1 cement sand ratio 1:3 with water fed to the trough

Height in meters	Points	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
0.1	A	89.5	83.8	5.7	6.802
0.3	B	91.8	87.9	3.9	4.437
0.5	C	92.4	89.4	3.0	3.356
0.8	D	88.3	85.9	2.4	2.794
1.0	E	87.6	85.6	2.0	2.336

c) Graph

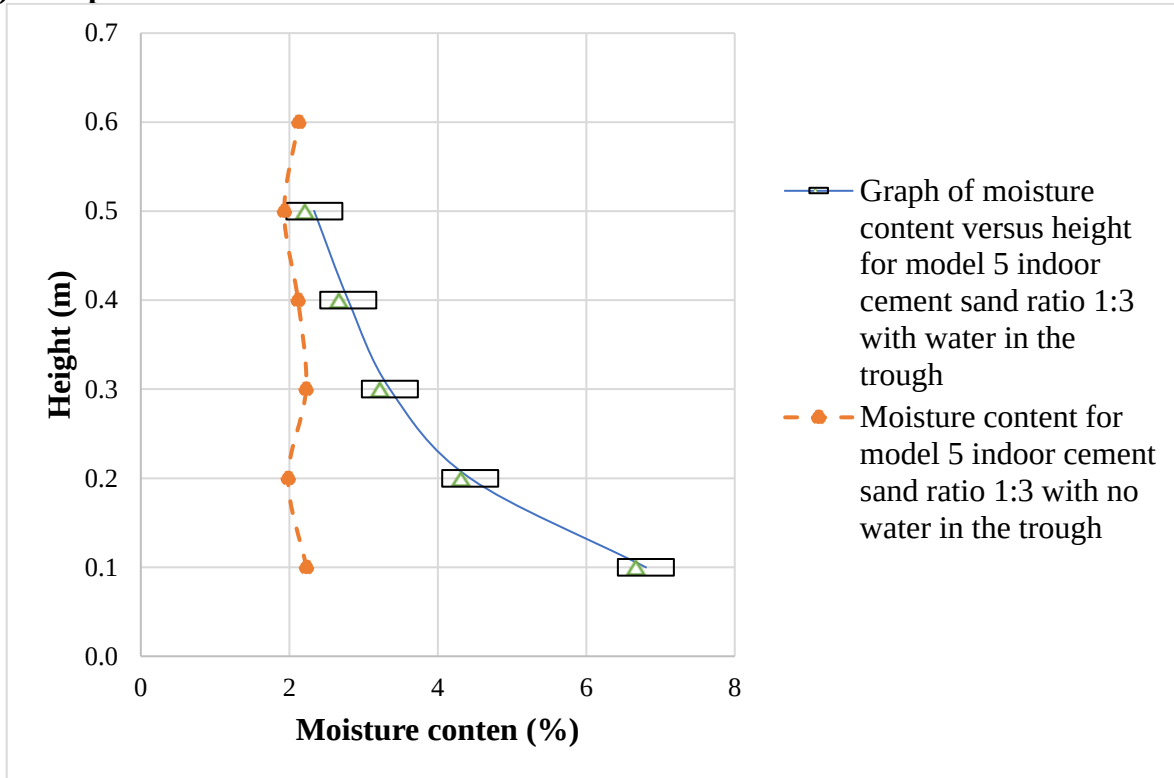


Figure 4.2: Height versus moisture content at different spots on the face of model 5 outdoor 1 cement sand ratio 1:3

While the moisture content of the model with water fed into the trough changes with height, as shown in Figure 4.1, the moisture content of the model without water on the trough, as shown in Figure 4.2, remains almost constant as the height increases. The moisture content was high at the DPC level (point A), and the value gradually decreases through points B, C, D, and E. This finding demonstrates how capillarity allowed moisture to ascend the wall. This offers a rationale for moisture related masonry flaws in walls. This serves as evidence for the study's focus, which was the rise in moisture through brick walls.

4.3.2 Determination of compressive strength and moisture content of ordinary clay bricks, (According to BS 3921:1985, and ASTM D2216)

The values that were obtained by use of Equation 4 and 5, and the results obtained were as shown in Table 4.3, 4.4, and 4.5 below:

a) Compressive strength for ordinary clay bricks

Table 4.3: Compressive strength of ordinary clay bricks

Specimen	Compressive Strengths in Mpa
1	2.75
2	2.78
3	2.81
4	2.79
5	2.65

Average compressive strength = 2.76Mpa

b) Moisture Content for mortar;

Table 4.4: Moisture content result for experimental mortar

Specimen	Moisture Content in %
1	2.12
2	2.18
3	2.14
4	2.16
5	2.13

Using the expression;

$$\text{Average m. c} = \sum_{i=1}^n \frac{m.c_i}{n}$$

The average moisture content = **2.15 %**

c) Moisture content for ordinary clay bricks;

Table 4.5: Sample moisture content result of experimental Ordinary Clay Bricks

Specimen	Moisture Content in %
1	2.31
2	2.42
3	2.46
4	2.20
5	2.27

Using the expression;

$$\text{Average m. c} = \sum_{i=1}^n \frac{m.c_i}{n}$$

The average moisture content = **2.33 %**

Any observation made regarding the moisture content throughout these tests would be helped to make sense of by the experimental value of the moisture content that was obtained above. The moisture content was discovered to be within the experimental range.

4.4 Experiments to justify the rise of moisture through walls:

4.4.1 Model 1 ratio; 1:1 Outdoor

Samples from model 1 were taken, and tested for moisture content, as shown in Table 4.6, 4.7, and Figure 4.3 below;

a) Plaster

Table 4.6: Moisture content of plaster (Ratio1:1 cement sand, model 1)

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	163.3	154.7	8.6	5.559
2	0.2	159.1	153.3	5.8	3.783
3	0.3	149.6	145.3	4.3	2.959

4	0.4	192.9	188.3	4.6	2.443
5	0.5	136.0	133.2	2.8	2.102
6	0.6	153.5	150.6	2.9	1.926
7	0.7	128.7	126.3	2.4	1.900
8	0.8	167.8	164.6	3.2	1.944
9	0.9	131.8	129.4	2.4	1.855
10	1.0	128.7	126.2	2.5	1.981
11	1.1	179.7	176.3	3.4	1.929
12	1.2	174.0	170.6	3.4	1.993

b) Bricks

Table 4.7: Moisture content of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	106.3	100.8	5.5	5.456
2	0.2	122.2	117.9	4.3	3.647
3	0.3	128.2	123.5	4.7	3.806
4	0.4	128.3	125.6	2.7	2.150
5	0.5	137.1	133.9	3.2	2.390
6	0.6	81.5	80	1.5	1.875
7	0.7	94.1	92.3	1.8	1.950
8	0.8	144.7	142.1	2.6	1.830
9	0.9	118	115.8	2.2	1.900
10	1.0	146.8	144.2	2.6	1.803
11	1.1	155.8	152.9	2.9	1.897
12	1.2	120.6	118.4	2.2	1.858

c) Graph

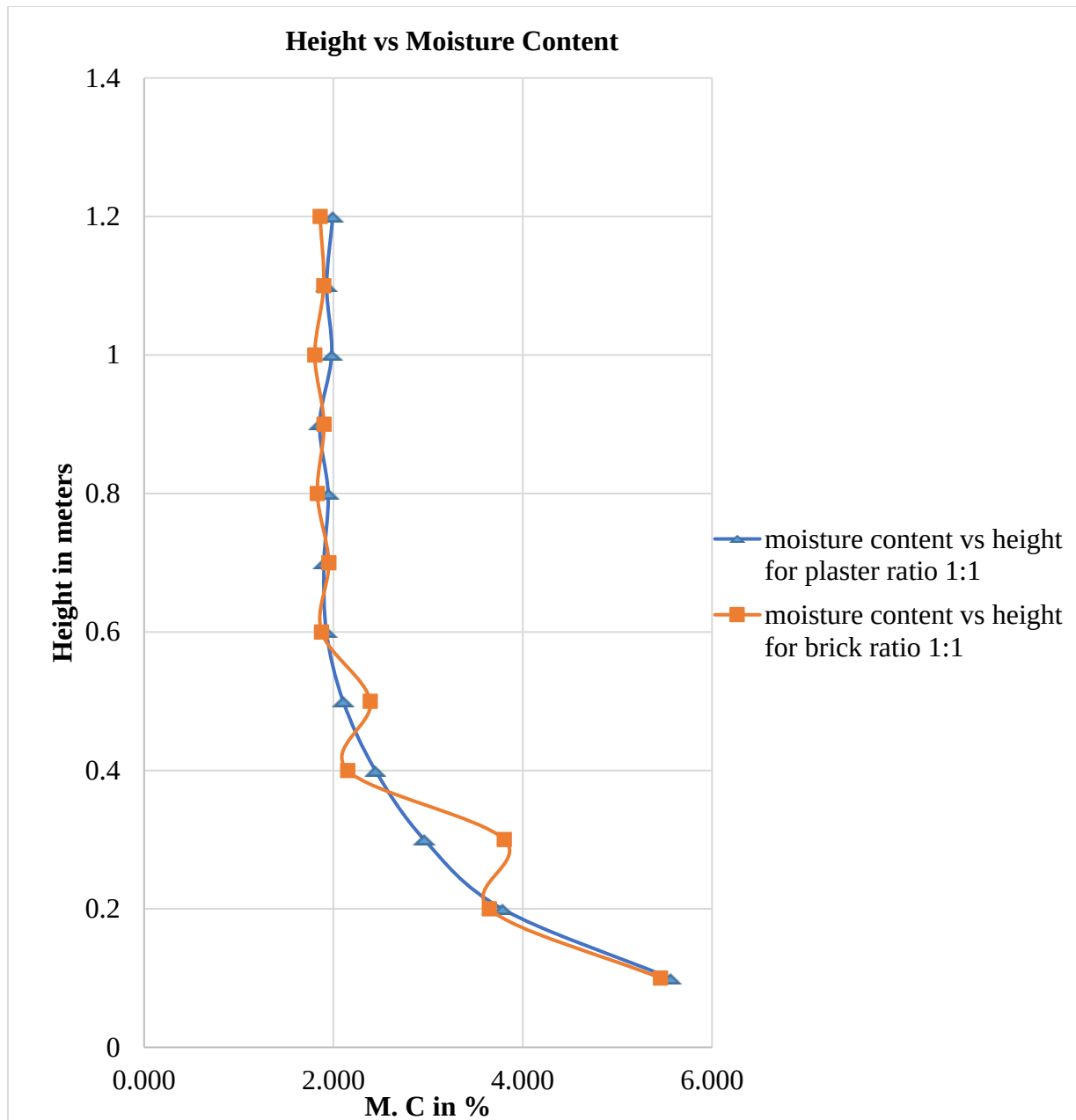


Figure 4.3: Height vs moisture content for plaster & brick, plaster ratio 1:1

As height increases, moisture content decreases to roughly 0.6 meters. After that, as height increased, it stayed unchanged. There was a lot of wiggle room in the brick wall's decreasing moisture content. This was as a result of moisture moving through the mortar joints, which have different moisture contents. Moisture moves upward because of capillarity. Additionally, between 0 to 0.6 meters in height, there is a greater rise in moisture through the brick wall than through the plaster. However, the moisture rise doesn't change much after 0.6 m.

4.4.2 Model 2 ratio; 1:2 Outdoor

Samples from model 2 were taken, and tested for moisture content, as shown in Table 4.8, 4.9, Figure 4.4 below;

a) Plaster

Table 4.8: Moisture content plaster from model 1 (1:2 cement sand mix)

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	117.2	109.9	7.3	6.642
2	0.2	119.5	114.9	4.6	4.003
3	0.3	137.9	133.6	4.3	3.219
4	0.4	115.9	112.8	3.1	2.748
5	0.5	140.7	137.3	3.4	2.476
6	0.6	140.5	137.3	3.2	2.331
7	0.7	195.2	190.7	4.5	2.360
8	0.8	156.6	153.1	3.5	2.286
9	0.9	140.2	136.9	3.3	2.411
10	1.0	147.2	143.9	3.3	2.293
11	1.1	160.6	157.1	3.5	2.228
12	1.2	168.5	164.7	3.8	2.307

b) Brick

Table 4.9: Moisture content for sample bricks (1:2 cement sand mix)

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	111.8	104.9	6.9	6.578
2	0.2	99.2	94.8	4.4	4.641
3	0.3	109.1	103.7	5.4	5.207
4	0.4	66.1	64.1	2	3.120
5	0.5	105.7	102.1	3.6	3.526

6	0.6	152.2	148.7	3.5	2.354
7	0.7	123.9	120.9	3	2.481
8	0.8	140.9	137.7	3.2	2.324
9	0.9	103.5	101.1	2.4	2.374
10	1.0	122.0	119.3	2.7	2.263
11	1.1	142.9	139.6	3.3	2.364
12	1.2	104.0	101.7	2.3	2.262

c) Graph

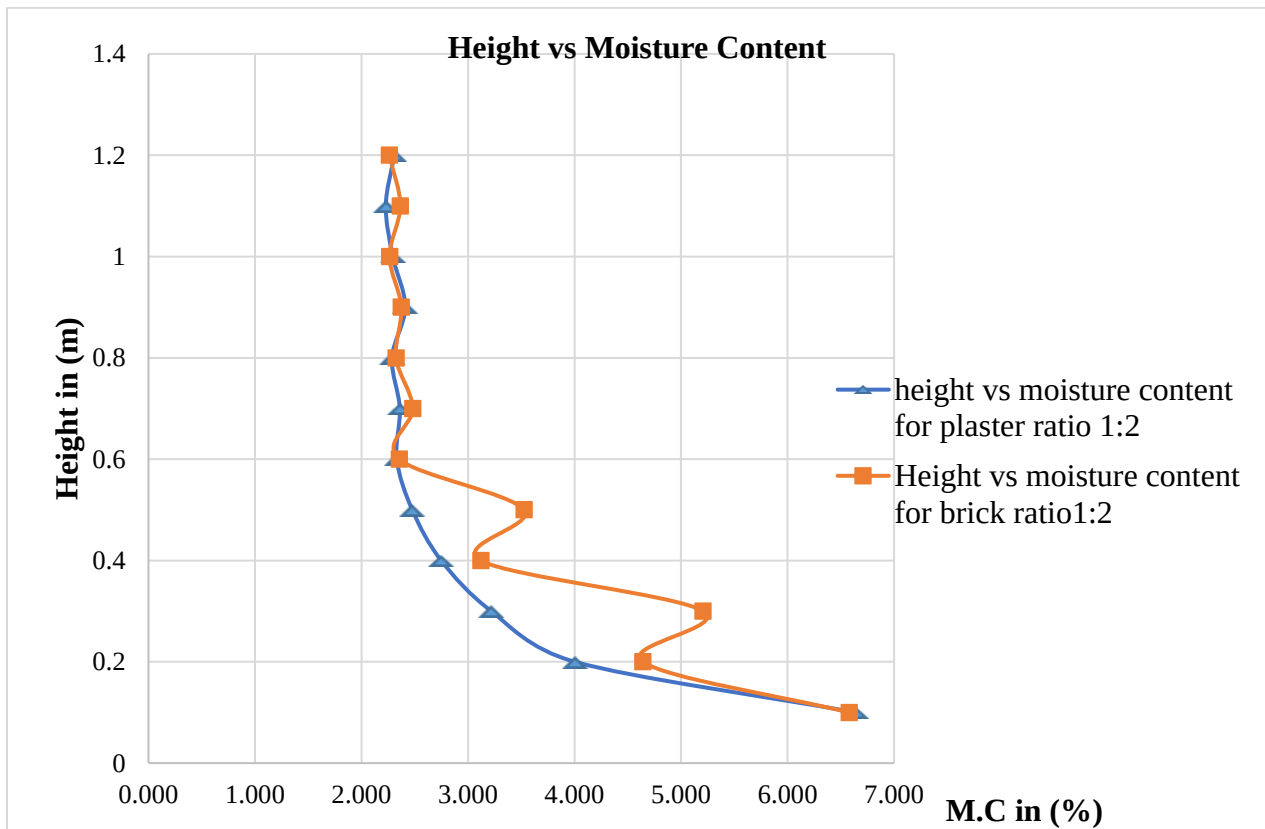


Figure 4.4: Height vs moisture content for plaster & bricks (1:2 cement sand mix)

Up to a height of 0.5 to 0.6 meters, the moisture content decreases with height increase; beyond that, it remains constant. The brick wall's decreased moisture content is seen to be highly variable. The reason for this was the passage of moisture via the mortar joints, which have different moisture contents. Capillarity was responsible for the moisture's upward migration. Additionally, before reaching 0.6 meters in height, the amount of moisture rising through the brick wall was greater than it is in the plaster; yet, after 0.6 meters, the moisture level was nearly even.

4.4.3 Model 3 ratio; 1:3 Outdoor

Samples from model 3 were taken, and tested for m.c, as shown in Table 4.10, Table 4.11 & Figure 4.5 below;

a) Plaster

Table 4.10: Moisture content plaster sample (1:3, cement: sand mix)

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	75.7	69.7	6	8.608
2	0.2	77.2	72.7	4.5	6.190
3	0.3	176.8	168.9	7.9	4.677
4	0.4	87.7	84.6	3.1	3.664
5	0.5	94.3	91.4	2.9	3.173
6	0.6	81.5	79.2	2.3	2.904
7	0.7	71.3	69.2	2.1	3.035
8	0.8	72.0	70	2	2.857
9	0.9	83.8	81.4	2.4	2.948
10	1.0	74.1	71.9	2.2	3.060
11	1.1	71.8	69.8	2	2.865
12	1.2	64.9	63.1	1.8	2.853

b) Bricks

Table 4.11: Moisture content for ordinary clay bricks extracted for sample wall with 1:3 plaster

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	231.5	213.5	18	8.431
2	0.2	86.2	80.7	5.5	6.815
3	0.3	103.3	96.5	6.8	7.047

4	0.4	97.2	92.5	4.7	5.081
5	0.5	111.5	105.9	5.6	5.288
6	0.6	85.9	83.5	2.4	2.874
7	0.7	122.0	118.6	3.4	2.867
8	0.8	110.0	107	3	2.804
9	0.9	100.7	97.9	2.8	2.860
10	1.0	67.1	65.3	1.8	2.757
11	1.1	109.5	106.5	3	2.817
12	1.2	112.7	109.7	3	2.735

c) Graph

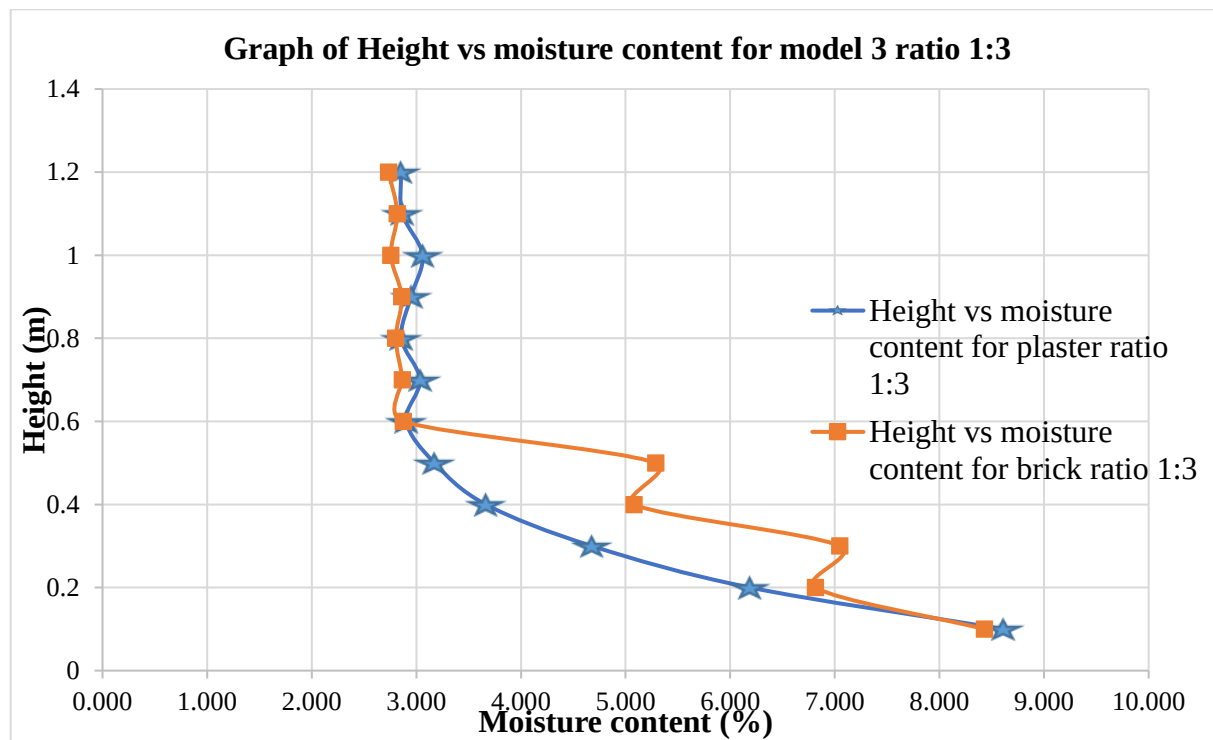


Figure 4.5: Height vs moisture content for plaster & brick (1:3, cement: sand mix)

Once a height above the DPC level was increased to approximately 0.6 meters, the moisture content decreases and then stays constant. Moisture moves through the mortar joints in the brick wall, causing a great deal of the undulation in the moisture content decrease. It was capillarity that causes the upward migration of moisture. When comparing the brick wall to the plaster, the amount of moisture rising through it was greater between DPC and 0.6m. Nevertheless, it stays the same over 0.6 meters in height.

4.4.4 Model 4 ratio; 1:4 Outdoor

Samples from model 4 were taken, and tested for m.c, as shown in Table 4.12, 4.13, & Figure 4.6 below;

a) Plaster

Table 4.12: Moisture content for plaster (1:4, cement: sand mix)

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	72.4	66	6.4	9.697
2	0.2	97.4	90.7	6.7	7.387
3	0.3	99	93.5	5.5	5.882
4	0.4	101.5	97	4.5	4.639
5	0.5	71.5	68.9	2.6	3.774
6	0.6	76.7	74.1	2.6	3.509
7	0.7	103.7	100.1	3.6	3.596
8	0.8	122.9	118.8	4.1	3.451
9	0.9	84.9	82.1	2.8	3.410
10	1.0	98.6	95.2	3.4	3.571
11	1.1	107.1	103.7	3.4	3.279
12	1.2	100.4	97	3.4	3.505

b) Bricks

Table 4.13: Moisture content of ordinary clay bricks in wall with 1:4 plaster

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	89.7	81.9	7.8	9.524
2	0.2	91.6	85.5	6.1	7.135
3	0.3	91	84.9	6.1	7.185
4	0.4	73.4	69.3	4.1	5.916
5	0.5	92.7	87.5	5.2	5.943
6	0.6	52.5	50.7	1.8	3.550
7	0.7	51.6	49.89	1.71	3.428
8	0.8	75.4	72.8	2.6	3.571
9	0.9	71.1	68.7	2.4	3.493
10	1.0	58.3	56.3	2	3.552
11	1.1	65.4	63.2	2.2	3.481
12	1.2	62.4	60.3	2.1	3.483

c) Graph

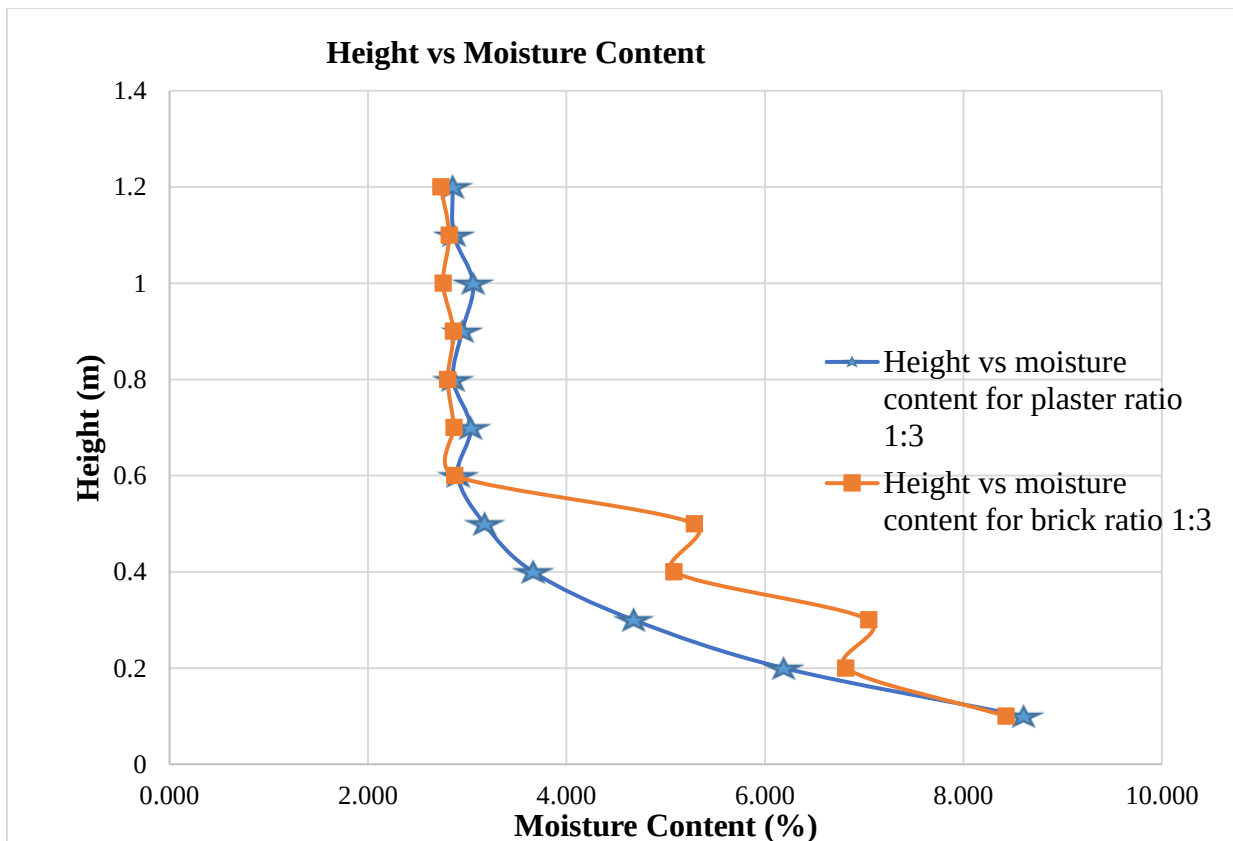


Figure 4.6: Graph of height vs moisture content for model 4 outdoor

As height increases from 0 meters to roughly 0.62 meters above DPC level, the moisture content decreases. When compared to plaster, there was a greater rise in moisture through the brick wall from 0 to approximately 0.62 meters. However, there is significant variation in the brick wall's moisture content decrease from the DPC level to approximately 0.6 meters, which was related to the joints. After that, the moisture content remained constant as the height increased. Furthermore, capillarity causes moisture to migrate higher. See section 4.6.2 for further information. This observation is consistent with the real physical observations made in the actual structures.

In general, it was noted that models 1, 2, 3, and 4 were all exposed. Furthermore, a 1:3 mix was selected since, based on the baseline survey performed for this study, it is the most popular blend in government projects. In order to replicate inside conditions, models 5, 6, 7, 8, and 9 were also constructed and tested in the shade. Tables 4.6 to 4.13 show these models.

Analysis revealed that the models' moisture content rises in the following ratios; 1:1,1:2,1:3, and 1:4. This is explained by the mortar's, or finishes' plaster's, decreased strength.

4.4.5 Model 5 No 1 indoor cement sand ratio 1:3

Samples from the model 5 No 1 above were taken, and tested for moisture content, as shown in Table 4.14, 4.15, & Figure 4.7 below;

a) Bricks

Table 4.14: Moisture content for ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	163.3	154.7	8.6	5.559
2	0.2	159.1	153.3	5.8	3.783
3	0.3	149.6	145.3	4.3	2.959
4	0.4	192.9	188.1	4.8	2.552
5	0.5	136	133.4	2.6	1.949
6	0.6	153.5	150.8	2.7	1.790

7	0.7	128.7	126.6	2.1	1.659
8	0.8	167.8	165.3	2.5	1.512
9	0.9	131.8	129.9	1.9	1.463
10	1.0	128.7	127.1	1.6	1.259
11	1.1	179.6	177.5	2.1	1.183
12	1.2	174.0	172.0	2	1.163

b) Plaster

Table 4.15: Moisture content of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	106.2	100.1	6.1	6.094
2	0.2	122.2	116.3	5.9	5.073
3	0.3	128.2	122.3	5.9	4.824
4	0.4	128.3	123.5	4.8	3.887
5	0.5	137.1	133.4	3.7	2.774
6	0.6	81.5	79.6	1.9	2.387
7	0.7	94.1	92.6	1.5	1.620
8	0.8	144.7	142.4	2.3	1.615
9	0.9	118.0	116.3	1.7	1.462
10	1.0	146.8	144.5	2.3	1.592
11	1.1	155.8	153.6	2.2	1.432
12	1.2	120.6	118.8	1.8	1.515

c) Graph

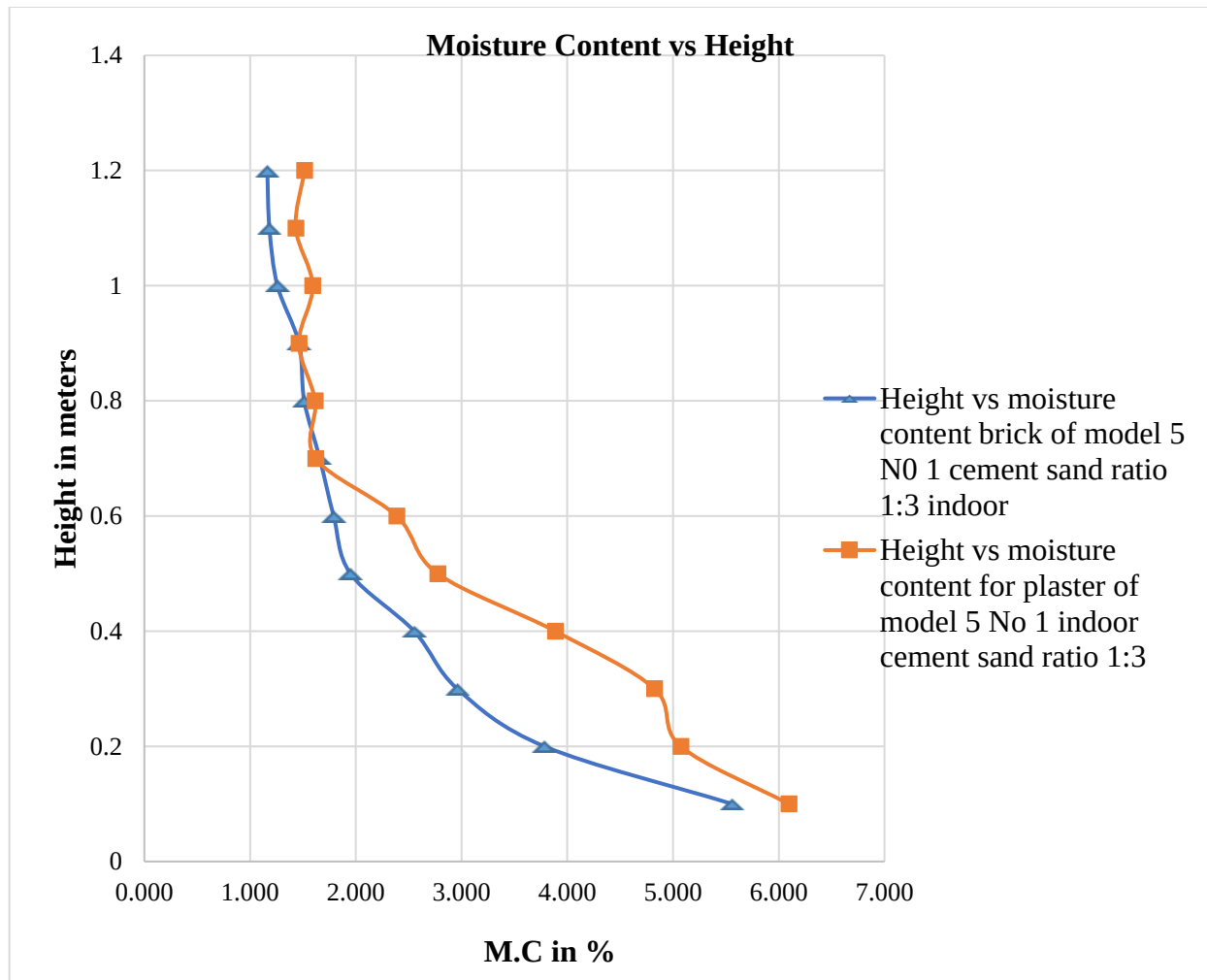


Figure 4.7: Height vs moisture content for model 5 No1 indoor, cement sand mix ratio 1:3

From DPC level to roughly 0.6 m, the moisture content decreases with height increase until remaining constant. As seen in section 4.6.2, the average height corresponds to the real observed height. This was a result of moisture seeping through the mortar joints. Capillarity was responsible for the upward flow of moisture.

4.4.6 Model 6 cement sand ratio 1:2 Indoor

Samples from model **6 cement sand ratio 1:2 above** were taken, and tested for **moisture content**, as shown in Table 4.16, 4.17, & Figure 4.8 below;

a) Plaster

Table 4.16: Moisture content of plaster

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	125.3	117.1	8.2	7.003
2	0.2	173.7	164.8	8.9	5.400
3	0.3	159.9	154.2	5.7	3.696
4	0.4	156.5	152.1	4.4	2.893
5	0.5	121.8	118.9	2.9	2.439
6	0.6	164.3	160.5	3.8	2.368
7	0.7	160.9	157.5	3.4	2.159
8	0.8	170.2	166.6	3.6	2.161
9	0.9	157.2	153.7	3.5	2.277
10	1.0	112.8	110.4	2.4	2.174
11	1.1	177.6	173.7	3.9	2.245
12	1.2	180.7	176.7	4	2.264
13	1.3	147.9	144.8	3.1	2.141

b) Bricks**Table 4.17: Moisture content result of Ordinary Clay Bricks**

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	106	99.1	6.9	6.963
2	0.2	150.1	140.8	9.3	6.605

3	0.3	166.8	156.7	10.1	6.445
4	0.4	131.2	123.2	8	6.494
5	0.5	147.3	140.5	6.8	4.840
6	0.6	159.5	151.9	7.6	5.003
7	0.7	166.2	162.8	3.4	2.088
8	0.8	138.8	135.8	3	2.209
9	0.9	166.1	162.7	3.4	2.090
10	1.0	140.8	137.9	2.9	2.103
11	1.1	163.9	160.4	3.5	2.182
12	1.2	168.1	164.4	3.7	2.251
13	1.3	141.4	138.5	2.9	2.094

c) Graph

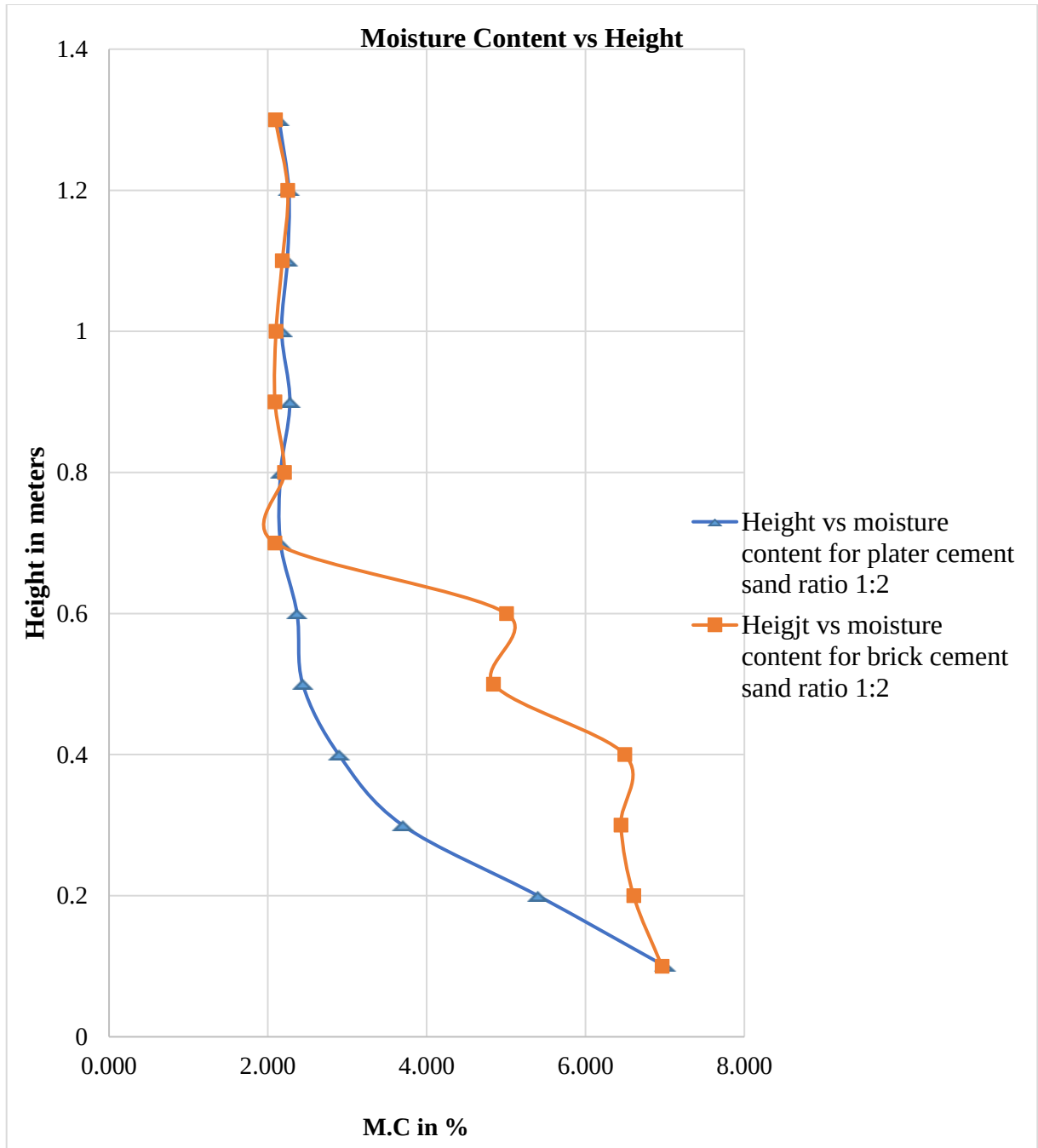


Figure 4.8: Height vs moisture content for model 6 indoor cement sand ratio 1:2

Up to a height of 0.52 to 0.71 meters, the moisture content decreases with height increase. Beyond that, it stays constant. The brick wall's decreased moisture content was seen to be highly variable. This occurs as a result of moisture passing through the mortar joints. Capillarity was the cause of the upward flow of moisture. Additionally, compared to the plaster, there was a greater rise in

moisture through the brick wall. Just above the DPC, at a height of roughly 0.62 meters, the capillary rise in brick was marginally lower than that in plaster.

4.4.7 Model 7 indoor, cement sand ratio 1:4

Samples from model 7 indoor cement sand ratio 1:4 were taken, and tested for moisture content, as shown in Table 4.18, 4.19, Figure 4.9 below

a) Plaster

Table 4.18: Moisture content of plaster

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	128	119.4	8.6	7.203
2	0.2	149.6	141.9	7.7	5.426
3	0.3	150.5	143.9	6.6	4.587
4	0.4	152.9	146.7	6.2	4.226
5	0.5	164.1	158.4	5.7	3.598
6	0.6	195.5	189.9	5.6	2.949
7	0.7	143.6	140.3	3.3	2.352
8	0.8	144.5	141.4	3.1	2.192
9	0.9	160.4	156.8	3.6	2.296
10	1.0	139.9	136.8	3.1	2.266
11	1.1	145.9	142.7	3.2	2.242
12	1.2	138	134.9	3.1	2.298
13	1.3	172.5	168.5	4	2.374

b) Bricks

Table 4.19: Moisture content of Ordinary Clay Bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	124.7	116.4	8.3	7.131
2	0.2	132.2	123.9	8.3	6.699
3	0.3	134.3	127.3	7	5.499
4	0.4	169.3	160.1	9.2	5.746
5	0.5	123	118.3	4.7	3.973
6	0.6	132.4	127.2	5.2	4.088
7	0.7	99.4	97.1	2.3	2.369
8	0.8	146.1	142.6	3.5	2.454
9	0.9	132.9	129.9	3	2.309
10	1.0	107.3	104.9	2.4	2.288
11	1.1	124.8	121.9	2.9	2.379
12	1.2	149.6	146	3.6	2.466
13	1.3	146.5	143.2	3.3	2.304

c) Plaster

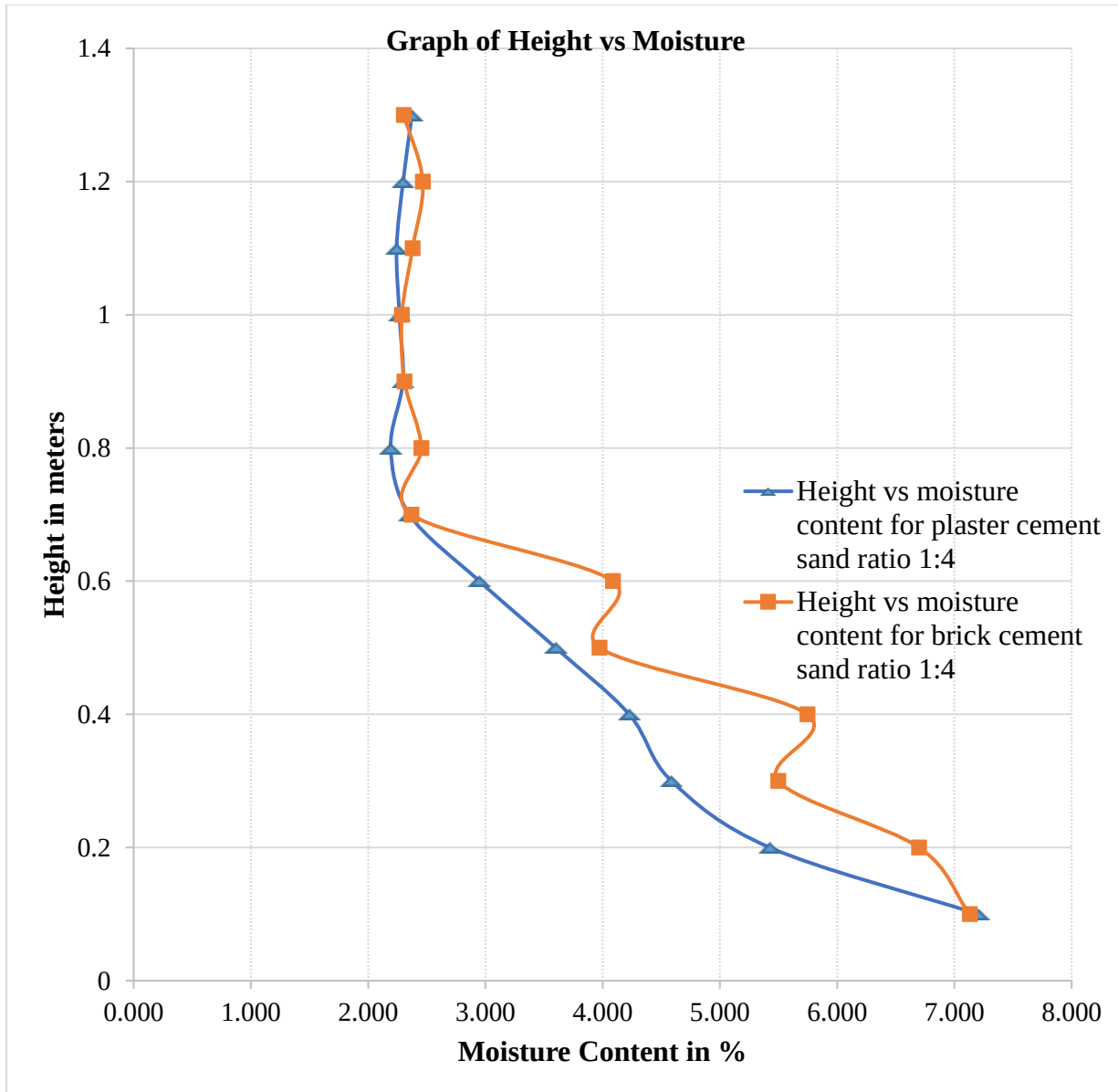


Figure 4.9: Height vs moisture content for Model 7 indoor cement sand ratio 1:4

The moisture content increases with height up to a point between 0.68 and 0.73 meters, beyond which it remains constant. The observed decreased moisture content of the brick wall was found to be highly varied. This is caused by moisture moving through mortar joints, which have varying binding strengths. The moisture moves upward due to capillarity. Moreover, from the DPC level to about 0.62 meters, a substantial amount of moisture rises through the brick wall rather than the plaster.

4.4.8 General curve for plaster

The curves for comparison of the moisture content for plaster are as shown in Figure 4.10 below;

Graph

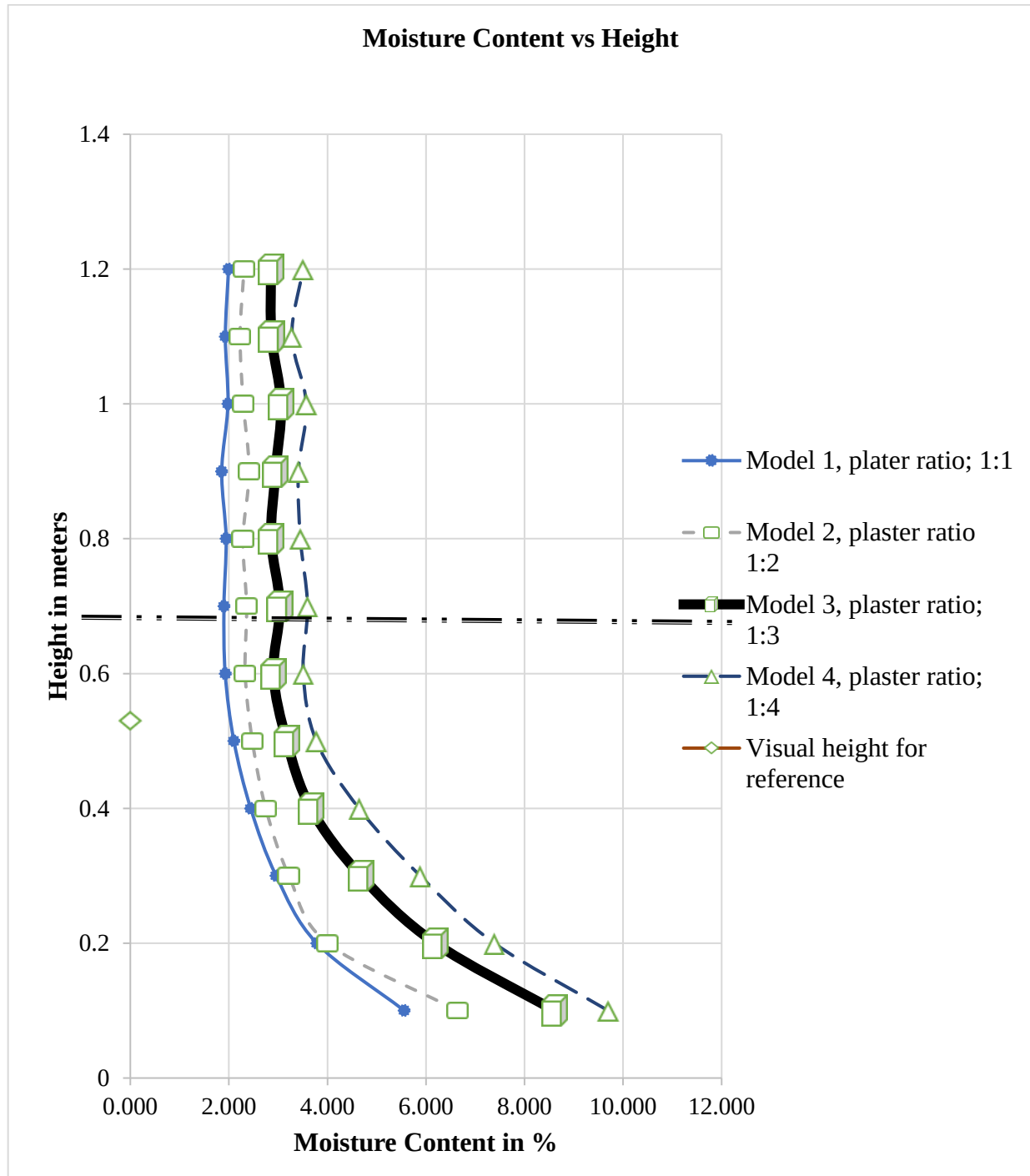


Figure 4.10: Height vs moisture content for plaster in models outside

When the height rises to around 0.6 meters, the moisture content starts to decline and then stabilizes. Certain models with varied plaster and mortar strengths show different variations in moisture content as the height increases. Moisture rising through the wall was determined by the strength of the cement sand mix. Moreover, the following order of decline occurs as moisture passes through the wall: $1:1 < 1:2 < 1:4 < 1:3$. The moisture content drop in the model was highly oscillatory. Moisture seeping through the mortar joints causes this to happen. The outside plaster's moisture content has increased more than the interior plaster's. The moisture migrates upward because of capillarity.

4.4.9 Curve of plaster for external walls

The curves for comparison of the moisture content for plaster for external walls are as shown in Figure 4.11 below;

Graph

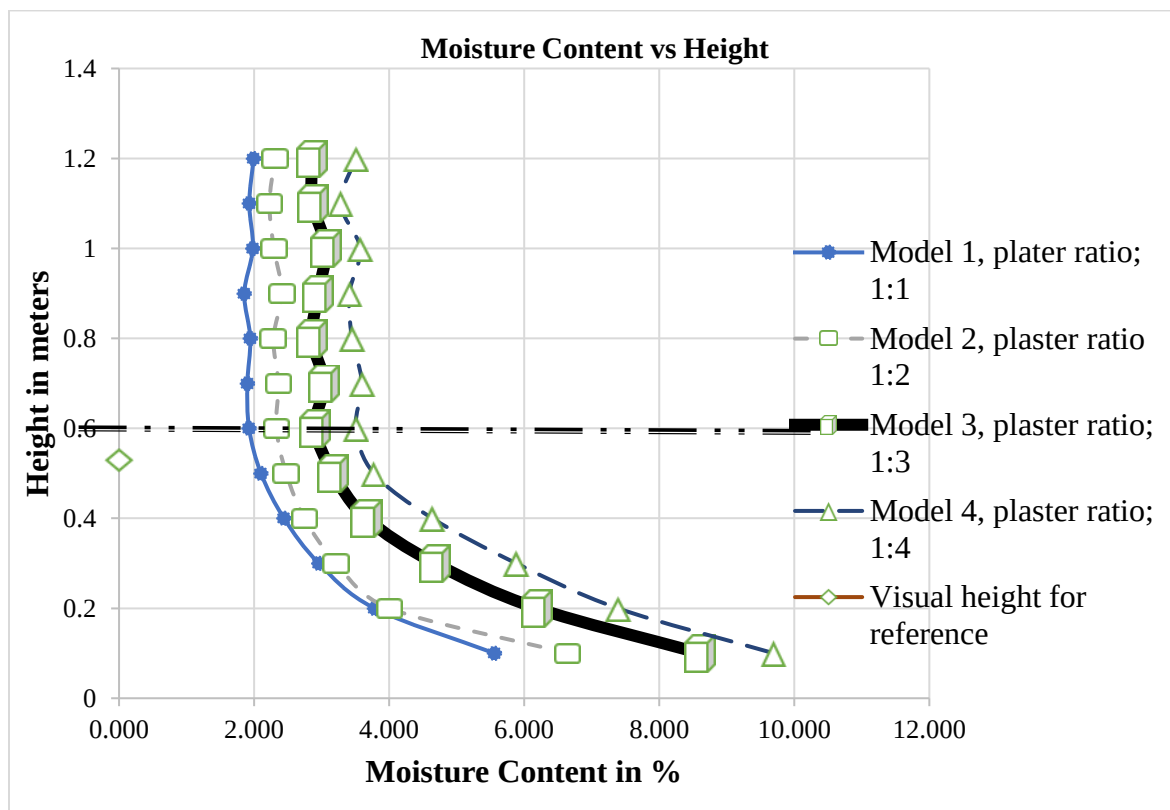


Figure 4.11: Height vs moisture content for plaster for external walls

The moisture rise decreases with increasing mix strength. The rise in moisture for plastered walls is consistent. The moisture content vs height is constant at around 0.60m. When the height increases by 0.62 meters, the moisture rise stays the same. This outcome was nearly identical to the natural height of roughly 0.63 meters.

4.4.10 Curves concerning plaster for internal walls

The curves for comparison of the moisture content for plaster for internal walls are as shown in Figure 4.12 below;

Graph

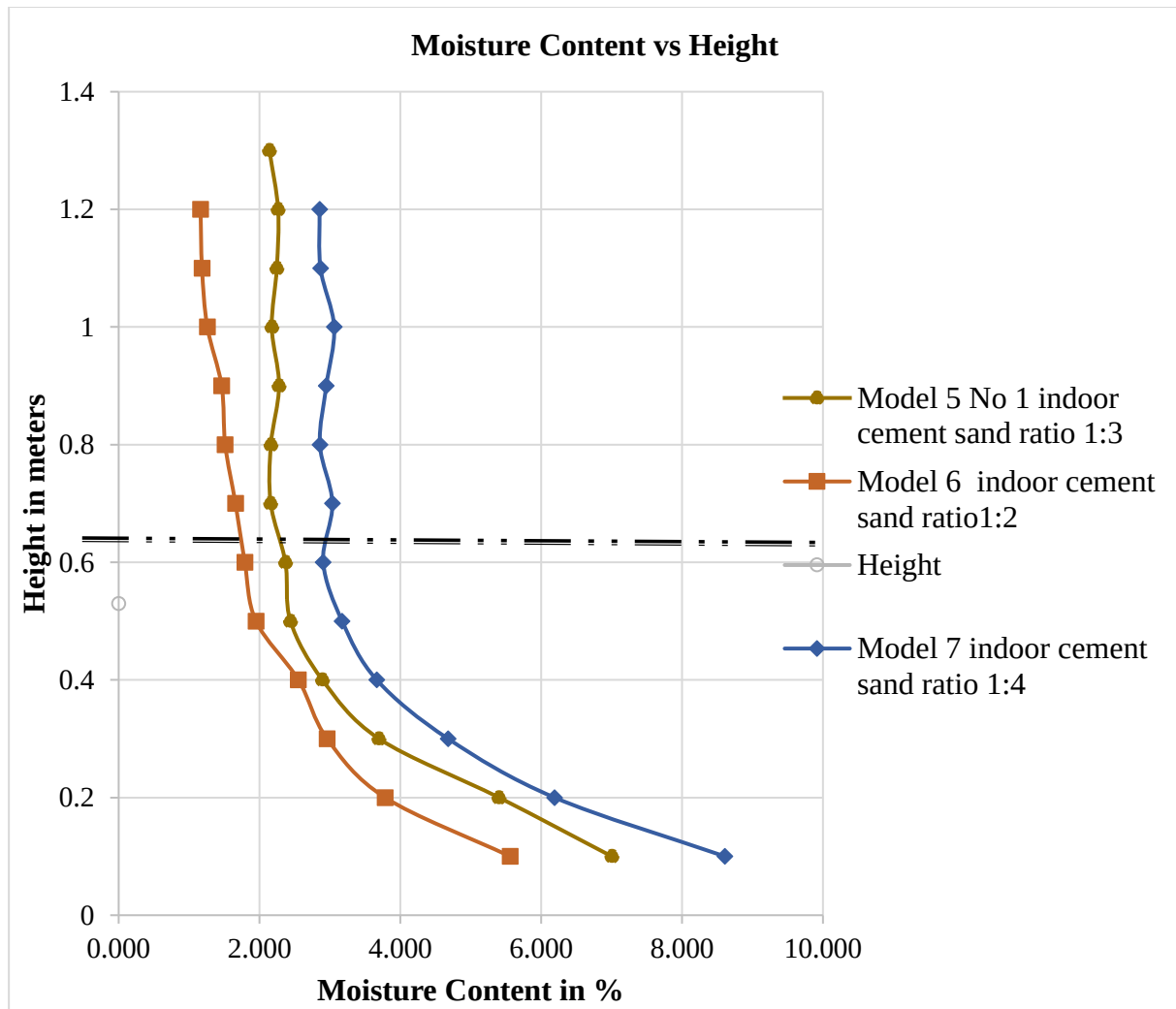


Figure 4.12: Height vs moisture content for plaster for internal walls

As mix strength increases, the moisture rise diminishes. Moisture levels in plaster walls were constantly rising. Additionally, there was a consistent moisture content versus height of 0.60 meters. This result was almost exactly the same as the average natural height of 0.63 meters.

The non-uniform curve created by the mortar joints breaks up moisture rises. Furthermore, moisture rise gradually diminishes with height. As mortar strength increases, the model's observed moisture rise diminishes.

4.4.11 Curves concerning bricks for external walls

The curves for comparison of the moisture content for brick for external walls are as shown in Figure 4.13 below;

Graph

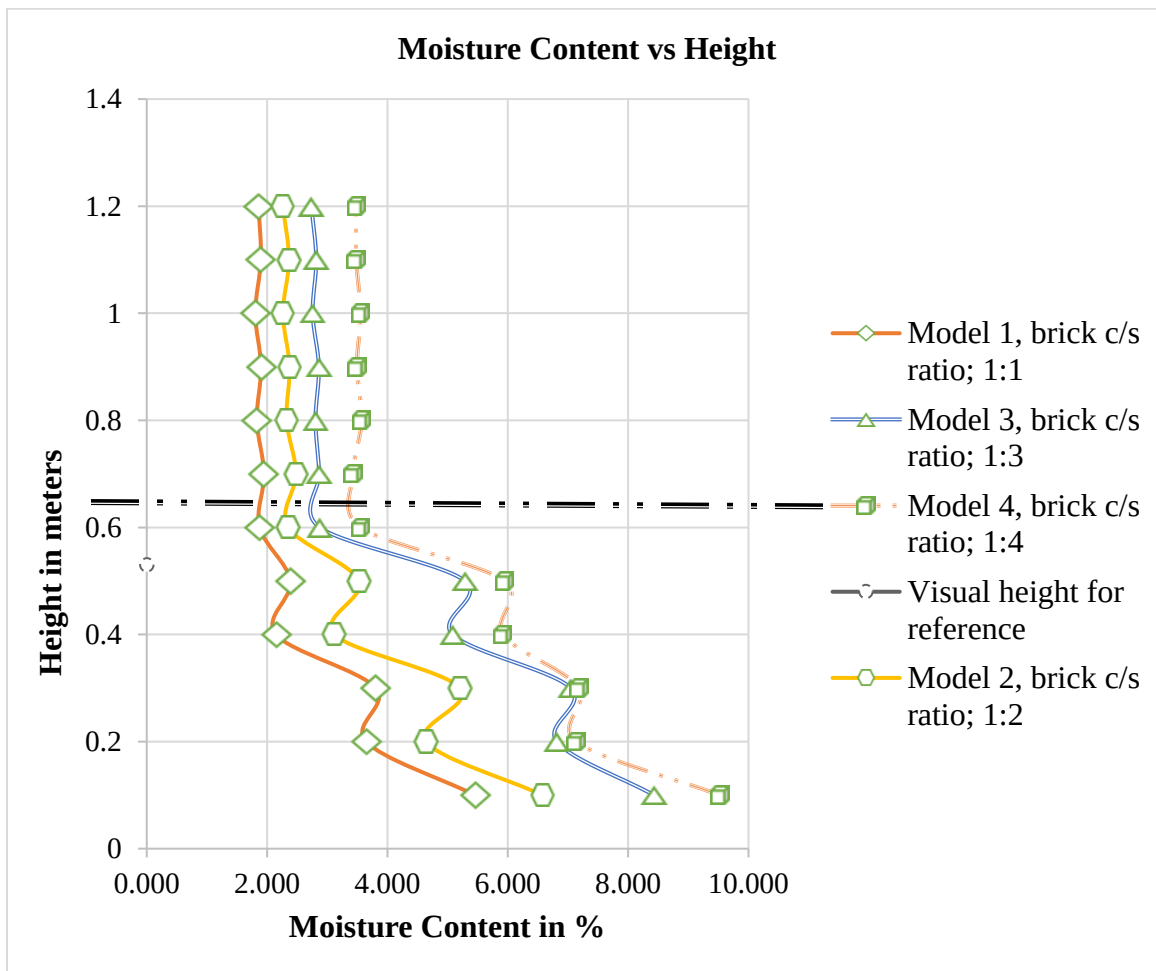


Figure 4.13: Height vs moisture content for bricks for external walls

Moisture rises are interrupted by the non-uniform action caused by the mortar joints. The observed moisture rise through the model decreases with increasing mortar strength.

4.4.12 Curves concerning bricks for internal walls

The curves for comparison of the moisture content for clay bricks for internal walls are as shown in Figure 4.14 below;

Graph

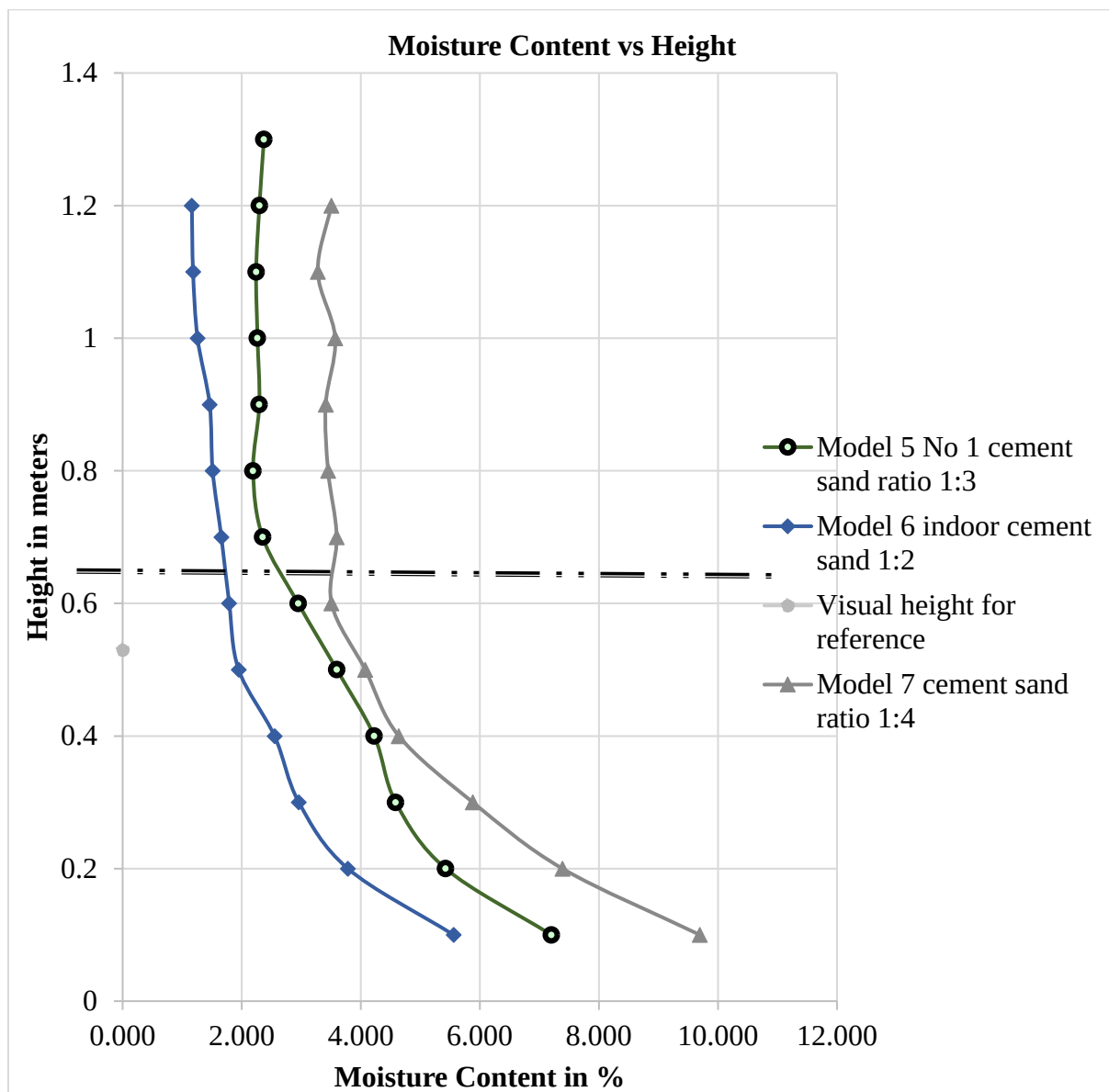


Figure 4.14: Height vs moisture content for bricks for internal walls

The uneven movement brought on by the mortar joints interrupts moisture rises. As mortar strength increases, the model's observed moisture rise diminishes.

4.4.13 Physical maximum heights of water measured after a period of 72 days

The heights in moisture level were measured. This is represented by Table 4.20 below;

Table 4.20: Sample m.c result of Ordinary Clay Bricks

S/No	Model No	Height (cm)	M.C in %
1	1 (cement sand ratios; 1:1 outdoor)	5.4	1.927
2	2 (cement sand ratios; 1:2 outdoor)	5.6	2.382
3	3 (cement sand ratios; 1:3 outdoor)	7.4	2.751
4	4 (cement sand ratios; 1:4 outdoor)	7.6	2.828
5	5 (cement sand ratios; 1:3 indoor)	5.5	4.048
6	6 (cement sand ratios; 1:2 indoor)	7.7	4.812
7	7 (cement sand ratios; 1:4 indoor)	7.5	2.852
		Average Height 6.67	

It's observed that; moisture rises gently through the model, and its magnitude reduces in the order of models; $6 > 5 > 4 > 3 > 2 > 1$

4.4.14 General observation on variation in moisture content across models;1, 2, 3, 4, 5, 6, 7, 8, & 9.

The moisture content of models 1, 2, 3, 4, 5, and 6 steadily rises. This was explained by the plaster's and mortar's decreased strength. The moisture content variation mentioned above was measured, and Figure 4.17 below displays the sample result;

Graph

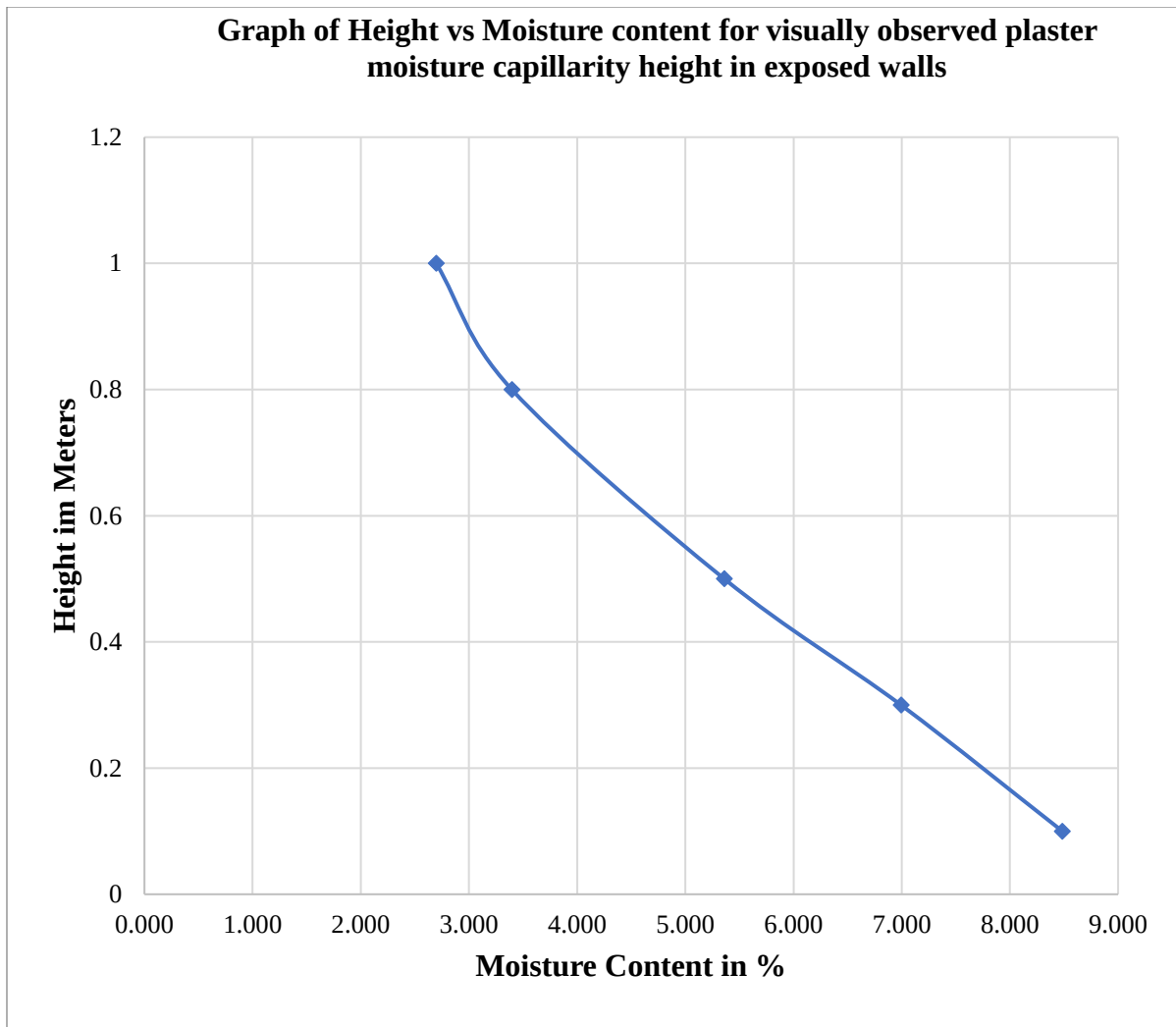


Figure 4.15: Height vs moisture content for plaster of the different models

When height increases, moisture content usually decrease. The non uniform curve was caused by mortar joints, which block the flow of moisture up through the joints.

4.5 Experiments conducted using materials that reduces the rise of moisture through walls:

4.5.1 Slates

The above variation in moisture content was measured, and result represented by Table 4.21, 4.22 & Figure 4.16 below;

a) Slates

Table 4.21: Moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	48.80	48.60	0.20	0.412
2	0.2	85.10	84.86	0.24	0.283
3	0.3	75.10	74.92	0.18	0.240
4	0.4	43.00	42.90	0.10	0.233
5	0.5	89.70	89.49	0.21	0.235
6	0.6	46.90	46.80	0.10	0.214

b) Bricks**Table 4.22: Moisture content result of ordinary clay bricks**

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	45.40	44.14	1.26	2.855
2	0.2	51.00	49.81	1.19	2.389
3	0.3	40.20	39.39	0.81	2.056
4	0.4	85.60	83.89	1.71	2.038
5	0.5	69.10	67.71	1.39	2.053
6	0.6	111.80	109.59	2.21	2.017

c) Graph

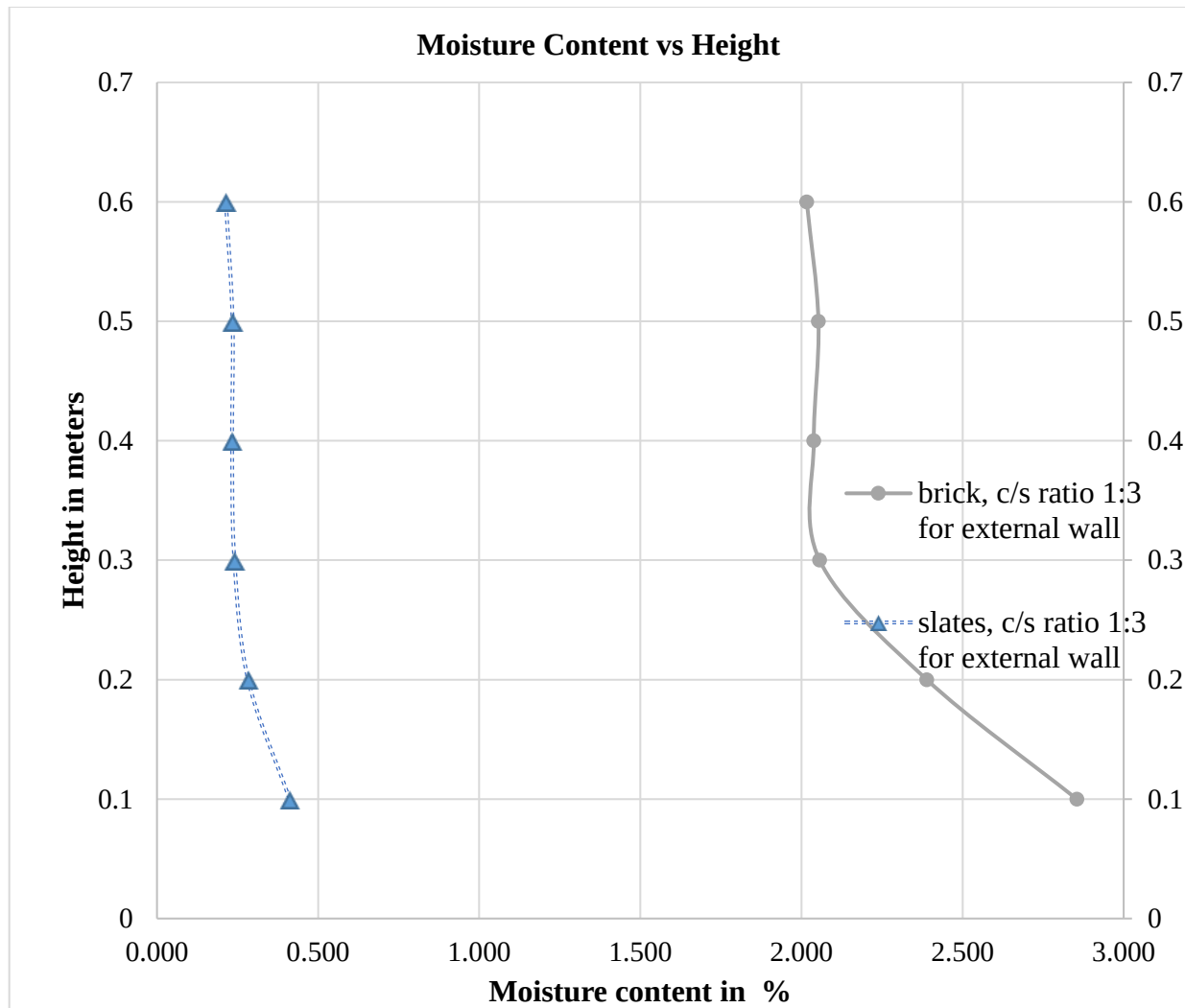


Figure 4.16: Height vs moisture content for slates & clay bricks

It has been noted that the rise in moisture content through slate wall finish was substantially less than that through brick walls. When used as building materials, slates can better withstand an increase in moisture content. It was a more effective water-proofing substance when applied to walls.

4.5.2 Glazed Tiles:

The variation in moisture cement were calculated, and the result is represented by Table 4.23, 4.24 and Figure 4.17 below;

a) Glazed tile

Table 4.23: Sample moisture content result of glazed tiles

Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2		(M1-M2)	(M1 -M2/ M2) x 100 %
0.1	57.70	56.10		1.60	2.852
0.2	80.10	78.79		1.31	1.663
0.3	79.00	78.30		0.70	0.894
0.4	62.60	62.29		0.31	0.498
0.5	83.50	83.30		0.20	0.240
0.6	83.90	83.83		0.07	0.084

b) Bricks**Table 4.24: Sample moisture content result of ordinary clay bricks**

Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
0.1	64.50	62.80	1.70	2.707
0.2	63.60	62.20	1.40	2.251
0.3	55.30	54.10	1.20	2.218
0.4	38.20	37.35	0.85	2.276
0.5	53.20	52.04	1.16	2.229
0.6	81.80	79.99	1.81	2.263

c) Graph

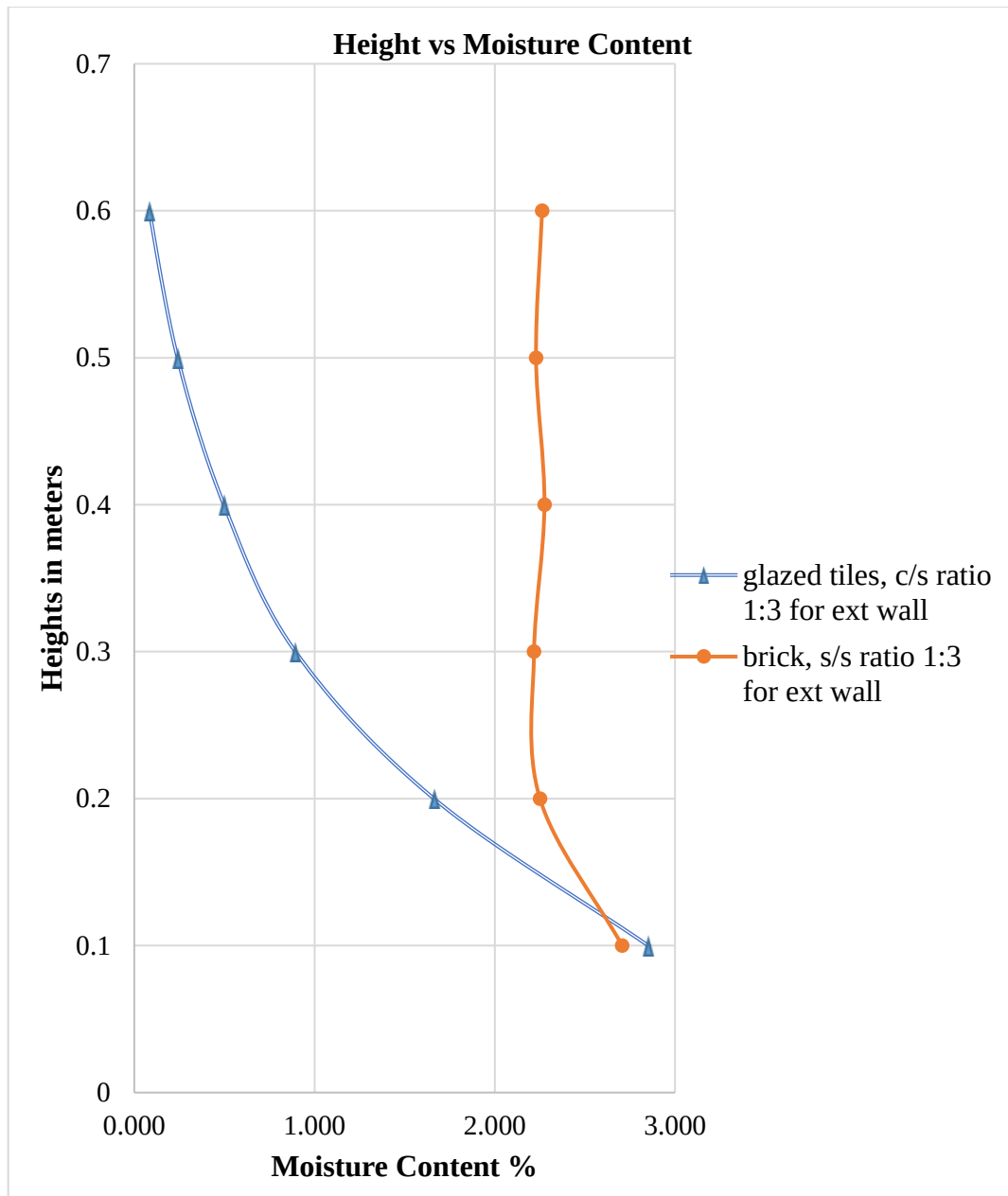


Figure 4.17: Height vs moisture content for glazed tiles & clay bricks

The rise in moisture content via glazed tile was found to be significantly less than that through brick walls. As a building material, glazed tiles can prevent the growth in moisture content. It's a good water resistant material that may be applied to walls. Furthermore, at 0.6 meters, very little to no moisture may penetrate through glazed tiles.

4.5.3 Bituminous Paint

The variation in moisture content were calculated, and the result was represented by Table 25, 26 and Figure 4.18 below;

a) Bituminous Paint

Table 4.25: Moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	68.10	65.60	2.50	3.811
2	0.2	58.70	57.31	1.39	2.425
3	0.3	86.30	84.31	1.99	2.360
4	0.4	48.80	47.66	1.14	2.392
5	0.5	48.00	46.91	1.09	2.324
6	0.6	74.60	72.88	1.72	2.360

b) Bricks

Table 4.26: Moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	51.00	48.15	2.85	5.919
2	0.2	72.90	69.81	3.09	4.426
3	0.3	72.80	69.71	3.09	4.433
4	0.4	68.90	66.00	2.90	4.394
5	0.5	99.60	95.41	4.19	4.392
6	0.6	85.10	81.70	3.40	4.162

b) Graph

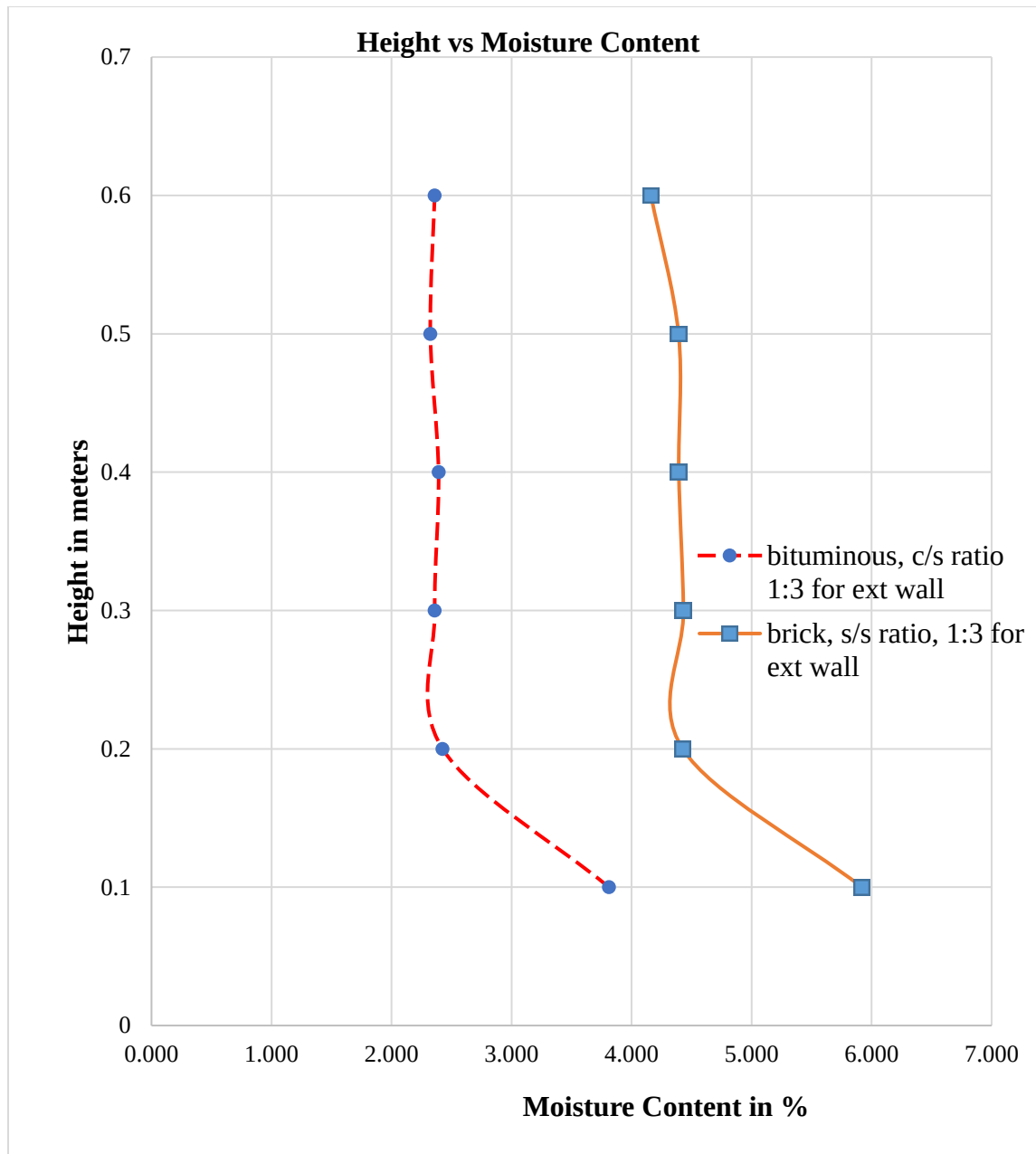


Figure 4.18: Height vs moisture content for plaster with bituminous paint & clay bricks

When bricks were painted with 2 to 3 coats of bituminous paint, the moisture content rise was substantially less than when brick walls are used with bituminous paint. One of the best building materials was bituminous paint, which can better prevent masonry walls' moisture content from rising. It is a sufficient waterproof material for usage on walls.

4.5.4 Facing Bricks

The variation in moisture content were calculated, and the result was represented by Table 27, 28 and Figure 4.19 below;

a) Facing Bricks

Table 4.27: Moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	68.20	66.50	1.70	2.556
2	0.2	121.70	118.89	2.81	2.364
3	0.3	77.60	75.81	1.79	2.361
4	0.4	87.91	85.89	2.02	2.352
5	0.5	110.11	107.58	2.53	2.352
6	0.6	62.55	61.11	1.44	2.356

b) Clay bricks

Table 4.28: Moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	104.20	100.21	3.99	3.982
2	0.2	87.60	85.01	2.59	3.047
3	0.3	104.50	102.11	2.39	2.341
4	0.4	117.90	115.21	2.69	2.335
5	0.5	84.20	82.31	1.89	2.296
6	0.6	107.90	105.52	2.38	2.255

c) Graph

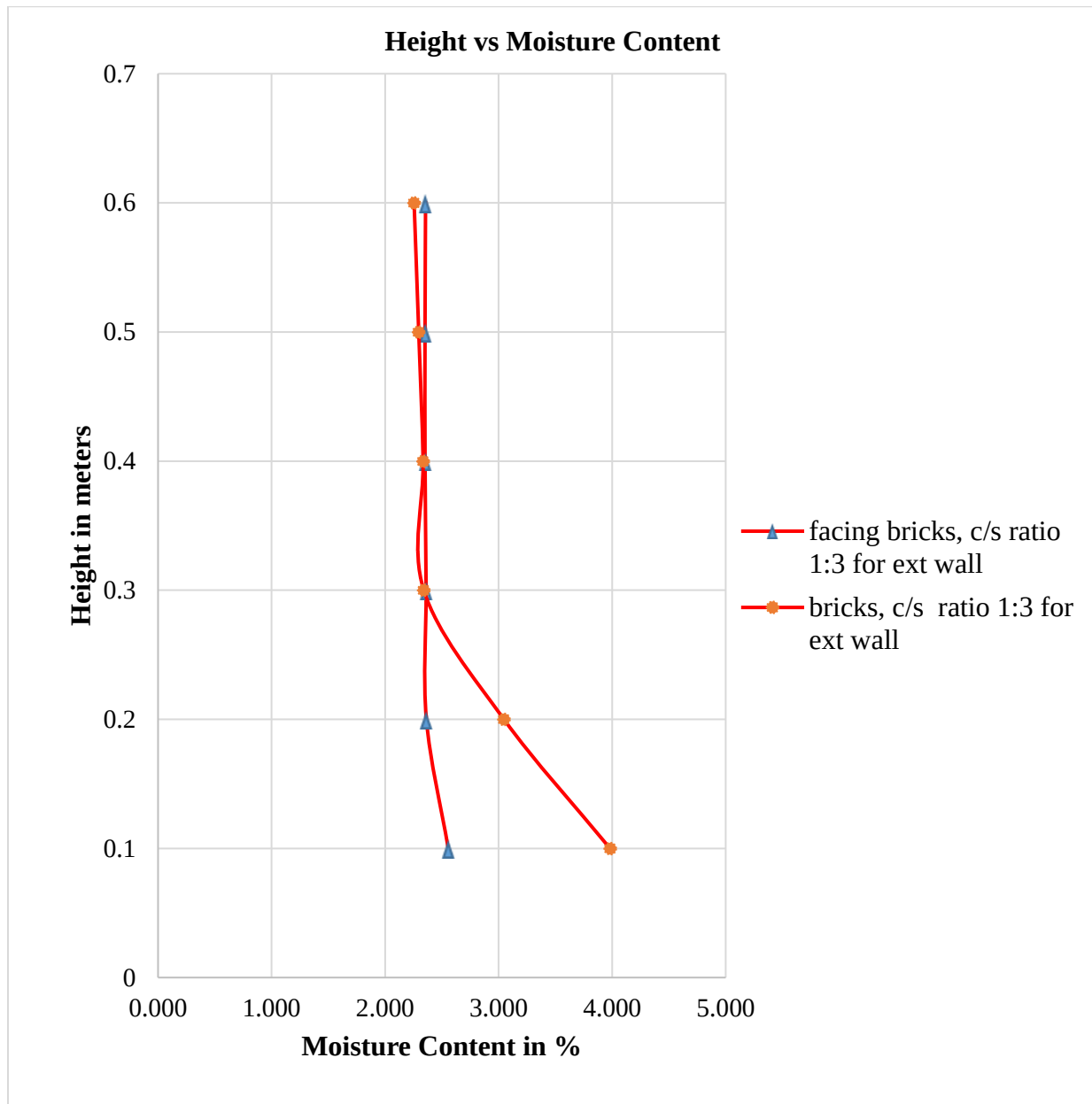


Figure 4.19: Height vs moisture content for facing bricks & ordinary clay bricks

The facing brick, which normally has a significantly lower moisture content than an average clay brick wall between 0 and 0.3 meters, causes the moisture content to climb steadily after a height of 0.2 meters. In construction projects, brick facing can assist stop the rising moisture content. When used on a wall, this material remains a good waterproofing material.

4.5.5 Cement: Sand Ratio 1:3 With 4% Clay

The variation in moisture content were calculated, and the result was represented by Table 29, 30 & Figure 4.20 below;

a) Cement: Sand Ratio 1:3 With 4% Clay

Table 4.29: Sample moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	60.90	58.50	2.40	4.103
2	0.2	87.90	86.30	1.60	1.854
3	0.3	76.80	75.90	0.90	1.186
4	0.4	57.90	57.31	0.59	1.029
5	0.5	69.10	68.40	0.70	1.023
6	0.6	67.40	66.70	0.70	1.049

b) Bricks

Table 4.30: Sample moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	85.00	79.91	5.09	6.370
2	0.2	77.50	73.81	3.69	4.999
3	0.3	93.00	89.10	3.90	4.377
4	0.4	90.30	87.61	2.69	3.070
5	0.5	89.40	86.85	2.55	2.936
6	0.6	80.40	78.11	2.29	2.932

c) Graph

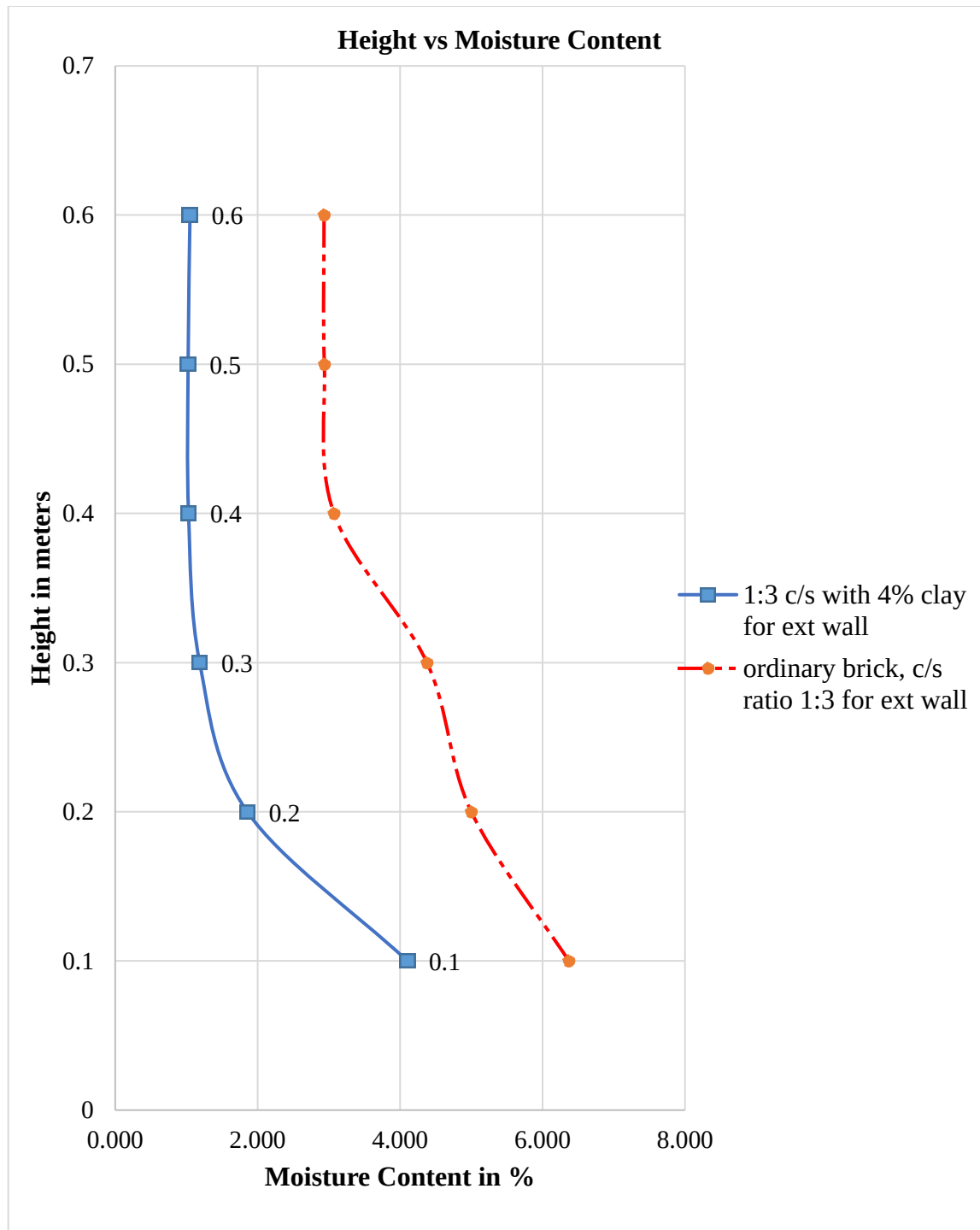


Figure 4.20: Height vs moisture content for plaster of cement: sand ratio 1:3 With 4% clay & clay bricks

When using a 1:3 cement-sand plaster mix with 4% clay, the moisture content rise was observed to be substantially less than when using a brick wall. For enhanced resistance against rising

moisture content, wall finishes made of a 1:3 cement-sand plaster mixture mixed with 4% clay might be utilised. It has the ability to shield walls when applied to them properly.

4.5.6 Weep Holes-Pipes

The variation in moisture content were calculated, and the result was represented by Table 4.31, 4.32 and Figure 4.21 below;

a) Weep Holes - Pipes

Table 4.31: Moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	87.44	81.93	5.51	6.725
2	0.2	74.20	71.30	2.90	4.067
3	0.3	87.40	84.61	2.79	3.297
4	0.4	91.40	88.92	2.48	2.789
5	0.5	95.20	92.73	2.47	2.664
6	0.6	107.80	105.10	2.70	2.569

b) Bricks

Table 4.32: Moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	76.51	72.82	3.69	5.067
2	0.2	71.80	68.96	2.84	4.118
3	0.3	76.50	74.41	2.09	2.809
4	0.4	65.60	64.31	1.29	2.006
5	0.5	44.00	43.12	0.88	2.041
6	0.6	57.40	56.27	1.13	2.008

c) Graph

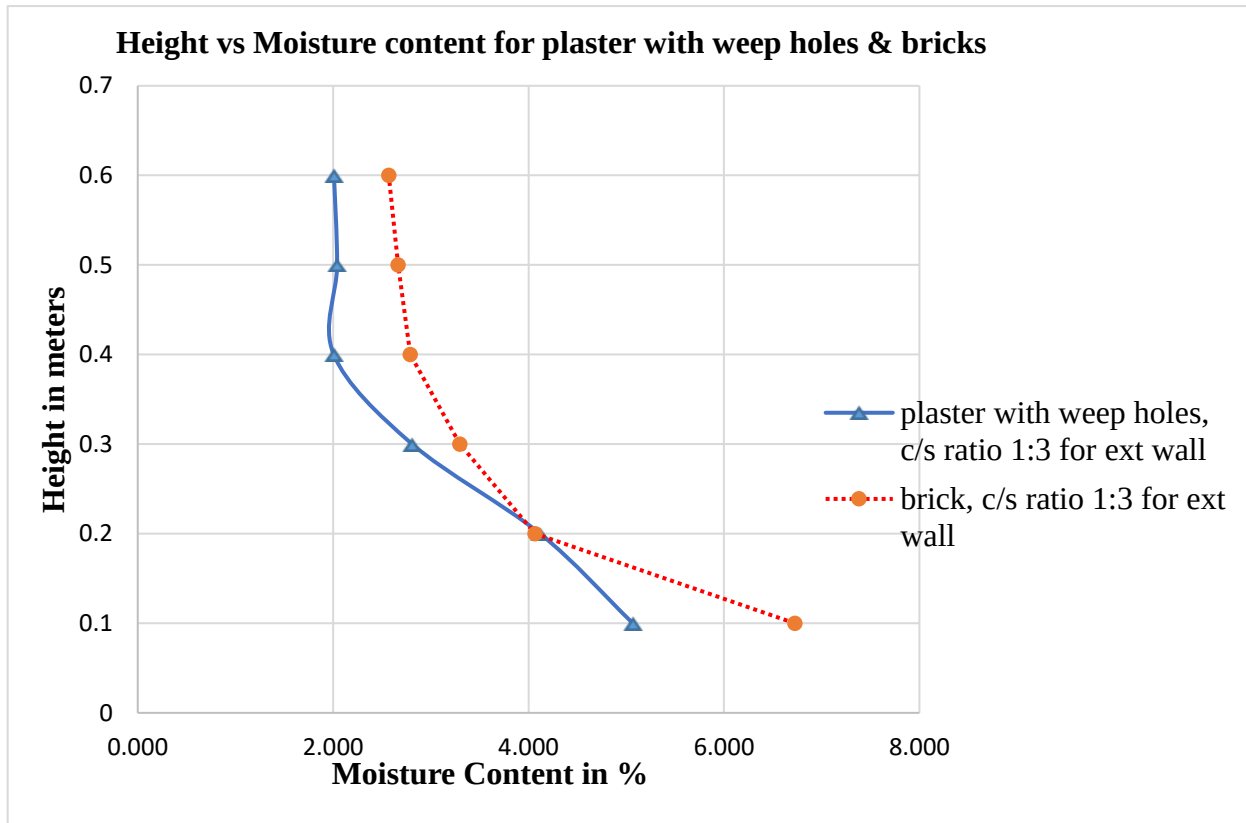


Figure 4.21: Height vs moisture content for plaster and clay bricks when using weep holes

There was less rise in moisture content via plastered walls with weep holes than through brick walls. When utilized as a wall finish, a plastered wall with weep holes helps reduce the rise in moisture content.

4.5.7 Overlapping DPC

The variation in moisture content were calculated, and the result is represented by Table 4.33, 4.34 and Figure 4.22 below;

a) Overlapping DPC

Table 4.33: Moisture content result of ordinary clay bricks

SAMPLE: **PLASTER**

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	69.490	69.280	0.21	0.304
2	0.2	63.300	63.125	0.18	0.278
3	0.3	59.000	58.882	0.12	0.200
4	0.4	63.000	62.868	0.13	0.210
5	0.5	67.900	67.776	0.12	0.183
6	0.6	74.100	73.972	0.13	0.173

b) Bricks

Table 4.34: Moisture content result of experimental ordinary clay bricks

SAMPLE: **BRICKS**

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	115.50	114.98	0.52	0.452
2	0.2	78.51	78.16	0.35	0.448
3	0.3	98.11	97.72	0.39	0.399
4	0.4	89.20	88.84	0.36	0.405
5	0.5	87.20	86.89	0.31	0.357
6	0.6	98.56	98.21	0.35	0.356

c) Graph

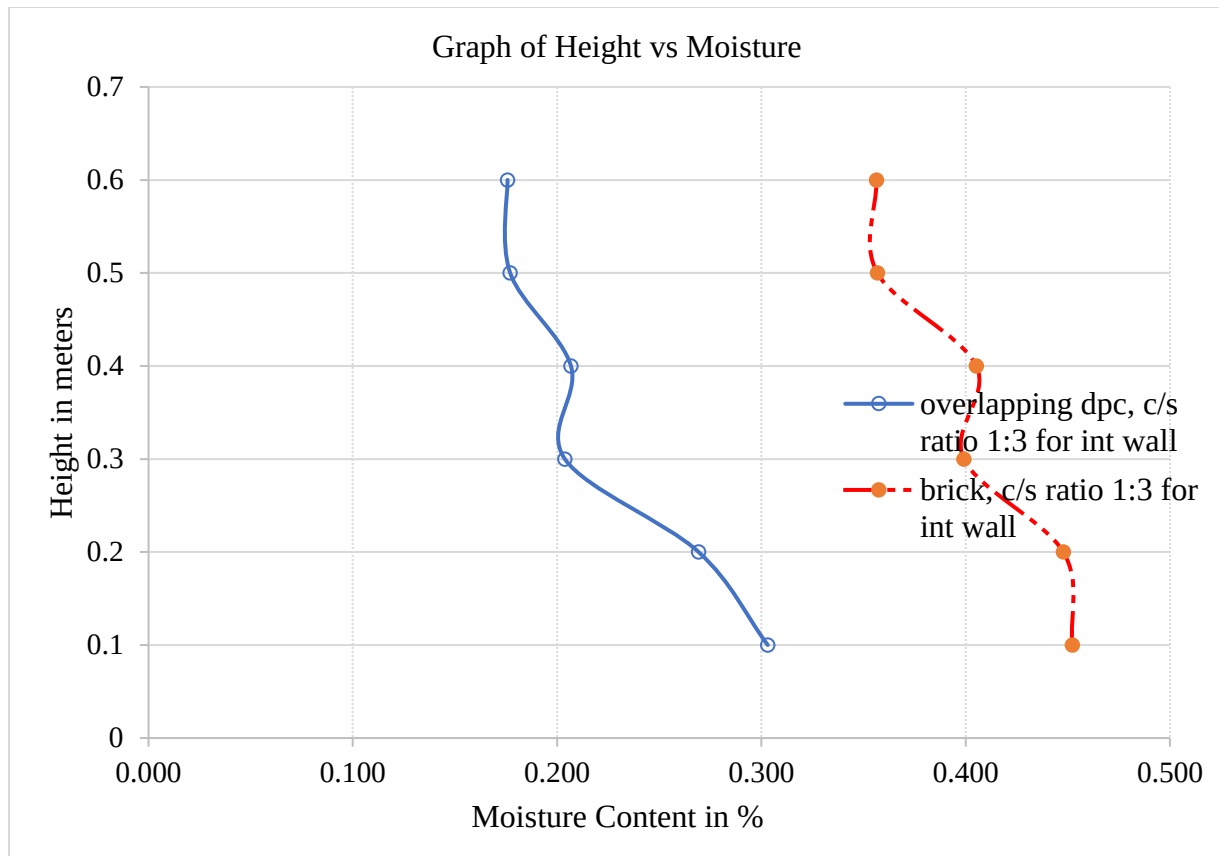


Figure 4.22: Height vs moisture content for plaster & clay bricks when using overlapping DPC

Plastered walls with overlapping DPC have a smaller moisture content rise than brick walls. When utilized properly as a water proofer, overlapping DPC can reduce moisture content from rising through walls. This can be implemented in civil works as an ideal practice.

4.5.8 Cement: sand with lining of cement sand mortar / plaster 1:3 mix along the DPC

The variation in moisture content were calculated, and the result is represented by Table 4.35, 4.36 and Figure 4.23 below;

a) Cement: sand with lining of cement sand mortar / plaster 1:3 mix along the DPC

Table 4.35: Moisture content result of ordinary clay bricks

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 -M2/ M2) x 100 %
1	0.1	53.62	51.94	1.68	3.235
2	0.2	99.71	96.73	2.98	3.081
3	0.3	53.60	52.02	1.58	3.037
4	0.4	99.70	96.86	2.84	2.932
5	0.5	67.50	65.59	1.91	2.912
6	0.6	161.70	157.46	4.24	2.693

b) Bricks**Table 4.36: Moisture content result of ordinary clay bricks**

S/No	Height / m	Weight of Wet Sample / g = M1	Weight of Dry Sample / g = M2	(M1-M2)	(M1 / M2) x 100 %
1	0.1	82.40	79.91	2.49	3.116
2	0.2	56.70	55.15	1.55	2.811
3	0.3	53.70	52.56	1.14	2.169
4	0.4	170.70	167.31	3.39	2.026
5	0.5	70.10	68.71	1.39	2.023
6	0.6	145.00	142.20	2.80	1.969

c) Graph

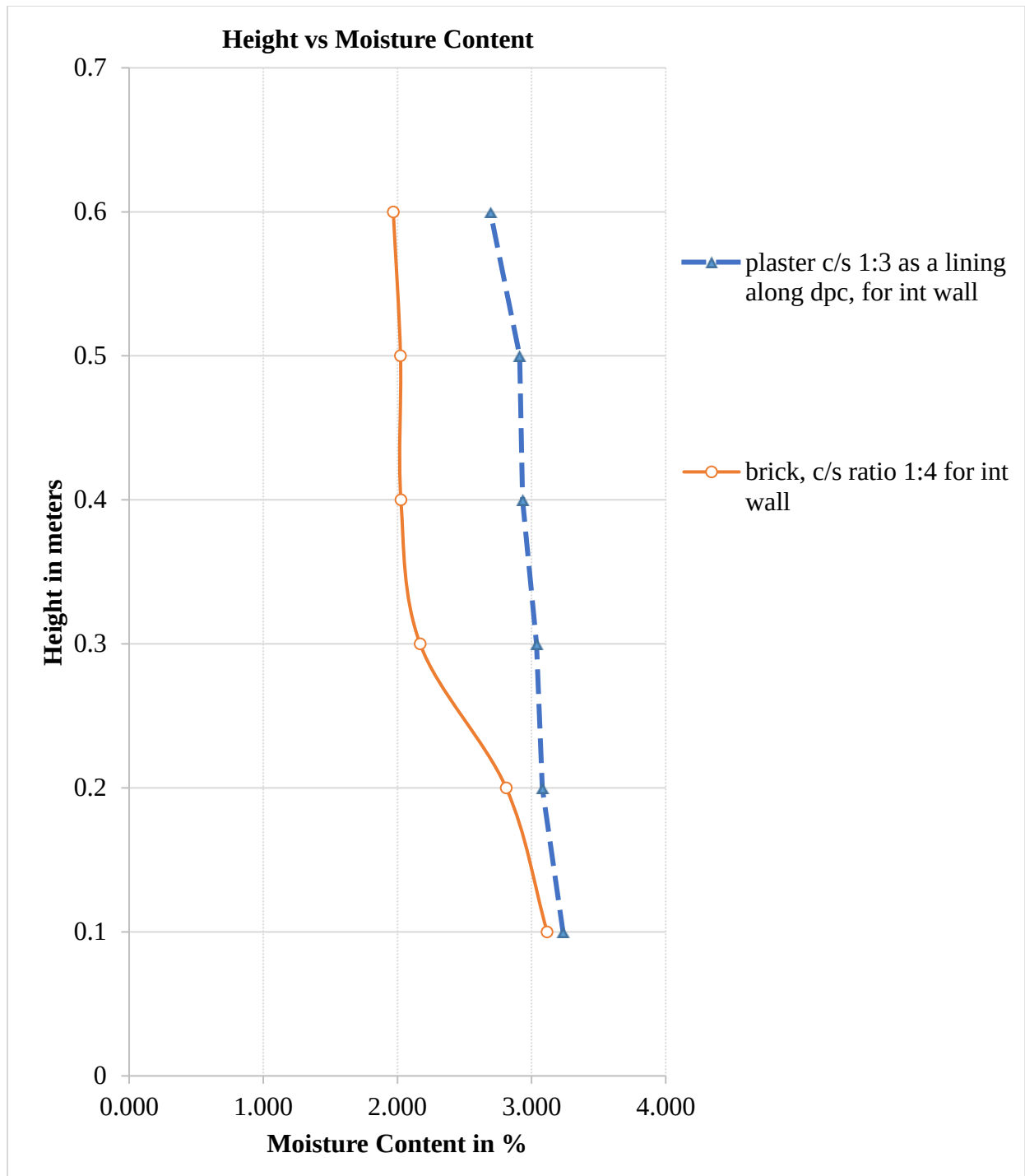


Figure 4.23: Height vs moisture content for plaster & clay bricks when using cement sand with lining of cement sand mortar / plaster 1:3 mix along the DPC & clay bricks

The rise in moisture content through a plastered wall with a strong mortar lining that is bonded to the DPC was less than that through a brick wall without. When utilized as a wall finish, a plastered wall with a strong mortar liner bonded to the DPC can prevent moisture content from rising through walls. This can be used for construction projects.

4.5.9 Material used for solution to moisture rise in masonry walls

The variation in moisture content for the different experimental material were calculated, and the result is represented by Figure 4.24 below;

Graph

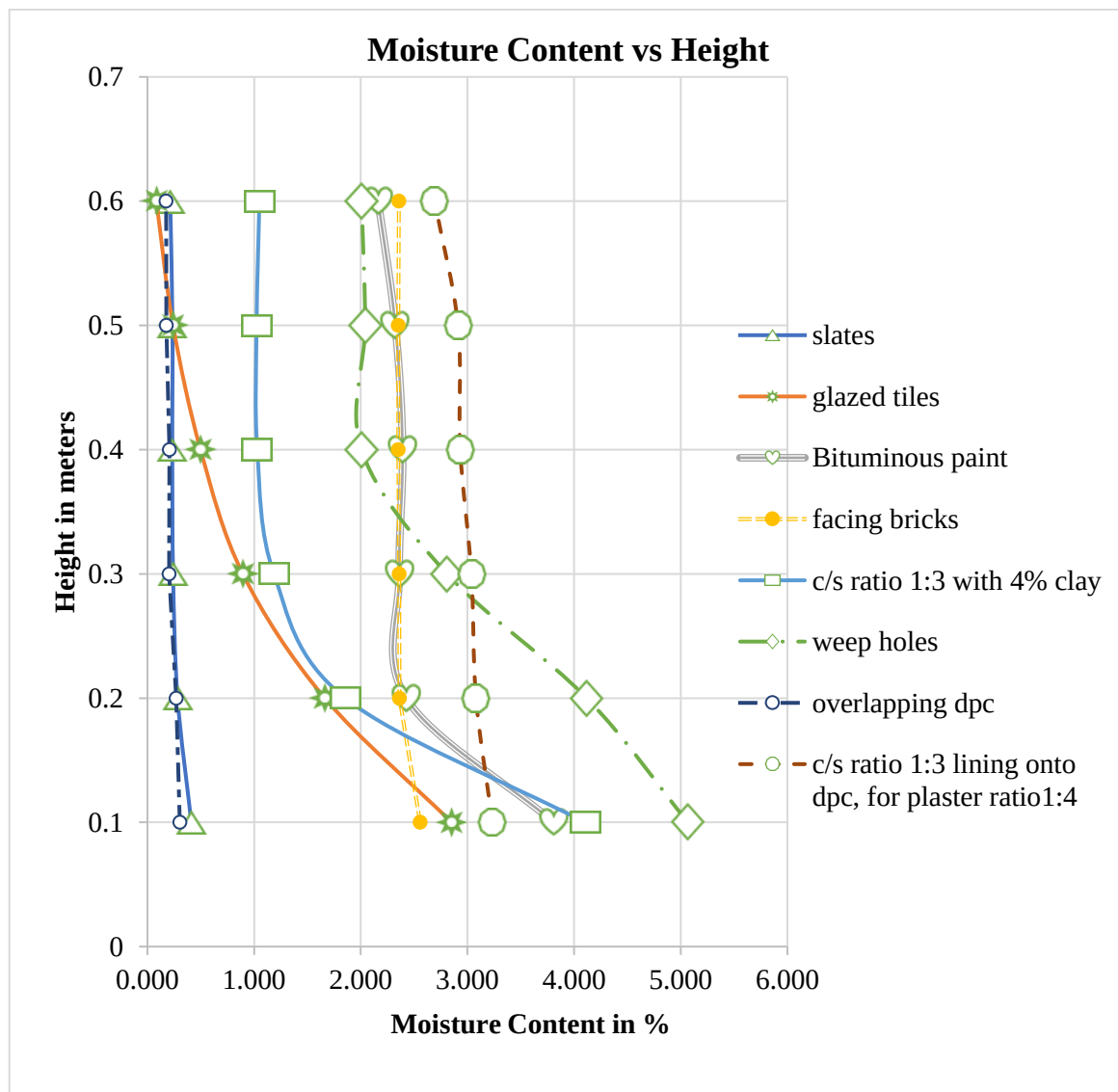


Figure 4.24: Graph of height vs moisture content for different materials for water proofing

The degree to which various building materials stop moisture content rise varies. In decreasing order, these materials provide water proofing: bituminous paint, face brick, weep holes, glazed tiles, cement sand plaster ratio 1:3 with 4% clay, stone slates, overlappind DPC, cement sand mortar, and plaster lining to DPC. These can be used for engineering works.

4.5.10 Effect of water proofing construction materials on bricks

The variation in moisture content for the different water proofing material were calculated, and the result was represented by Figure 4.25 below;

Graph

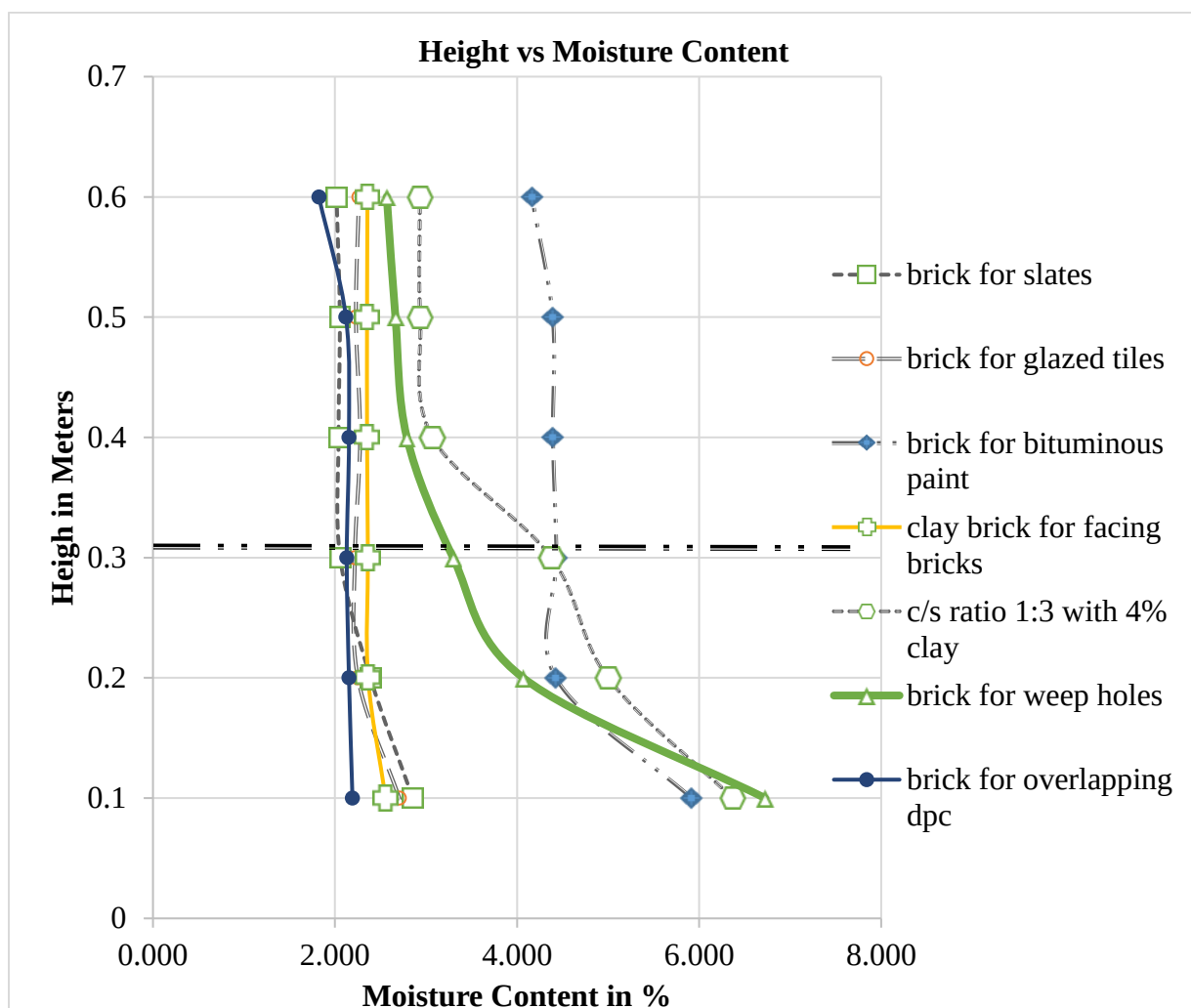


Figure 4.25: Height vs moisture content for effect of water proofing materials on ordinary clay bricks

Various water proofing building materials reduce the amount of moisture that penetrate through bricks by varying degrees. For minimizing moisture content rise through brick walls, overlapping DPC works best. Tiles, facing bricks, brick with a thick plaster lining that bonds to the DPC, weep holes, cement : sand of ratio 1:3 with 4% clay combination, and bituminous paint come next. For any building project or masonry wall, good construction practices utilizing overlapping DPC should be promoted.

4.5.11 Comparison of the different construction materials used for reduction of moisture rise through masonry walls / models

The comparison in moisture content for the different water proofing materials were calculated, and the result was represented by Table; 4.37, 4.38, 4.39, and 4.40 below;

Table 4.37: Moisture content result of ordinary clay bricks

Height in m	Slate s in %	Glazed tiles in %	Bituminous paint in %	Facing bricks in %	c/s ratio 1:3 with 4% clay in %	Weep holes in %	Overlapping dpc in %	c/s mortar / plaster ratio 1:3 bonding to dpc in %	Standard Plaster ratio 1:3 in %
0.1	0.412	2.852	2.881	2.556	4.103	5.067	0.304	3.235	8.608
0.2	0.283	1.663	2.425	2.364	1.854	4.118	0.278	3.081	6.190
0.3	0.240	0.894	2.360	2.361	1.186	2.809	0.200	3.037	4.677
0.4	0.233	0.498	2.392	2.352	1.029	2.006	0.210	2.932	3.664
0.5	0.235	0.240	2.324	2.352	1.023	2.041	0.182	2.912	3.173
0.6	0.214	0.084	2.160	2.356	1.049	2.008	0.173	2.693	2.904

Table 4.38: Moisture content result of ordinary clay bricks

General reduction of moisture content in %								
0.1	8.196	5.756	5.727	6.052	4.505	3.541	8.304	5.373
0.2	5.907	4.527	3.765	3.826	4.336	2.072	5.912	3.109
0.3	4.437	3.783	2.317	2.316	3.491	1.868	4.477	1.640
0.4	3.431	3.166	1.272	1.312	2.635	1.658	3.454	0.732
0.5	2.938	2.933	0.849	0.821	2.150	1.132	2.991	0.261
0.6	2.690	2.820	0.744	0.548	1.855	0.896	2.731	0.211

Table 4.39: Moisture content result of ordinary clay bricks

Reduction of moisture content as a percent of plaster cement sand ratio 1:3									
0.1	0.95	0.67	0.67	0.70	0.52	0.41	0.96	0.62	8.608
0.2	0.95	0.73	0.61	0.62	0.70	0.33	0.96	0.50	6.190
0.3	0.95	0.81	0.50	0.50	0.75	0.40	0.96	0.35	4.677
0.4	0.94	0.86	0.35	0.36	0.72	0.45	0.94	0.20	3.664
0.5	0.93	0.92	0.27	0.26	0.68	0.36	0.94	0.08	3.173
0.6	0.93	0.97	0.26	0.19	0.64	0.31	0.94	0.07	2.904
Average	0.941	0.828	0.440	0.437	0.668	0.377	0.950	0.305	
Av in %	94.1	82.8	44.0	43.7	66.8	37.7	95.0	30.5	

Table 4.40: Moisture content result of ordinary clay bricks

Summary of average order of moisture content reduction in %								
Materials								
Overlapping dpc	Slates %	Glazed Tiles %	c/s ratio 1:3 with 4% clay %	Bituminous Paint %	Facing Brick %	Weep Holes %	c/s mortar / plaster ratio 1:3 bonding to dpc %	
95.0	94.10	82.8	66.8	44.0	43.7	37.7	30.5	

As indicated by the average values in Tables 4.37, 4.38, 4.39, and 4.40 above. The construction materials have varied degrees of moisture content reduction by overlapping DPC, slates, glazed tiles, cement sand plaster ratio 1:3 with 4% clay, facing brick, bituminous paint, cement sand mortar / plaster ratio 1:3 bonding to DPC, and weep holes. According to the aforementioned finding, the best material or technique to minimize moisture rise in masonry walls is to utilize DPC properly. Building standards might benefit from this in terms of the permitted moisture content in brick walls.

4.6 Visual observation of rise in moisture

4.6.1 Introduction

Moisture was observed to rise through the wall. And after 72 days, the rise was as shown in the photo Figure 4.26 below;



Figure 4.26: Photo of moisture rise in one of the models

Capillarity was regarded as the cause of moisture flow upward as shown in Figure 4.26 above. Therefore, this provides explanation for the imperfections that were noted at particular wall heights.

4.6.2 Measurement of the capillary rise

The visual observation of capillary rise was measured after 72 days using a tape ruler, and the observed values were as shown in Table 4.41 below;

Table 4.41: Moisture content result of ordinary clay bricks

S/No	Model Number	Height (cm)
1	1 Cement: Sand ratio; 1:1 Outdoor	5.4
2	2 Cement: Sand ratio; 1:2 Outdoor	5.6
3	3 Cement: Sand ratio; 1:3 Outdoor	7.4
4	4 Cement: Sand ratio; 1:4 Outdoor	7.6
5	5 Cement: Sand ratio; 1:3 Indoor-1	7.5
6	6 Cement: Sand ratio; 1:2 Indoor	5.8
		Average Height 6.55

This results in a moisture rise that is an average of 6.55 cm. This observation provides evidence of water problems in masonry walls at these elevations of roughly 0.65 meter.

CHAPTER FIVE – CONCLUSION AND RECOMMENDATION

5.1 Conclusion;

According to the baseline survey that was conducted on a population of 213 respondents that consist of; private property owners, civil and building engineering practitioners, contractors, and district engineers. Capillary moisture rise was a serious problem, and it has affected very many structures in Uganda. The study observed structures visited in the districts of: Dokolo, Lira, Abim, Moyo, and Kampala; 96.2% were affected by capillarity, and 92.4% used cement sand ratio of 1:3.

New and existing structures need to be treated well, and the study also observed that reliable treatments include; water proofing like the use of damp proof course, water resistant materials and good construction methods. **The study concludes that;** in the building industry practice in Uganda, the cement sand plaster ratio most commonly used was 1:3, and capillary rise of moisture is a common cause of dampness in buildings resulting in related defects. This was in line with the physics of capillarity (Hall & Hoff, 2007).

The study also concludes that; the height of water rise by capillarity in most masonry walls from damp proof courses was 600mm. This agrees with observed measured heights, and earlier research (Agyekum, Ayardwa and Kofi, 2014), & (Eric & Zhongy, 2010). This also agrees with earlier scholarly works that was done by Leslie Sellers, that the average height of capillary moisture rise rarely exceeds 1.5m.

This has provided enough proof, and justification of the existence and occurrence of all forms of failures and defects that affects these areas of the wall, whose heights fall below dpc, and zero to 0.65m above dpc. And this shows that special treatment is always required to prevent these areas of the wall from being affected. Also, the walls already affected need to be given engineering treatment (Sayed, Miklewski, Kahangi and Shareza, 2021). Also, moisture content remained constant from around 0.63m to 1.4m. This was attributed to maximum capillary rise in moisture.

Most importantly, to reduce moisture rise in masonry walls, this study observed a number of construction materials, and methods of application. The percentage efficiency of the materials and method, in terms of cement sand mix of ratio 1:3 include; overlapping dpc 95.0, Slates 94.1, glazed tiles 82.3, cement sand ratio 1:3 with 4% clay giving 66.8, bituminous paint 44.0, facing bricks 43.7, weep holes 37.7, cement sand mortar / plaster ratio 1:3 making it bond directly to the DPC

30.5. And the best method was the use of overlapping DPC, while the least was the use of weep holes.

Since all these methods gave proof of reduction in moisture rise, they can be used to reduce moisture rise in structures. also, in support of these observations, slate was the material that gave the highest reduction of moisture through masonry walls, followed by glazed tiles, plaster of cement sand mix ratio 1:3 with 4% clay, facing bricks and bituminous paint. Due to their percentage moisture content reduction results of 95 and 94.1, for **dpc and slates respectively**, these materials are one of the best materials for reduction in moisture rise in walls. This therefore provide an engineering solution to pretreatment of walls (Lesslie, 2017), within the height of 0m to 0.7m above dpc level, or post treatment of masonry walls to prevent moisture rise in walls, and related defects that includes; peeling off of plaster, rusting of reinforcements, cracks, peeling off of paints, and wall staining (Assingwire, Muhwezi, & Ssenigozi, 2021). **This study therefore makes further conclusion that;** there are different construction materials and methods that can be used to mitigate moisture rise in masonry walls. This also agrees with earlier works by those scholars like suitable materials and construction methods can be used to limit capillary water rise in masonry walls (Ercio & Hipolito, 2014). This study therefore makes a general conclusion that, **“Assessment of moisture related defects in masonry walls”**, remains a fundamental thorn in the construction industry (Agyekum, Ayardwa and Kofi, 2014). All stakeholders should keep watch on the issue, to find more elaborate, and realistic solution including recommending the outcome that been confirmed in the main, and specific objectives of this study.

5.2 Recommendation;

And this study recommends the use of overlapping of damp proof course, together with slates as the best water proofing. And there is also a dire need for all practicing engineers and other parties in the construction industry to ensure that workmanship is done well, and the damp proof course, or water proofing should adequately cover the plaster finish neatly (overlap) extending not less than 30mm internally and externally to the wall, such that there should be no room for moisture rise through masonry walls (Austin, Robins, & Godier, 2002). Most masons make damp proof courses to just flash with the walls during construction, such that the finishes especially cement - sand always cover these damp proof courses rendering them incapable of stopping capillary moisture rise. These finishes becomes the pathway for moisture, due to their affinity for water (Laldintluanga, Ramhmachluani

and Ramthlangliani, 2020). Moreso, plaster should be of adequate strength. This stems from the fact that, the stronger the plaster, the more resistant the wall to moisture rise. More studies are needed to assess the relation between mortar / plaster strength, and the moisture penetration through them (Chew, 2021).

Further research shall also be needed in the areas of; the failure mechanism of water proofing materials, and the variation in strength of building units with moisture content. Additionally, as the supplementaries demonstrate, there were other aspects that were frequently cited in the main body of the research; their specifics are included in the references and appendices sections of this document. Appendix A3 has more images that provide details about the study.

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APPENDIX A1 - QUESTIONNAIRES

Questionnaire for baseline survey one on identification of structures whose masonry walls were affected by capillary moisture rise.

1.0 Section A: Introduction

This questionnaire is aimed at collecting data for academic research purposes on “**identification of masonry walls affected by moisture, causes of masonry wall defects, and plaster ratio used for finishes in Dokolo District & Northern Uganda in general**”. This base line survey was done involving 213 respondents. The study was in partial fulfilment of the requirements for the award of a degree in Master of Science in Structural Engineering of Kyambogo University. Respondents were urged to be assured that, any information collected through this questionnaire was to be treated with utmost confidence, and to be used for research purposes only. Positive responses were highly appreciated.

2.0 Section B: Background Information

2.1: Please indicate your Gender: 1. Female ☐ 2. Male ☐

2.2: What is your position _____

2.3: What is your highest educational qualification? Please tick as appropriate;

1. Certificate ☐ 2. Diploma ☐ 3. Undergraduate ☐ 4. Postgraduate ☐

2.4: For how long have you worked in this dept.?

1. Below 5 years ☐ 2. 6-10 years ☐ 3. 11-15 years ☐ 4. 16-20 years ☐ Over 20 years

3.0 Section C: Identification; of masonry walls affected by moisture, and plaster ratio used for finishes in Dokolo District, Northern Uganda, & Kampala in general;

Using the following table and the scale provided below, please tick on the statements which best describes your opinion of procurement processes in Lira Municipal Local Government.

Scale: (Strongly agree=5, agree=4, Neutral=3, Disagree=2, strongly Disagree=1)

3.1 Wall defects

WD	Wall defects occurrence in masonry walls					
WD1	Wall defects selectively occurs in masonry walls in Dokolo District & Northern Uganda in general	5	4	3	2	1
WD2	Wall defects are not severe in masonry walls in Dokolo District & Northern Uganda in general	5	4	3	2	1
WD3	Wall defects does not occur in masonry walls in Dokolo District & Northern Uganda in general	5	4	3	2	1

3.2 Wall finishes

WF	Wall Finishes					
WF1	Plaster ratio of 1:1 used in masonry walls construction & finishes	5	4	3	2	1
WF2	Plaster ratio of 1:2 used in masonry walls construction & finishes	5	4	3	2	1
WF3	Plaster ratio of 1:3 used in masonry walls construction & finishes	5	4	3	2	1
WF4	Plaster ratio of 1:4 used in masonry walls construction & finishes	5	4	3	2	1
WF5	Plaster ratio of 1:5 used in masonry walls construction & finishes	5	4	3	2	1
WF6	Plaster ratio of 1:6 used in masonry walls construction & finishes					

3.3 Quality Control Regulations

QCR	Quality Control Regulations					
QCR1	Building regulation is always adhered to	5	4	3	2	1
QCR2	Good construction techniques always used on site	5	4	3	2	1
QCR3	Good equipments used on site	5	4	3	2	1
QCR4	Correct mix design used on site	5	4	3	2	1

QCR5	Qualified personnels on site	5	4	3	2	1
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4.0 Section C: Performance of construction projects

Using the following table and the scale provided below, please tick on the statements which best describes your opinion of performance of construction projects in Lira City Local Government.

Scale: (Strongly agree=5, agree=4, Neutral=3, Disagree=2, strongly Disagree=1)

	Durability of structures					
DS1	Construction projects are highly durable against moisture	5	4	3	2	1
DS2	Construction projects are not highly durable against moisture	5	4	3	2	1
DS3	Construction projects resist capillary rise of moisture	5	4	3	2	1
DS4	Material which are water resistant are used in construction works	5	4	3	2	1
DS5	Material which are not water resistant are used in construction works	5	4	3	2	1

APPENDIX A2 - INTERVIEW GUIDE

- i.** Are the selection criteria of the local contractors being transparent?
- ii.** Are call for bids is made public to all potential bidders in Lira city?
- iii.** Before awarding the contract, do the contracts committee carry out due diligence to confirm the existence of the contracted companies?
- iv.** Do the awarding committee follow the PPDA guidelines to award contracts?
- v.** How does tendering process influence performance of construction projects in Lira city?
- vi.** How does bid criteria influence on the performance of construction projects in Lira city?
- vii.** How do quality Control regulations influence the performance of construction projects in Dokolo District & Northern Uganda in general?

APPENDIX A3 – PHOTOS



Figure A3.1: Defects in different structures in Kyambogo University - Kampala



Figure A3.5: showing moisture rise through the researcher's experimental model 1, simulating a masonry wall, at Kyambogo University Soil Laboratory.



Figure A3.6: showing moisture rise through the researcher's experimental model 2 simulating a masonry wall, at Kyambogo University Soil Laboratory



Figure A3.7: showing moisture rise through the researcher's experimental model 4 simulating a masonry wall, at Kyambogo University Soil Laboratory



Figure A3.8: showing moisture rise through the researcher's experimental model R simulating a masonry wall, at Kyambogo University Soil Laboratory



Figure A3.10: showing the researcher feeding the experimental models with water, at Kyambogo University Soil Laboratory



Figure A3.12: showing the researcher reserving water at the models, at Kyambogo University Soil Laboratory



Figure A3.13: showing the researcher picking samples for m.c examination at different heights on the vertical face of one of the models, at Kyambogo University Soil Laboratory



Figure A3.14: showing the researcher comparing samples for m.c examination at different heights on the vertical face of one of the internal models, at Kyambogo University Soil Laboratory



Figure A3.15: showing the researcher examining m.c on the samples in an oven, at Kyambogo University Soil Laboratory



Figure A3.16: showing the different materials being examined for solution to moisture rise in masonry walls, at Kyambogo University Soil Laboratory