INVESTIGATION OF JOINT THICKNESS & MORTAR STRENGTH ON THE MECHANICAL BEHAVIOUR OF BRICK MASONRY

A DISSERTATION

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Submitted by:

Anshoo Yadav

(2K21/STE/06)

Under the supervision of

Dr. Shilpa Pal

DEPARTMENT OF CIVIL ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of
Engineering)Bawana Road, Delhi-
110042

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M.Tech (Structural Engineering) **Anshoo Yadav** **2023**

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CANDIDATE'S DECLARATION

I, **Anshoo Yadav**, Roll No. 2K21/STE/06, student of M. Tech (Structural Engineering), hereby declare that the project dissertation entitled "**Investigation of Joint Thickness & Mortar Strength on the Mechanical Behavior of Brick Masonry**" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

Place: Delhi **(ANSHOO YADAV)**

Date: May 31, 2023

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi-110042

CERTIFICATE

I hereby certify that the Project Dissertation entitled "**Investigation of Joint Thickness & Mortar Strength on the Mechanical Behavior of Brick Masonry**" which is submitted by **Anshoo Yadav**, Roll No. 2K21/STE/06, to Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by him under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi
Date: May 31, 2023

(DR. SHILPA PAL)
ASSOCIATE PROFESSOR &
SUPERVISOR
Department Of Civil Engineering

ABSTRACT

The knowledge of brick masonry structures is essential to advance our understanding of their behaviour, performance, and design principles. The unique characteristics and challenges associated with brick masonry, such as material heterogeneity, mortar properties, and structural complexities, necessitate dedicated research efforts. Although there has been significant research conducted on masonry structures, limited attention has been given to the influence of mortar thickness. The lack of comparative studies simultaneously examining the effects of both mortar type and thickness on compressive and shear strength is evident. Most research has primarily focused on the compressive strength of masonry structures, neglecting other important parameters such as shear strength and diagonal tension.

This study aims to address the existing research gap by focusing on the following objectives. Firstly, it seeks to examine the influence of different types of mortar on the strength of clay brick masonry. Secondly, the study aims to investigate the influence of joint thickness on the strength of masonry constructed with clay bricks. Lastly, the study aims to evaluate the shear response of brick masonry. Understanding the shear behaviour is crucial for accurately assessing the structural performance of masonry elements.

The methodology for this research project involved several essential steps. Initially, basic materials such as bricks, sand, lime, and cement were procured and

evaluated for their properties through various tests. The next phase encompassed the careful construction of specimens including brick masonry prisms, brick triplets, and a wall. These specimens were cured under specific conditions to ensure proper hydration. Once the curing period concluded, the samples underwent testing using a Universal Testing Machine (UTM) and a hydraulic jack to assess their compressive capacity, bond strength, and diagonal tension resistance.

The study reveals that mortar strength has a significant impact on the compressive and shear strength of brick masonry. Cement mortar exhibits higher strength compared to lime mortar, with differences of approximately 253% in compressive strength and 255% in shear strength. Increasing mortar thickness initially improves compressive strength, but exceeding the optimal range leads to a decline. Similarly, shear strength decreases with increased mortar thickness. The diagonal tension test demonstrates the superior shear strength of cement mortar compared to lime mortar at a thickness of 13 mm. These findings underscore the importance of mortar strength and optimal thickness in determining the mechanical behaviour of brick masonry structures.

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ANSHOO YADAV

2K21/STE/06

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CHAPTER 1

INTRODUCTION

1.1. MASONRY AND ITS IMPORTANCE

Brick masonry is a construction technique that involves using bricks and mortar to build structures such as walls, columns, and arches. It is a time-honoured and widely employed construction method that has been utilized throughout the world for centuries. Brick masonry can be practiced for both load-bearing and non-load bearing walls, depending on the design and purpose of the structure. The process of brick masonry involves laying individual bricks in a specific pattern, with mortar used to bond the bricks together. There are various types of brick masonry, including English bond, Flemish bond, and stretcher bond. Each bond has a specific pattern of laying bricks and is chosen based on the intended use and design of the structure. Brick masonry has been used to construct a wide variety of structures, from small houses to large commercial buildings. The versatility of brick masonry has made it a popular building material, and it continues to be used today despite the emergence of other building materials. Brick masonry has several advantages over other construction methods. Here are some of the key benefits:

1. **Durability:** Brick masonry is known for its strength and durability, making it a popular choice for buildings that need to withstand harsh weather conditions and other external factors.
2. **Aesthetic Appeal:** Brick masonry can be used to create a wide range of textures, colours, and patterns, making it a versatile choice for both interior and exterior design. It also ages well and adds character to a building over time.
3. **Fire Resistance:** Brick masonry is fire-resistant, which means it can help prevent the spread of fires and protect the building and its occupants.
4. **Low Maintenance:** Brick masonry requires very little maintenance, which makes it a cost-effective choice over the long term.

5. **Sustainable:** Brick masonry is an environmentally friendly option, as it is made from natural materials that are long-lasting and can be recycled.

Despite its many advantages, brick masonry also has some limitations. One of the main limitations is its weight. Brick masonry walls are heavy, and require strong foundations to support them. This can make brick masonry more expensive than other building materials, particularly in areas with poor soil conditions or high seismic activity. Another limitation of brick masonry is its susceptibility to water damage. Bricks are porous, and can absorb water, which can lead to the growth of mold and other fungi. This can cause damage to the walls and create health hazards for occupants of the building.

All things considered, brick masonry is a time-tested technique that has been used for centuries to create beautiful, durable, and long-lasting structures. Its benefits, including durability, aesthetic appeal, fire resistance, low maintenance, and sustainability, make it a popular choice for construction today. Whether you are building a new home or restoring an old one, brick masonry is a technique worth considering for its craftsmanship and longevity. However, it also has some limitations, such as its weight and susceptibility to water damage.

1.2. ELEMENTS THAT IMPACT MASONRY STRUCTURES

The sturdiness and longevity of masonry structures can be impacted by various components. These components include the compression capacity of the bricks and mortar, the thickness of the mortar, and the interaction between the brick and mortar. Understanding these factors is important in designing and constructing brick masonry structures that can withstand external forces and stresses, and last for many years without significant deterioration.

1.2.1. Strength of Brick

Compressive strength is a crucial aspect in defining the strength of bricks, which is the amount of force that a brick can withstand before it breaks. The strength of the bricks can be influenced by features such as the quality of the raw materials, the firing temperature, and the manufacturing process. The strength of numerous types of bricks was investigated in several experimental studies that included the construction of multiple masonry prisms. The findings indicated a strong interrelation between the strength of the bricks and the resulting compressive strength of the masonry prisms[1].

1.2.2. Strength of Mortar

The strength of the mortar used in masonry construction is also important for the overall strength and durability of the structures. The strength of the mortar can be influenced by many aspects such as the ratio of cement to sand, the water-cement ratio, and the curing time. The proportion of cement to sand needs to be carefully balanced to create a strong bond without causing shrinkage or cracking. The water-cement ratio can impact the workability and strength of the mortar, and if it is too high, it can weaken the structure. On the other hand, if it is too low, the mortar mix may be difficult to work with. Lastly, curing time is crucial in ensuring the mortar sets and hardens correctly. Several authors investigated the effect of various binders on the overall strength of masonry and the findings indicate a positive correlation between the compressive strength of the masonry and the compressive strength of the mortar, suggesting that as the compressive strength of the mortar increases, so does the compressive strength of the masonry [2], [3].

1.2.3. Thickness of Mortar

The performance of masonry structures can be significantly influenced by the thickness of mortar joints. When the mortar joints are too thin, they may not provide adequate bonding between the bricks, resulting in a weak and unstable structure. On the other hand, if the mortar joints are too thick, they can cause stress concentration and reduce the overall strength of the masonry. Consequently, it is important to practice an appropriate thickness of mortar joints to ensure the overall strength of the masonry structures.

The consequence of mortar thickness on brick structure can be explained in terms of stress distribution and load transfer mechanisms. In a well-designed masonry structure, the load is transferred from one brick to another through the mortar joints. The mortar serves as an adhesive that bonds the bricks together and distributes the load evenly across the structure. When the mortar joints are too thin, they may not be able to provide enough bonding between the bricks, resulting in stress concentration and localized failure. Conversely, if the mortar joints are too thick, they may create a weak layer that is susceptible to cracking and failure under stress. The thick mortar joints may also create voids and reduce the actual cross-sectional area of the building, which can decrease its load-carrying capacity.

Research has shown that the optimal thickness of mortar joints relies on several aspects, such as the size and shape of the bricks, mortar types, climate and environmental conditions, and the building method. Consequently, it is crucial to consider these factors when determining the appropriate thickness of mortar joints for a specific masonry structure[2], [4], [5].

1.2.4. Interaction between Mortar and Brick

The interaction among the brick-and-mortar is important for creating a strong and stable structure. The bond between the brick and mortar determines how well stresses are transferred between the units and can be influenced by the type of bond used in brick masonry, such as the English bond or Flemish bond[6], [7].

Lastly, it can be concluded that understanding the features that influence the strength and durability of brick structures is important for ensuring the longevity and stability of these structures. By paying attention to the quality of the materials used, the thickness of the binder, and the interface amid the brick and mortar, brick masonry structures can be designed and constructed to withstand external forces and stresses.

1.3. SIGNIFICANCE OF THE STUDY

The mortar joints are an integral component of masonry structures as they provide bonding between individual units, distribute loads, and absorb differential movements due to shrinkage, thermal expansion, and other factors. Therefore, the properties of the mortar, including its thickness and strength, directly impact the overall structural integrity of the masonry structures. The appropriate thickness and strength of mortar are critical for ensuring that the structure can withstand the expected loads and stresses. If the mortar is too weak, or if the joints are too thin, the structure may be susceptible to failure under even normal loads. On the other hand, if the joints are too thick, they can create weak planes in the structure, and reduce the carrying capacity for loads of the masonry. As such, understanding how these factors influence the performance of the mortar can help identify best practices and design guidelines that can lead to stronger and more durable masonry structures.

Overall, research on the thickness and strength of mortar is critical for advancing our understanding of masonry construction, and improving the safety and durability of masonry structures.

1.4. OBJECTIVES OF THE STUDY

This work aims to examine the impact of mortar thickness and strength on the mechanical behaviour of brick structures. Research is motivated by the need to enhance the structural performance and durability of brick structures, which are widely used in construction worldwide. To achieve this objective, a comprehensive experimental program is designed and implemented, which involves testing various types of brick masonry specimens subjected to different loading conditions. A comprehensive review of the literature was conducted prior to delineating the specific aims of the study. The conclusions of this review are presented in Chapter 2. The following are the primary goals of this research:

1) To examine the influence of the different types of mortar on the strength of clay brick masonry

2) To investigate the influence of the joint thickness of mortars on the strength of masonry made of clay bricks

3) To evaluate the shear response of brick masonry

1.5. OUTLINE OF THE THESIS

This M. Tech dissertation is structured into five chapters, each addressing a specific aspect of the research topic.

Chapter 1: Introduction

The opening chapter of this M. Tech dissertation provides an overview of masonry structures, their importance, and their significance in the field of construction. The chapter outlines the specific objectives of the research and highlights the need for a comprehensive investigation of the behavior of Unreinforced Masonry (URM) for different mortar strengths as well as different thicknesses for each mortar.

Chapter 2: Literature Review

The second chapter of the thesis offers a detailed review of previous investigations on masonry, focusing on compressive, and shear strength-related research work. The chapter is divided into several sections and provides a comprehensive understanding of the past research efforts that inform the present study.

Chapter 3: Masonry Constituents and Properties

The third chapter of the dissertation is dedicated to the description of masonry constituents and their properties. It includes a detailed account of the experimental setup and the results of compressive and shear strength tests conducted on the masonry specimens.

Chapter 4: Results and Analysis

This chapter includes the experimental results in a structured manner, enabling easy evaluation of the results of two different mortars and three different thicknesses under the loading. The chapter also includes a detailed analysis of the results, which provides valuable insights into the behaviour of brick structures.

Chapter 5: Conclusion and Future Work

The concluding section of the thesis presents a comprehensive discussion of the research findings, drawing conclusions from the experimental results and the analysis. The chapter also includes recommendations for future research work in the field, which can contribute to the further development of design guidelines and recommendations for enhancing the performance and safety of masonry structures.

CHAPTER 2

LITERATURE REVIEW

2.1. GENERAL

A literature review is a crucial part of any research project, as it provides a comprehensive overview of the existing knowledge on a particular topic. The purpose of this literature review is to recognize the current advances in the field of masonry and related areas, and to highlight the research gaps that this study aims to address. To achieve this goal, a thorough review of the literature has been conducted, covering a wide range of topics related to brick masonry. The literature review covers the recent research on the consequence of mortar thickness and strength on masonry.

The aim of the thesis is to investigate the influence of mortar thickness and strength on the compressive and shear strength of brick masonry. This is an important area of investigation because it has significant practical implications for the design and construction of masonry structures. The compressive strength of masonry is critical to its ability to withstand vertical loads, while the shear strength is important for resisting lateral forces, such as wind or seismic loads. Despite the importance of mortar properties in masonry construction, there is still a lack of consensus on the optimal thickness and strength of mortar for different types of masonry structures. This has led to significant variation in the design and construction practices used in the industry. There is therefore a need for a comprehensive review of the existing literature on the effect of mortar thickness and strength on masonry's compressive and shear strength.

This literature review chapter provides a detailed overview of the existing research in the field of masonry structures. The literature is systematically reviewed and the methodologies and findings of each study are evaluated. This allows for the identification of any gaps or inconsistencies in the existing research and a deeper understanding of the factors that influence the performance of masonry structures.

2.2. BRICK MASONRY

The strength and lifespan of brick masonry are determined by the quality of the bricks and mortar employed. The load-bearing capacity of masonry constructions is determined by the compressive strength of the bricks, whilst the quality of the mortar controls the adhesion and cohesion between the bricks. The thickness of the mortar joints is also crucial for total brickwork strength. The interplay of bricks and mortar is crucial in determining the performance of masonry constructions.

2.2.1. Bricks

Zengin and Kocak (2017) tested different bricks and two mortars, including compressive strength, modulus of elasticity, and water absorption. The findings revealed that the type of brick used in masonry walls has a considerable impact on the wall's characteristics. As the compressive strength of the bricks grew, so did the compressive strength of the walls. Similarly, when the modulus of elasticity of the bricks grew, so did the modulus of elasticity of the walls[8]. Water absorption of the walls was found to be affected by both the type of brick and the type of mortar used.

Prieto et. al. (2016) sought to explore the impact of various brick qualities on the compressive strength of masonry walls. The research was carried out utilising 44 distinct types of bricks taken from Medellin, Colombia. The compressive strength, water absorption, density, porosity, and size of the bricks were all measured. Following that, the bricks were used to construct masonry walls using a standard mortar mix. The compressive strength of the masonry walls was determined using compression tests. According to the study's findings, the compressive strength of masonry walls was substantially influenced by the compressive strength and density of the bricks used[9]. Water absorption and porosity of the bricks also had a moderate influence on wall compressive strength.

2.2.2. Mortar

Haach et. al. (2010) investigated the effect of different types of mortar on the compressive strength of concrete masonry prisms. The study involved testing prisms with different mortars and comparing their compressive behaviour. The results showed that the type of mortar used significantly affects the compressive behaviour of the prisms, with stronger mortars resulting in higher compressive strength[10]. The study concludes that mortar selection is an important factor to consider in designing and constructing masonry structures.

El-Dakhakhni and El-Sheikh (2021) evaluated the effect of mortar characteristics on masonry wall seismic behaviour. The research was carried out utilising a total of 12 full-scale masonry walls built with various types of mortars. The walls were put through a series of cyclic loading tests, and their performance was assessed in terms of strength, stiffness, and ductility. The study's findings revealed that the kind of mortar used has a major impact on the seismic behaviour of masonry walls. Walls constructed with high-strength mortars exhibited higher strength, stiffness, and ductility than walls constructed with low-strength mortars. The study also showed that the thickness of the mortar joints has a small but significant effect on the seismic behaviour of masonry walls[11]. Walls with thicker mortar joints exhibited lower strength and ductility than walls with thinner mortar joints.

2.3. MASONRY PRISM TEST

The compressive strength of a brick prism is an essential measurement in the construction of masonry structures. It is the greatest compressive load that a brick prism can endure before it breaks. The compressive strength of brick masonry is influenced by a number of factors, including the kind of brick used, mortar strength, joint thickness, and building process. Several academic researchers investigated the compressive strength of brick prisms and published their findings in peer-reviewed publications. Previous research on the compressive strength of brick masonry prisms is discussed in this section.

Jagadish et al. (2016) performed an experimental examination utilizing brick masonry specimen with various mortar mixes to determine the influence of mortar mix on the compressive strength of brick masonry. The specimens' compressive strength is then determined using a compression testing equipment. The study's findings indicate that the mortar mix has a considerable impact on the compressive strength of brick masonry. The study discovered that increasing the cement component of the mortar mix enhanced the compressive strength of the brick masonry specimens[3]. The authors also discovered that a 1:4 cement-sand mortar mix produced greater compressive strength than a 1:6 cement-sand mortar mix.

Joshi and Jain (2013) examined the compressive behavior of unreinforced clay brick masonry. Masonry compressive strength is an important attribute to consider while designing, repairing, or retrofitting masonry buildings. The paper includes a description of the testing technique as well as the experimental findings for bricks, mortar, and brick masonry prisms. The experimentally determined average compressive strength of bricks matches the BIS value for the Maharashtra area. The prism test yielded an average compressive strength of masonry of 0.781 MPa, which was compared to the findings obtained by other studies. The experimental results were confirmed by comparing the basic compressive stress obtained from the prism test to the basic compressive stress derived from IS1905:1987[12]. According to the findings, the average basic compressive stress of masonry determined by prism test is 0.2 MPa and IS1905:1987 is 0.292MPa.

Thamboo and Dhanasekar (2019) explored the strength and deformation characteristics of masonry under uniaxial compression. While prisms and wallettes are commonly used for testing, there is a lack of established correlation between these methods. Existing masonry design standards provide data for determining compression characteristics from either method, but little attention has been paid to how these standards were developed. In an effort to address this gap, researchers constructed and tested 50 prisms and 40 wallettes using different unit types and mortar mixes. The results showed that prisms consistently demonstrated higher compressive strength than wallettes. A linear relationship between prism and wallette compressive strengths was found. Furthermore, a simplified analytical model was proposed to correlate deformation characteristics between prisms and wallettes[13]. This study sheds light on important considerations for masonry design standards and provides valuable insights for future research in this field.

Chen et. al. (2021) investigated the use of modified oyster shell ash mortar (MOSA mortar) to strengthen ancient brick masonry structures in China. The article provides laboratory studies on the compressive behaviors of brick masonry that have been improved by replacing MOSA mortar for the original lime-clay mortar. The results reveal that the compressive strength of the brick masonry specimens reinforced using the proposed method meets the design parameters. The research also found a formula for calculating the compressive strength of brick masonry strengthened by modifying mortar, and the anticipated values agreed with the measured values[14]. A parabolic model was used to simulate the stress-strain relationship of the tested specimens under axial compression, and it was found to be congruent with the experimental data. The study finds that more experimental research is needed to demonstrate the viability of this brick masonry strengthening approach in practice.

2.4. TRIPLETS TEST OF BRICK MASONRY

Brick masonry failure is frequently related to shear failure of the brick-mortar bond, which has been recognized as one of the most common failure types. Previous study has suggested that a masonry wall's brick-mortar junction might break due to insufficient binding strength. As a result, the shear bond strength of brick masonry is an important metric that must be carefully considered. This section provides a survey of the literature on this subject.

Lan et. al. (2020) delved into the intricacies of shear testing methods for earth block masonry mortar joints, conducting a series of triplet shear strength tests and numerical simulations. The following factors were carefully considered: block type, horizontal mortar joint, loading position, mortar substance, specimen form, block size, and elasticity modulus. The results show that the shear test procedure has a substantial impact on the shear performance of earth brickwork along the length of the mortar joint. In general, specimens with horizontal mortar joints had better shear strength, and the loading position impacted the shear strength of the 6-block specimen. The distribution of shear stress throughout the height of the mortar joint varied irregularly depending on the specimen shape, but moved towards homogeneity as the block elasticity modulus increased[15]. After a comprehensive evaluation, the 4-block triplet shear strength test was found to be the most favorable and suggested as the typical valuation for earth block brickwork.

Alecci et. al. (2013) examined the direct prediction of masonry shear strength, which entails conducting experimental tests on triplets in accordance with EN 1052-3 or diagonal compression testing on panels in accordance with ASTM 509-2010 and RILEM LUMB6. The article describes the findings of an experimental study on brick masonry walls built with various types of mortar using these two methods. The paper compares the masonry shear strength values obtained by laboratory tests on shear triplets to those obtained by three equations available in the literature for diagonal compression test data.[16]. The paper concludes by highlighting the importance of such experimental tests for accurate prediction of masonry shear strength.

Lourenço et. al. (2004) concluded that stack-bonded masonry, primarily utilized for aesthetic purposes, provides a regular pattern that enables the placement of reinforcement in joints. However, the behavior of stack-bonded brickwork under shear pressure has received little attention. To contribute to this sector, an experimental study Programme containing aligned joints filled with micro-concrete was carried out. The shear behavior of stack-bonded masonry with micro-concrete joints was effectively examined, yielding typical failure modes that followed the Coulomb friction law[17]. It is worth noting that the masonry panels examined in this study included continuous vertical seams, as they are intended for constructing reinforced masonry shells, unlike the standard running bond with discontinuous vertical joints.

2.5. DIRECT DIAGONAL SHEAR TEST

Ghasemi et. al. (2022) studied the effect of various mortar kinds and thicknesses on masonry shear strength. The research was carried out on a total of 12 full-scale masonry walls that were built using various types of mortars and thicknesses. The walls were put through a series of direct diagonal shear tests, and their performance was measured in terms of shear strength. The study's findings revealed that the kind of mortar has a considerable impact on the shear strength of brickwork. Walls built with high-strength mortars have greater shear strength than walls built with low-strength mortars[18]. The study also discovered that the thickness of mortar joints has a tiny but substantial influence on masonry shear strength. Shear strength was lower in walls with thicker mortar joints than in buildings with thinner mortar joints.

Bustos-García et. al. (2019) evaluated the effect of mortar type and thickness on masonry diagonal shear strength. Direct diagonal shear tests on masonry specimens with different types of mortar (cement-lime and cement-sand) and thicknesses (10 cm, 15 cm, and 20 cm) are part of the experimental investigation. The results show that masonry shear strength rises with thickness, and the kind of mortar has a substantial influence on shear strength[19]. Shear strength is stronger in cement-sand mortar specimens than in cement-lime mortar specimens. The paper also includes regression equations for predicting masonry diagonal shear strength depending on mortar type and thickness.

El-Dakhakhni and El-Sheikh (2017) reported an experimental analysis of unreinforced masonry walls' direct shear behavior. The experiment included evaluating 20 brick walls with varying aspect ratios, thicknesses, and mortar kinds. The walls were loaded in shear until failure, and the shear strength, deformability, and failure modes were analyzed. The results showed that the shear strength of the walls was significantly affected by the thickness, aspect ratio, and mortar type. The walls with thicker and wider cross-sections exhibited higher shear strengths than the thinner ones. The walls constructed with stronger mortars showed higher shear strengths and less deformability than the ones with weaker mortars[20]. The failure modes observed were diagonal splitting, shear sliding, and tensile failure of the masonry units.

2.6. EFFECT OF MORTAR THICKNESS ON PRISMS

Murthi et. al. (2020) used supplemental cementitious materials to examine the strength of brick masonry produced with three different mortar mixes and two different mortar thicknesses. Masonry compressive strength was determined using prism specimens, while shear strength was calculated using triplets. The results reveal that masonry built with blended cement mortar has the same strength as cement mortar-based brickwork. Failure occurred in 12 mm mortar thickness masonry units owing to crushing of brick units and in 18 mm mortar thickness masonry units due to shear failure in the bond between brick and mortar[21]. Therefore, it is important to use appropriate mortar thickness and supplementary cementitious materials in brick masonry construction to improve its strength.

Mojsilović and Stewart (2015) concluded that the thickness of binder in structural masonry has a significant impact on its capacity. To study this impact, data was collected from 12-storey-high walls at 3 different building sites and 4 walls. The data allowed for an analysis of the joint thickness distribution and probability distribution. Statistical analysis was conducted on the data, including the calculation of central and dispersion measures and the fitting of probability distributions[22]. The results were compared across the 4 building sites, providing data about the superiority of work at each site. The probabilistic info obtained was then utilised to define reliability-based limit state specifications. It was found that probabilistic modeling of bed joint thickness resulted in higher reliability indices for structural masonry subjected to a concentric normal force.

Zengin et. al. (2018) investigated the mechanical characteristics of masonry walls and discovered that walls are complicated and may be influenced by the materials used, joint thickness, and type of bond. The goal of this study was to see how joint thickness and mortar type affected the mechanical behaviour of masonry walls. Six masonry walls were erected in the laboratory using a single brick type, cement mortar, and hydraulic lime mortar, with three different joint widths for each mortar type. Mechanical qualities of bricks, mortars, and walls were determined[23]. The results revealed that the mechanical qualities of the mortars impacted the failure mechanism of the brick masonry walls. For typical masonry wall construction, a bed joint thickness of at least 20 mm is suggested to guarantee that the bonding between bricks and mortar is maintained under stress.

Krishna et. al. (2017) investigated the influence of mortar thickness on the compressive strength of brick masonry. The authors conducted compressive strength tests on 30 masonry specimens with varying mortar thicknesses. The results showed that increasing the mortar thickness beyond a certain point did not result in a significant improvement in compressive strength. The authors attributed this to the fact that the thicker mortar joints resulted in greater shear stresses at the interface of the bricks and mortar, leading to a decrease in compressive strength[24]. The authors also suggested that reducing the mortar thickness up to a limit can result in cost savings without compromising the compressive strength of the masonry.

Shrestha et. al. (2020) tested three types of clay brick masonry specimens: single brick, double brick, and three-brick masonry walls, with mortar joint thicknesses varying from 5mm to 20mm. A compression testing equipment was used to determine the compressive strength of the specimens. The analysis also found that the failure mechanisms of the specimens varied with the thickness of the mortar joints. The collapse of the masonry examples with larger mortar joints was mostly due to mortar crushing[25]. However, for the specimens with thinner mortar joints, the failure was mainly due to the crushing of the bricks.

2.7. EFFECT OF MORTAR THICKNESS ON TRIPLETS

Khalaf and Deeb (2014) investigated the effect of varying mortar joint thickness on the shear strength of masonry made of clay brick and cement-sand mortar. The study involves conducting laboratory experiments on 84 masonry specimens with different mortar joint thicknesses ranging from 0.5 mm to 20 mm. The results show that the shear strength of masonry is significantly influenced by the thickness of the mortar joint. As the thickness of the joint increases, the shear strength decreases. The study also reveals that the reduction in shear strength is more significant for thinner bricks and weaker mortar. The authors suggest that this is due to the increase in the flexibility of the masonry structure with thicker mortar joints, leading to a higher likelihood of cracking and shear failure[26]. The study shows that a mortar joint thickness of 10 mm is the best value for obtaining maximum shear strength in clay brick and cement-sand mortar construction. In addition, the authors provide a mathematical model for estimating masonry shear strength with different mortar joint thicknesses.

Arias et. al. (2015) studied the effect of mortar joint thickness on the shear strength of brick masonry. The authors conducted an experiment on prismatic specimens of brick masonry with various mortar joint thicknesses ranging from 10 mm to 30 mm. A direct shear test was used to determine the specimens' shear strength. The study's findings revealed that increasing the thickness of the mortar joint enhanced the shear strength of the brick masonry. The authors discovered that bigger mortar joints resulted in more ductile masonry, resulting in better shear strength[27]. The investigation also revealed that the masonry's failure mechanism altered with the thickness of the mortar junction. The failure occurred along the bed joints of thinner mortar joints, while the failure happened through the bricks themselves of larger mortar joints.

Farzadnia et. al. (2019) evaluated the influence of bed joint thickness on masonry prism shear behaviour. The researchers conducted an experiment on brick prisms with various bed joint thickness and aspect ratios. The masonry prisms' shear strength and deformation properties were investigated, and the results were compared to those anticipated by existing analytical models. The study's findings revealed that as bed joint thickness grew, so did the shear strength of brick prisms[28]. The shear strength of masonry prisms with bigger bed joints was found to be up to 40% more than that of prisms with narrower bed joints, according to the authors. The higher contact area between the brick units and mortar in thicker bed joints was linked to the increase in shear strength.

Based on the review of previous studies, it can be concluded that a significant amount of research has been conducted on the compressive and shear strength of brick masonry prisms, as well as the effect of mortar thickness on their compressive strength.

However, there is still a lack of consensus regarding the optimal mortar thickness for achieving the highest compressive strength, as different studies have yielded varying results.

Furthermore, there is a gap in the literature regarding the effect of mortar thickness on the shear strength of brick masonry, which emphasises the need for more study in this area.

2.8. RESEARCH GAP

- Numerous research has been done on masonry, but very few researchers considered mortar thickness parameter in their study.
- There is a lack of comparative studies that have simultaneously investigated the effects of both mortar type and masonry thickness on compressive and shear strength in masonry structures.

- Masonry structures are considered compressive members, and because of that, the research has mostly been done on compressive strength only, but other parameters are not considered, like shear strength and diagonal tension.

CHAPTER 3

EXPERIMENTAL PROGRAM

This work comprises a series of experiments that aim to explore the mechanical properties of materials. The mechanical properties of interest include dimension tests, water absorption, efflorescence, compressive strength, and bond strength. This chapter provides a comprehensive account of the experimental program carried out, encompassing the description of the constituent materials employed, the fabrication of test samples, the apparatus utilized, and the experimental procedures implemented. The ultimate goal of this investigation is to deliver a thorough understanding of the mechanical behaviour of the materials.

3.1. PROBLEM FORMULATION

The mechanical behaviour of brick masonry is affected by various components including the compressive strength of bricks and mortar, bonding arrangement, and thickness of mortar joints. This research aims to explore the consequence of joint thickness and mortar strength on the mechanical behaviour of brick masonry through experimental testing. In the experimental testing phase, an investigation into the constituent materials of masonry was conducted. Following this, the preparation of specimens was carried out, which included masonry prisms, brick triplets, and masonry walls. Following a 28-day curing period, the specimens underwent testing. These tests aimed to measure various characteristics such as compressive and shear strength, and diagonal tension. The data acquired from tests provided insights into the performance of masonry structures and the factors that influence their strength and durability.

3.2. METHODOLOGY

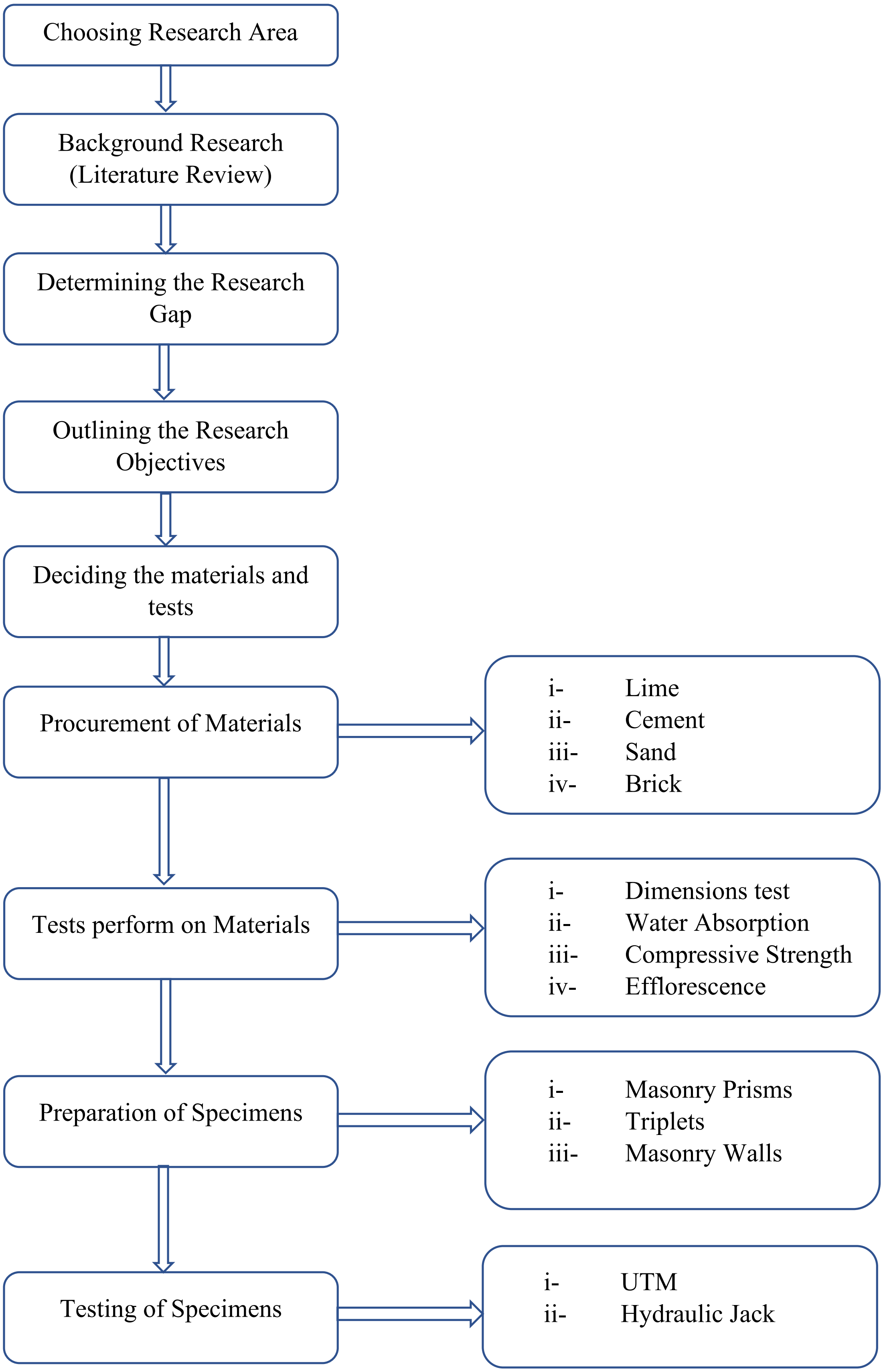

Figure 3.1. Flow chart of Methodology

The methodology for this project involved several key steps. The first step was the procurement of basic materials such as bricks, sand, lime, and cement. These materials were selected based on their availability and suitability for the testing procedures.

Next, the materials underwent testing to assess their properties. These tests included the dimensions test, water absorption, efflorescence, and compressive strength test of both bricks and mortars. The data obtained from these tests provided important information about the materials and their properties, which were used in the subsequent stages of the research.

After testing the materials, samples were constructed for testing. This involved the construction of five brick masonry prisms for each mortar and thickness, brick triplets for bond shear strength, and a wall for the direct diagonal test. The preparation of these specimens was done with great care and precision to ensure accurate results during testing. After the preparation of specimens, they were left to cure for 28 days. Lime mortar specimens were cured in air, while cement mortar specimens were cured in wet jute bags to prevent the evaporation of water.

Once the curing period was complete, the samples were then subjected to load by a Universal Testing Machine (UTM) and a hydraulic jack. The UTM was used to test the compressive capacity of the prisms while the hydraulic jack was utilized to test the bond strength of the brick triplets and the direct diagonal tension of the wall.

Overall, the methodology for this research project was designed to be rigorous and precise, with a strong focus on ensuring accurate results. The use of carefully prepared specimens and advanced testing equipment, combined with detailed data analysis, allows for a comprehensive investigation into the consequence of mortar thickness and strength on the mechanical behaviour of brick structures.

3.3. MATERIALS USED

Various materials, including bricks, cement, and sand, were employed to build test specimens as part of the experimental endeavour. In this study, bricks were employed as both the test sample and the unit material for creating masonry assemblages such as prisms and triplets. Mortar also included the use of cement and sand. The specifications for all the materials used in the experiments are described from sections 3.3.1 to 3.4.2.

3.3.1. Lime

Lime is a commonly used binder in construction, particularly in masonry and plastering applications. The process of creating lime involves burning limestone and then slaking it with water to produce a powder that hardens when exposed to air. For this particular work, hydrated lime was used, as described in IS:1540(Part I)-1980[29]. The supplier provided information on the features of the binder ingredients, which is summarized in Table 3.1. The chemical process of hydraulic lime reacting with water, known as hydration, can be expressed using Equation 3.1[30].

$$2(2Cao.Sio_2) + 4H_2o \Rightarrow 3Cao.2Sio_2.3H_2o + Ca\ (oH)_2 \quad (3.1)$$

Belite (C_2S) + Water ⇒ Calcium Silicate Hydrate + Portlandite

3.3.2. Cement

Ordinary Portland Cement (OPC) is a common construction binding material. It is made by burning limestone, clay, and other elements at high temperatures to produce a powder that hardens when mixed with water. In this experiment, 53-grade OPC, as described in IS:269-2015[31], was used. Table 3.1 summarizes the characteristics of the binder ingredients as given by the supplier.

Table 3.1. Properties of Binders

Properties	**Hydrated lime**	**OPC-53**
Chemical Composition (%)		
SiO_2	13.1	24.42
Al_2O_3	0.7	4.85
Fe_2O_3	2.81	3.80
CaO	66.3	66.16
MgO	0.5	1.85
K_2O	0.15	0.4
LoI	16.44	1.17
Physical Properties		
Specific Gravity	2.7	3.12
Fineness(cm^2/gm)	3800	3000
Color	White	Grey

3.3.3. Sand

In this study, natural sand was obtained from a local supplier, and its characteristics were analyzed. A sieve analysis was conducted in accordance with IS 2116-1980[32] to evaluate the particle size distribution of the sand. Additionally, the bulk density of the sand was calculated to be 1750 Kg/m^3. These measurements provide important information on the suitability of the sand for use in construction and can be used to determine the optimal mix ratios for mortar or concrete.

3.3.4. Bricks

Bricks are a widely used building material that provides durability, strength, and fire resistance to structures. They are made from clay that is molded and fired in a kiln to harden them. The quality of bricks depends on the properties of the clay and the firing temperature used during the manufacturing process. Bricks are available in different shapes, sizes, and colors, and are used for various construction purposes such as walls, pavements, arches, and columns. Bricks are an essential component of masonry construction, and it is crucial to test their quality before using them in construction projects. Brick testing can help ensure that the bricks are strong, durable, and capable of withstanding the stresses and loads imposed on them in construction.

There are several tests that can be performed on bricks to determine their quality, including dimensions tests, compressive strength, water absorption, efflorescence, and soundness tests. These tests can provide information about the physical and mechanical characteristics of the bricks, such as their strength, durability, porosity, and resistance to weathering.

3.4. PREPARATION OF SPECIMENS

This research includes brick, mortar, and masonry specimens. The specimens included five brick masonry prisms, three brick-high stacks bonded triplets, and a wall for diagonal shear testing. The brick masonry prisms were prepared by bonding the bricks with mortar, with each prism consisting of 10 brick units. The triplets were prepared by stacking three brick units and bonding them with mortar. The wall for diagonal shear testing was constructed by bonding 27 brick units with mortar in a stretcher bond pattern. Table 3.2 shows the Total number of specimens prepared for complete work.

Calculation of Specimens for testing

Table 3.2. Number of specimens for each test

Tests	**Lime Mortar**			**Cement Mortar**			**Total**
	13 mm	20 mm	27 mm	13 mm	20 mm	27 mm	
Compressive Strength (Prism)	3	3	3	3	3	3	18
Shear Strength (Triplet)	3	3	3	3	3	3	18
Diagonal Shear Strength (Wall)	3	-	-	3	-	-	6

After conducting thorough testing on various thicknesses of mortars, it was evaluated that the maximum shear strength for the triplet occurred at a thickness of 13 mm for both types of mortar. As a result, further testing and analysis were focused solely on this thickness for diagonal shear testing, and for this, only 6 specimens were prepared for the diagonal shear testing.

3.4.1. Brick

In this study, standard-fired clay bricks were utilized as the prime building material. The bricks were sourced from a reliable supplier and were of uniform size and quality. The sizes of the bricks were 220 mm in length, 110 mm in width, and 75 mm in depth. The bricks were tested for compressive strength, water absorption, effloresce, and dimensional accuracy in accordance with relevant standards to ensure they met the required specifications for use in construction.

3.4.2. Mortar

Mortar is an essential material in construction that is used to bind individual masonry components together. It is typically made by mixing cement or lime with sand to create a smooth paste. For this study, hydraulic lime mortars with a binder-to-aggregate ratio of 1:3 were selected. This type of mortar is often used in historic masonry conservation projects due to its ability to allow walls to naturally breathe and thus improve long-term performance. Alternatively, cement is now the most efficient binder available, and OPC-53 mortar was used in this study due to its effectiveness. The ratio of binder to aggregate in this mortar is also 1:3, which is a common ratio used in construction. The strength of the mortar is an important factor in determining the compressive strength of brickwork. In this study, the strength values of the designed brickwork mortar were computed using mortar cubes with a face area of 50 cm^2. The mortar cubes were prepared using the same ratio of binder to aggregate as used in the brickwork construction, which was 1:3. The cubes were then cured under standard conditions for 28 days before being tested for compressive strength.

3.4.3. Masonry Assemblages

Masonry assemblies refer to the structures formed by bonding bricks or other masonry units together with mortar. In the current study, various masonry assemblages were prepared for testing. These included brick masonry prisms, three brick-high stacks bonded triplets, and a wall for a diagonal shear test.

Masonry Prisms

In this work, masonry assemblages were prepared utilizing different mortars lime, and cement, and three different thicknesses of mortar, including 13 mm, 20 mm, and 27 mm. To evaluate the strength of these masonry prisms, standard procedures were followed. The method for testing masonry prisms was outlined in IS 1905-1987[33], while ASTM E447-80[34] and ASTM C1388-97[35] were also used to assess the strength of the brickworks. According to IS 1905-1987, the number of samples to be evaluated is not stated; however, the IBC 2000[36] mandates that three prisms should be tested. Therefore, three specimens were prepared in the current study, and the avg. strength value was used to calculate the strength of the prisms.

The preparation of brick specimens involved ensuring that they met the minimum height and height-to-thickness ratio requirements set by the relevant standards. Both IS1905-1987 and ASTM E447-80 require a minimum height of 381 mm or 400 mm, respectively, and a height-to-thickness ratio of 2 to 5. The samples were constructed by laying bricks in five layers, with varied joint thicknesses. Vertical joints were spaced apart in the brick arrangement to ensure the accuracy of the measurements. Fig. 3.2 depicts the lime mortar and cement mortar specimens after preparation. The samples were cured for 28 days with the help of wet jute bags in the case of cement mortar and air curing was done in the case of lime mortar, after which they were tested. The dimensions of the specimens were determined based on the brick specifications and code requirements.

Figure 3.2. Masonry Prism Specimens

Brick Triplets

In this study, brick triplets were prepared using both hydraulic lime mortar and OPC-53 cement mortar, with each thickness of 13mm, 20mm, and 27mm. The preparation of triplets involves laying three standard-fired clay bricks on top of each other using mortar.

The bricks were carefully laid and levelled, with the mortar applied evenly to achieve consistent thickness. The mortar was allowed to cure for 28 days under wet jute bags for cement mortar and air cured for lime mortar before conducting the shear strength tests. EN 1052-3[37] is a European standard that describes the triplet test, which is commonly utilised to assess the shear strength of brickwork. The tests were conducted separately for each mortar type and thickness to assess the effect of the mortar type and thickness on the shear strength of the brick triplets and the masonry assemblages. Fig. 3.3 displays the triplet specimens after construction.

Figure 3.3. Brick Triplet Specimens

Masonry Wall for Diagonal Test

A direct diagonal test is used to find the diagonal tensile strength of masonry walls (Fig. 3.4). For this test, a masonry wall was built with the bricks and mortar being tested, with the bricks arranged in a stretcher bond pattern. A load was then applied to the wall in a diagonal direction until failure occurs. The load was measured, and the diagonal tensile strength is calculated based on the dimensions and properties of the wall. The test method is described in ASTM E488-96[38].

Figure 3.4. Masonry Wall for Diagonal Testing

3.5. EXPERIMENTAL TESTS AND PROCEDURE

A series of experimental experiments were performed to determine different mechanical properties of brick units, including size, water absorption, efflorescence, and compressive strength of both bricks and mortar. Masonry assemblies were also tested to determine their compressive strength and shear bond strength. This section provides a detailed explanation of the experimental methodologies employed for each test.

3.5.1. Dimensions Test of Bricks

The relevant Indian Standard code for the dimensions test of bricks is IS 1077:1992[39]. This code specifies the dimensions of bricks, including length, width, and height, as well as the permissible variations in these dimensions. It also provides guidance on the methods for measuring the dimensions of bricks, as well as the tolerances that must be maintained.

3.5.2. Water absorption Test of Bricks

This test of bricks is utilized to evaluate the ability of the brick to absorb water. "The test is performed by weighing a dry brick and then fully immersing it in water for a definite time of 24 hours. The brick is then taken out from the water, wiped with a cloth to remove surface water, and weighed again. The difference in weight between the dry brick and the saturated brick is utilised to evaluate the percentage of water absorbed by the brick". The test is important in determining the suitability of bricks for use in construction as it can affect the durability and strength of the structure. The Indian Standard Code IS 3495 (Part 1):1992[40] is used for this test.

3.5.3. Efflorescence Test

Efflorescence is a phenomenon in which soluble salts rise to the surface of a porous material, such as bricks, and form a white, powdery deposit. This not only causes an unsightly appearance but can also lead to deterioration of the material over time. Therefore, an efflorescence test is important to find the quantity of soluble salts present in the bricks and to assess their potential for efflorescence. In this test, a sample of bricks is put in a vessel with water, and the amount of salts that dissolve and migrate to the surface of the bricks is observed over time. The samples are then examined visually for any white deposits or discoloration. The degree of efflorescence is usually classified into four categories: nil, slight, moderate, and heavy. The test helps in identifying the quality of bricks and their suitability for use in construction. The IS code for efflorescence test of bricks is IS 3495 Part 1:1992[40]. This standard specifies the method for defining the degree of efflorescence of clay building bricks.

3.5.4. Compressive Strength Test of Brick

Brick compression capacity is an essential mechanical parameter that influences a brick's capacity to bear loads and stresses. The strength is evaluated by subjecting a standard specimen of the brick to a compressive load until failure. The highest load is recorded, and the compressive strength is computed as the maximum load divided by the specimen's cross-sectional area. IS 3495 (Part 1):1992[40] is the Indian Standard code that provides the guidelines for finding the compressive strength of burnt clay building bricks. The procedure for conducting this test of bricks as per IS 3495 (Part 1):1992 involves selecting at least five bricks of the same batch for testing. The bricks are then cleaned of any irregularities and loose material from the surfaces to ensure even loading during testing. The bricks are placed lengthwise on the base of the compression testing machine, which is adjusted so that the load is applied at a even rate of 14 N/mm^2 per minute along the longitudinal axis of the brick until it fails. The peak load at failure is noted for each brick, and the average compressive capacity is determined using the peak load at failure and the cross-sectional area of the brick. The average compressive strength is then compared with the specified minimum value for the grade of the brick being tested. The guidelines also specify the minimum compressive strength requirements for various grades of bricks used in masonry, ranging from 3.5 N/mm^2 for the lowest grade to 10.5 N/mm^2 for the highest grade. The compressive strength of bricks is an important parameter that is used to ensure the quality of bricks used in construction projects.

3.5.5. Compressive Strength Test of Mortar

The compression capacity of mortar is a significant property that determines the load-carrying capacity of masonry. This can be determined by testing standard mortar cubes in a compression testing machine. This test involves molding standard mortar cubes of a specified mix proportion and water-cement ratio and allowing them to cure for a specified period. The specimens are then placed in a compression testing machine and compressed until they fail. The peak load is prolonged by the cube before failure is noted down and the compressive strength of the cube was calculated. The process for evaluating the strength of mortar is described in various standards such as ASTM C109/C109M[41] and IS 2250:1981[42]. These guidelines ensure that the strength of the mortar utilized in masonry is accurately established, allowing for reliable structural design. The code also covers the testing of mortars for their workability, consistency, compressive strength, and other properties.

3.5.6. Compressive Strength Test of Masonry Prism

The compression capacity of a masonry prism is a test used to determine the load-bearing capability of masonry walls composed of brick units and mortar joints. In this test, masonry prisms are constructed by stacking and bonding brick or block units using mortar. The prisms are then placed in a compression testing machine, which applies an axial load until the prism fails. The peak load that the prism can sustain before failure is recorded as the load-bearing capacity of the masonry. This test is essential to ensure the structural integrity of masonry walls and to find the safe load-carrying capacity of a building. Standards such as ASTM E 447[34] and IS 1905[33] provide guidelines for conducting the compressive strength test of masonry prisms. According to the IS 1905 standard, the tests should be carried out prior to construction using prisms constructed using comparable materials, under the same circumstances, and with the same bonding arrangement as the building. The units' moisture content during installation, the mortar's quality, the mortar joints' thickness, and the workmanship. The compressive strength values obtained from the tests should be rectified by multiplying them by the factor shown in Table 12 of this code. If the h/t ratio of the prisms examined is less than 5 in brickwork and greater than 2 in blockwork, they should all be the same. The constructed specimen must be at least 40 cm tall and have a height-to-thickness ratio (h/r) of at least 2, but no more than 5. If the h/t ratio of the prisms tested is less than 5 in brickwork and greater than 2 in blockwork, the compressive strength values obtained by the tests should be rectified by multiplying by the factor specified in Table 12 of this code. By following these rules, you may be confident that the compressive strength of masonry is precisely determined and reliable for structural design needs. Prisms must be checked after 28 days in a testing equipment with a spherically seated top platform, between sheets of nominal 4 mm plywood somewhat longer than the prism's bed area. The load must be applied at a rate of 350 to 700 kN/m and must be distributed evenly throughout the top and bottom surfaces of the specimen. The failure load should be noted. Fig. 3.5 depicts the failure of masonry prisms in both the cases i.e., lime mortar and cement mortar masonry prisms.

Figure 3.5. Prism Specimens after testing

3.5.7. Shear Strength Test

It is an important mechanical property of brick masonry that is evaluated through various tests. One such test is the diagonal shear strength test, which involves subjecting a prismatic specimen of brick masonry to a diagonal compressive load until failure. The load is applied at a specific angle to the vertical axis of the sample, and the peak load bear by the specimen is recorded. Another test that is commonly used to evaluate shear strength is the triplet test, which involves preparing three brick masonry prisms of identical dimensions and bonding them together with mortar to form a triplet. The central prism is subjected to a shear force until it fails, and the maximum shear stress that can be sustained by the triplet is recorded. These tests are important for assessing the structural integrity of brick masonry and ensuring that it can withstand the shear forces that it may encounter in use. The test was carried out following standards such as ASTM C1531 and EN 1052-3, which provide detailed procedures for the test.

Diagonal compression test

This test on masonry panels is a standardized test utilized to evaluate the shear strength of masonry. In India, the procedure for conducting the diagonal compression test on masonry panels is described in the Indian Standard IS 1905:1987 ("Method of test for determination of lateral load resisting factor of wall assemblies"), which is based on the RILEM LUMB6 specifications. The test involves constructing a square masonry panel with dimensions of at least 500 mm by 500 mm, using the same materials, workmanship, and curing conditions as the masonry to be tested. The panel is then placed horizontally on a suitable loading platform with a diagonal brace or load transfer plate positioned under the diagonal compressive loading point. A compressive load is exerted along one diagonal of the panel at a constant rate until failure occurs. The loading rate should be at a constant rate, typically in the range of 0.005 to 0.025 MPa/s. The shear strength of the masonry is determined by dividing the maximum load by the area of the diagonal section.

Triplet test

The brick triplet test is a popular method for determining the shear strength of brickwork. Three bricks are linked together using two different types of mortar and three distinct thicknesses, resulting in 220* 110* 220 mm^3 masonry triplets. All bricks are soaked in water for at least 3 hours prior to manufacture to guarantee excellent bonding with the mortar joints and to prevent the samples from drying too quickly, which might create fractures. The brick triplets are constructed with care to ensure that they are as straight as possible, eliminating any irregularities that might impair the shear testing. Following construction, the masonry triplets are placed in the laboratory for a minimum of 28 days to cure. Fig. 3.6 shows the triplets before testing and after testing.

Figure 3.6. Brick Triplet before testing and after testing

3.6. CONCLUDING REMARKS

Chapter 3 provides a detailed account of the experimental work performed for this research study. The chapter outlines the constituent materials used, the construction of the samples, and the apparatus utilized. The research examines a range of mechanical properties of masonry specimens including dimension testing, water absorption, efflorescence, compressive strength, and shear bond strength. The section provides an in-depth understanding of the experimental outlines employed and highlights the significance of these tests in assessing the properties of masonry specimens.

CHAPTER 4

RESULTS AND DISCUSSION

The Results and Discussion chapter presents the findings of the tests performed to determine the mechanical properties of masonry specimens. This chapter aims to provide an in-depth analysis and interpretation of the data obtained from the experiments. The chapter is divided into sections, each focusing on a specific mechanical property of the masonry specimens. The results are presented in the form of tables, graphs, and figures, with accompanying descriptive statistics to provide a clear understanding of the data. The discussion section presents a critical analysis of the results, highlighting the strengths and weaknesses of the experimental methods used and their implications for masonry construction. The chapter concludes with a summary of the key findings and their significance in the context of masonry construction.

4.1. TESTS ON BRICK

Bricks are commonly used in the construction industry for building walls, pavements, and other structures. It is essential to determine their mechanical properties to ensure the quality and durability of the structures. Various tests are conducted to evaluate the different properties of bricks, including dimensions, water absorption, efflorescence, compressive strength, and shear strength. These tests help in assessing the performance of bricks and ensuring their suitability for specific construction applications. In this section, we will discuss the different tests conducted on bricks to determine their mechanical properties.

4.1.1. Dimensions Test

Bricks are typically rectangular in shape and have a variety of dimensions. (Length x depth x height). The dimensions of a brick can vary depending on the type of brick, the manufacturer, and the country in which it is made. However, it should be noted that not all of the bricks possess exact and precise measurements. The various brick samples are referred to as B1, B2, B3, B4, and B5. The measurements of these specimens are shown in Table 4.1.

Table 4.1. Dimensions of bricks

Specimen no.	Dimensions(mm)
B_1	220*110*76
B_2	221*110*75
B_3	223*110*75
B_4	221*110*73
B_5	220*110*75

4.1.2. Water Absorption of Bricks

The water absorption test is a common test performed on bricks to evaluate their porosity and the amount of water they can absorb. This test is important as it helps in assessing the durability and weather resistance of the bricks, which are crucial factors in their selection for construction purposes. The water absorption of the brick specimens was calculated using Equation (4.1).

$$\text{Water Absorption (\%)} = \frac{M_2 - M_1}{M_1} \times 100 \qquad (4.1)$$

Table 4.2. Values of water absorption

Specimens	Weight after oven-dry(M_1) (Kg)	Weight after 24 hours in water(M_2) (Kg)	Water absorption (%)	Avg. Water absorption (%)
B_1	2.99	3.29	10.03	
B_2	3.02	3.37	11.59	
B_3	3.11	3.44	10.61	11.08
B_4	3.13	3.46	10.54	
B_5	3.01	3.39	12.62	

The results of the water absorption test for the brick specimens in this study are presented in Table 4.2. This table provides information on the water absorption characteristics of the different brick samples, which can be used to evaluate their suitability for specific applications.

After conducting the test on the specimens, the average water absorption was determined to be 11.08%. According to Indian standards, "when tested in the manner described, the average value should not surpass 20% by weight for Class 12.5, and 15% by weight for higher classes". This is because excessive water sorption can result in structural damage, including cracking, warping, and deterioration of the brick. Consequently, it is essential to monitor the characteristics of bricks and ensure they meet the appropriate standards for the specific class of brick being used.

4.1.3. Efflorescence Test of the Bricks

The efflorescence test was performed on the units to evaluate the presence of soluble salt deposits. The results indicated that the efflorescence was below 4% (Table 4.3), which is within the permissible limit set by IS 3495:1992. This standard specifies that for Class 12.5 bricks, the allowable efflorescence limit is less than or equal to 10%, while for higher classes, it should be less than or equal to 5%. Since the efflorescence of the bricks in this study falls well within the specified limits, it can be concluded that the bricks meet the required standards and are suitable for use in construction.

Table 4.3. Efflorescence Test Result

Test	As per IS 3495:1992	Experimental Result
Efflorescence	10% or less for Class 12.5 bricks and 5% or less for Higher Classes of bricks	Below 4%

4.1.4. Compressive Strength of Bricks

The compression capacity of bricks is a crucial factor in determining their usability for construction. IS 3495:1992 specifies the minimum compressive strength requirements for bricks of different classes. According to the standard, "Class 12.5

bricks should have a minimum strength of 3.5 N/mm^2, while higher classes should have a minimum strength ranging from 4.5 to 7.5 N/mm^2". In order to ensure that the bricks meet the required standards, the compression capacity of the samples was calculated using equation (4.2).

$$\text{Compressive Strength of Bricks (MPa)} = \frac{P}{A} \quad (4.2)$$

Where P = Peak Load at collapse (N)

A = Cross-section area (mm^2)

Table 4.4. Compressive strength of brick Specimens

Specimen No.	Compressive Strength (MPa)	Average Strength (MPa)
B_1	22.89	
B_2	22.05	22.30
B_3	22.10	
B_4	22.60	
B_5	21.87	

The strength values of individual samples are presented in Table 4.4. Based on the calculations, the average strength was determined to be 22.30 MPa, suggesting that the samples belong to Class A according to the IS code.

Comment on Brick

After conducting the tests on the brick specimens, the following observations were made: the water absorption is found to be 11.08% which is less than 15%, as indicating in Fig. 4.1; the compressive strength as given in Fig. 4.2 is 22.30MPa which exceeded 12.5 N/mm² as specified by code; and the efflorescence is below 4% (Table 4.3). Based on these results, it can be concluded that the brick specimens conform to Class A classification according to Indian standards. This classification indicates that the bricks possess desirable properties, including low water absorption, high compressive strength, and minimal efflorescence. The findings highlight the suitability of these bricks for various construction applications where durability and performance are crucial.

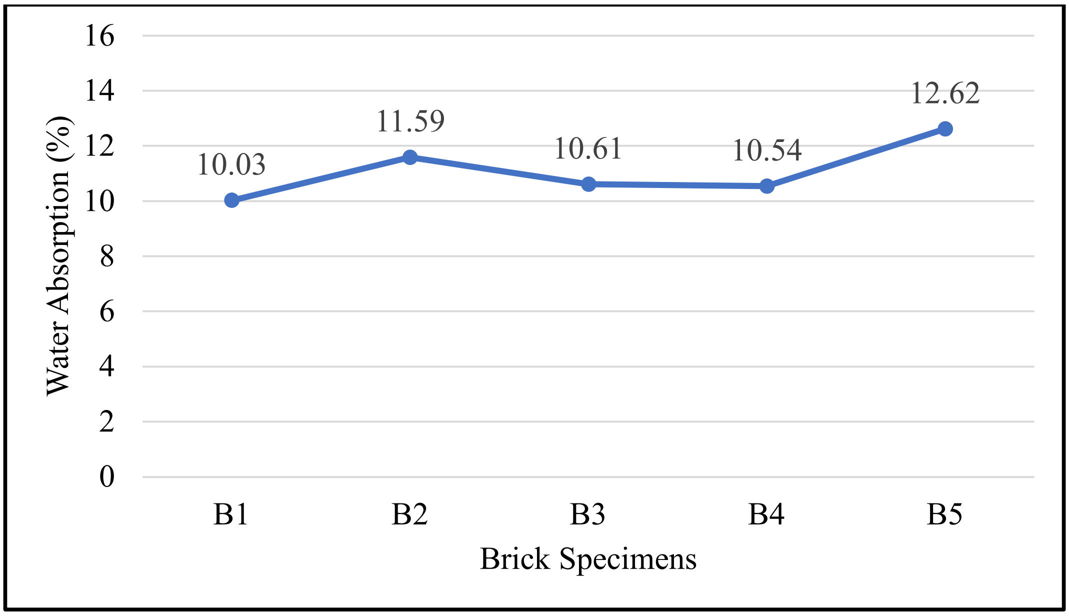

Figure 4.1. Water Absorption of the Bricks

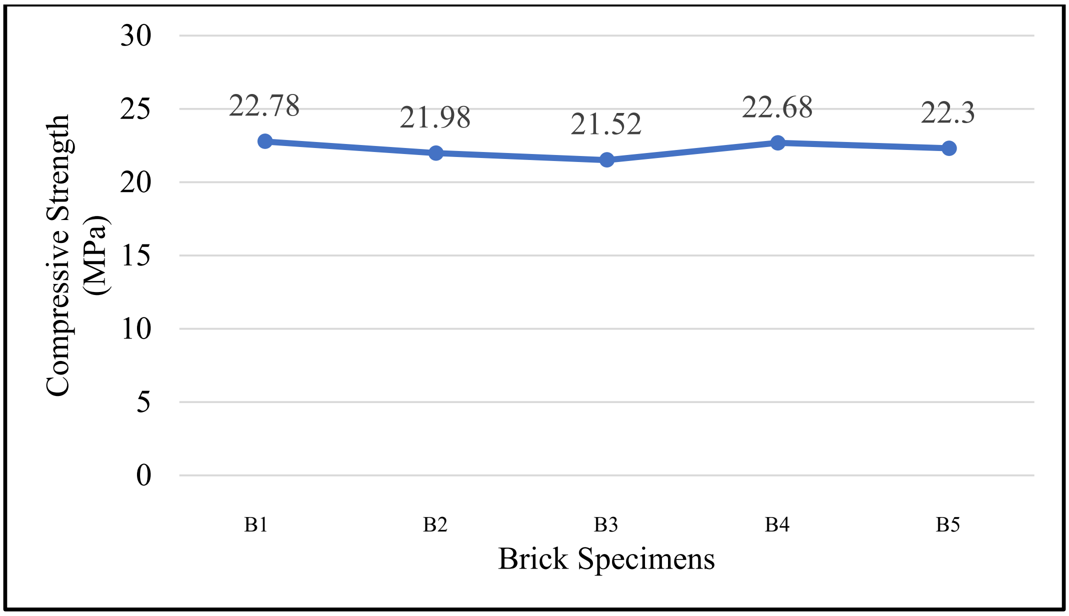

Figure 4.2. Compressive Strength of the Bricks

4.2. TEST ON MORTAR

The mortar is an essential component in brick masonry, providing the necessary bond and support between the bricks. In this study, hydraulic lime mortars were used with a binder-to-aggregate ratio of 1:3. Hydraulic lime mortars have been traditionally used in historic buildings due to their compatibility with older masonry materials. On the other hand, modern construction practices use cement as the primary binder due to its efficiency. For this reason, OPC-53 mortar, which is a common type of cement mortar with a binder-to-aggregate ratio of 1:3, was chosen for the study. The choice of mortar and the ratio of binder to aggregate used are crucial factors in defining the mechanical properties of the brickwork.

4.2.1. Compressive Strength of Mortar

In order to determine the compressive strength of the brickwork, it is important to evaluate the strength of the mortar used. The strength of the mortar was calculated by testing mortar cubes with a face area of 50 cm^2. The results of the 28-day strength test of the masonry mortar used in the study are shown in Table 4.5.

Table 4.5. Compressive Strength of Mortars

Specimens	Lime Mortar (MPa)	Cement Mortar (MPa)
1	5.80	20.43
2	5.50	19.85
3	5.23	20.87
Avg. Value	5.51	20.38

The average strength of the lime mortar was found to be 5.51 MPa, while the cement mortar had an average strength of 20.38 MPa, which is approximately 270% higher than the strength of lime mortar. The lime and cement mortar specimens are labelled L1, L2, L3, and C1, C2, and C3, respectively. These results demonstrate the significant difference in strength between lime and cement mortar, and highlight the importance of selecting the appropriate mortar for construction projects. Fig. 4.3 depicts the compression capacity of the mortar specimens. As the strength variance between the mortars is much hire so, it will be helpful to identify the consequence of mortar capability on the mechanical behaviour of the brick masonry. Although, the strength of both the mortar is less as compared to the strength of the bricks used in this study. As per the several studies, the durability of masonry construction is also influenced by mortar strength. A stronger mortar can enhance resistance to weathering, erosion, and other external factors, thereby improving the long-term durability of the masonry structure.

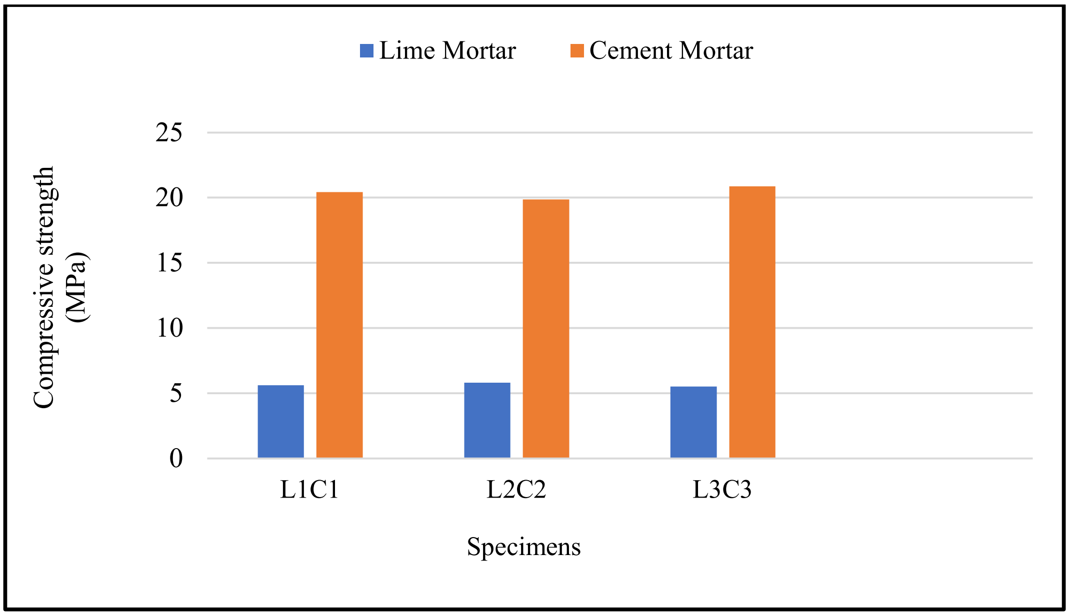

Figure 4.3. Compression Capacity of Mortars

4.3. BRICK MASONRY PRISM

The prism specimens were tested using a Universal Testing Machine (UTM) with a capability of 100kN that was available in the earthquake engineering lab after a 28-day curing period. The specimens were carefully positioned in the UTM between two plywood sheets, following IS1905-1987 criteria. During the testing phase, the weight was given uniformly to the specimens until they failed.

4.3.1. Load Carrying Capacity of Prism for Different Mortar

To measure the compression capacity of the masonry, brick prisms were produced according to the requirements specified in IS 1905:1987. The masonry prisms in this study were built with lime mortar and cement mortar. Three specimens were created for each kind of mortar, and the average peak load value from these specimens was utilised to find the compression capacity of the brickwork. Table 4.6 shows the load-carrying capacity values for each specimen made with cement mortar and lime mortar. The average peak load found in lime mortar was 126.55kN, whereas the average peak load measured in cement mortar prism was 457kN.

Table 4.6. Peak Load Carried by Masonry Prisms

Mortar		Dimensions(mm*mm*mm)	Peak Load(kN)
Lime Mortar	1	220*220*460	128.55
	2	220*220*460	120
	3	220*220*460	131.10
Avg. Value			**126.55**
Cement Mortar	1	220*220*450	477.45
	2	220*220*450	440.10
	3	220*220*450	453.55
Avg. Value			**457**

4.3.2. Calculation of Compressive Strength of Masonry Prism

A masonry prism's compressive strength is a key parameter used to assess the performance of masonry constructions. The compressive strength of masonry prism specimens made with lime mortar and cement mortar is shown in Table 4.7. To account for the specimens' height-to-thickness ratio, the estimated values were multiplied by a correction factor. These correction factors were taken from Table 12 of IS 1905 and the code provided the correction factor for specific heights, and for other heights, interpolation is allowed to determine the corresponding values. In the case of a lime mortar prism with a height of 460mm, the correction factor is 0.744, while for a cement mortar prism with a height of 450mm, the correction factor is 0.730. These correction factors were used to evaluate the compression capacity of the masonry prism.

Table 4.7. Compressive Strength of Specimens

Mortar	Specimen Size (mm)	Avg. Peak load (P) (kN)	P/A (MPa)	Correction Factor for h/t	Compressive Strength (MPa)
Lime	220*220*460	126.55	2.62	0.744	1.95
Cement	220*220*450	457.00	9.44	0.730	6.89

4.3.3. Impact of mortar strength on Compressive Strength of Prism

Numerous studies have demonstrated a positive correlation between mortar strength and the compressive strength of masonry prisms. This observation is consistent with the findings obtained in this study, where an increase in mortar strength led to a substantial enhancement in the compressive strength of the masonry prism. Analysis of the compressive load tests conducted on prisms demonstrates a significant impact of the mortar type on the strength of the prisms. The results reveal that the load-bearing capacity of cement mortar prisms is approximately 3.5 times higher than that of lime mortar prisms. From Fig. 4.4, it is evident that there is approximately a 270% difference in compressive strength between the two types of mortar. Furthermore, a similar trend is observed in the case of compressive strength of masonry prisms and their peak load carrying capacity, with a difference of about 250% and 260% respectively between lime and cement.

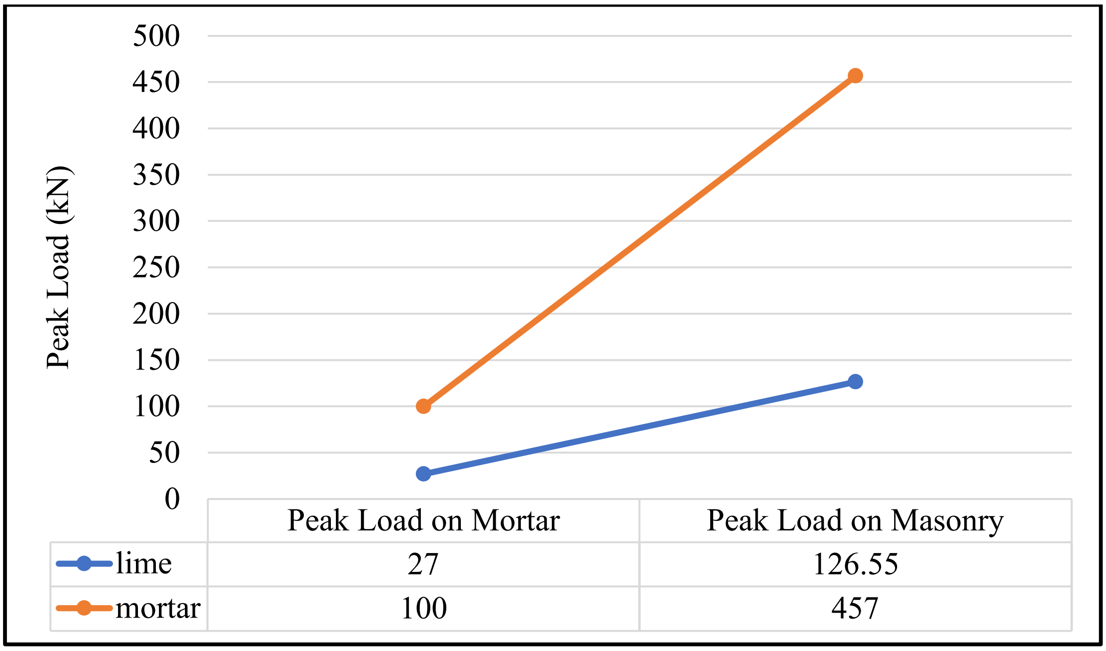

Figure 4.4. Differences in Mortar Strength, Compressive Strength of Prism, and Peak Load Carrying by Masonry Prism

Significance of the Result

The significance of these results lies in the understanding that the type of mortar used has a substantial influence on the strength and load-bearing capacity of masonry prisms. The findings indicate that the use of cement mortar, compared to lime mortar, can lead to a significant improvement in both compressive strength and the ability of the masonry to carry peak loads. This information is valuable for engineers and construction professionals involved in designing and constructing structures, as it highlights the importance of selecting an appropriate mortar type to ensure the desired strength and load-bearing capabilities of masonry elements. Additionally, the observed trends provide insights into the relationship between mortar strength and masonry performance, contributing to the body of knowledge in the field of construction materials and structural engineering.

4.3.4. Load Carrying Capacity of Prism for Different Thickness

The maximum load of masonry prisms is a critical factor in structural design and construction. Understanding how different mortar thicknesses impact the load-carrying capacity is essential for ensuring the structural integrity and safety of masonry structures. In this study, tests were performed to examine the load-carrying capacity of prisms with varying mortar thicknesses. The aim was to analyse and compare the performance of prisms constructed with different mortar thicknesses, providing valuable insights into the influence of mortar thickness on load-carrying capacity.

Table 4.8. Load-bearing Values by Lime Mortar Specimens

Thickness/Specimens		Dimensions(mm*mm*mm)	Peak Load(kN)
13 ± 3 mm	1	220*220*460	128.55
	2	220*220*460	120
	3	220*220*460	131.10
Avg. Value			**126.55**
20 ± 3 mm	1	220*220*490	145.25
	2	220*220*490	152.07
	3	220*220*490	123.13
Avg. Value			**140.15**
27 ± 3 mm	1	220*220*535	112.6
	2	220*220*535	109.27
	3	220*220*535	95.63
Avg. Value			**107.5**

Table 4.9. Load-bearing Values in Cement Mortar Specimens

Thickness/Specimens		Dimensions(mm*mm*mm)	Peak Load(kN)
13 ± 3 mm	1	220*220*450	477.45
	2	220*220*450	440.10
	3	220*220*450	453.55
Avg. Value			**457**
20 ± 3 mm	1	220*220*485	523.67
	2	220*220*485	504.29
	3	220*220*485	459.29
Avg. Value			**495.75**
27 ± 3 mm	1	220*220*525	403.75
	2	220*220*525	411.21
	3	220*220*525	367.04
Avg. Value			**394**

The obtained data are presented in Table 4.8 for lime mortar and Table 4.9 for cement mortar. Three specimens for each thickness were prepared for both the mortars, and for calculating the compressive strength of brick masonry for that particular thickness the average of these three specimens were taken.

Among the prisms tested, those constructed with joint thicknesses of 20 mm, using either cement mortar or lime mortar, exhibited the highest lateral load capability. Following closely were the prisms with joint thicknesses of 13 mm, as shown in Fig. 4.5. Notably, the cement mortar prism with a joint thickness of 20 mm demonstrated the maximum lateral load capacity, measuring 495.75 kN. Conversely, the lime mortar prism with a joint thickness of 30 mm exhibited the lowest load capacity, measuring 107.55 kN.

4.3.5. Calculation of Compressive Strength of Masonry Prism

A masonry prism's compressive strength is a key parameter used to assess the performance of masonry constructions. Table 4.10 and Table 4.11 provide data on the compressive strength of masonry prism specimens using cement mortar and lime mortar, respectively, for various thicknesses. To account for the height-to-thickness ratio of the specimens, the calculated values were multiplied by a correction factor. These correction factors were taken from Table 12 of Indian Standard code IS 1905. The designations LT13, CT13, LT20, CT20, and LT27, CT27 represent prisms with different lime mortar thicknesses (LT) and cement mortar thicknesses (CT) in Table 4.10 and Table 4.11.

Table 4.10. Compressive Strength of Cement Mortar Specimens

Thickness (mm)	Specimen Size (mm)	Avg. Peak load (P) (kN)	P/A (MPa)	Correction Factor for h/t	Compressive Strength (MPa)
CT13±3	220*220*450	457.00	09.44	0.730	6.89
CT20±3	220*220*485	495.75	10.24	0.760	7.78
CT27±3	220*220*525	394.00	08.14	0.784	6.38

Table 4.11. Compressive Strength of Lime Mortar Specimens

Thickness (mm)	Specimen Size (mm)	Avg. Peak load (P) (kN)	P/A (MPa)	Correction Factor for h/t	Compressive Strength (MPa)
LT13±3	220*220*460	126.55	2.62	0.744	1.95
LT20±3	220*220*490	140.15	2.90	0.762	2.21
LT27±3	220*220*535	107.55	2.22	0.790	1.75

When comparing the results for cement mortar, it was observed that increasing the thickness resulted in a mere 13% increase in strength. However, upon further increasing the thickness to 27 mm, the strength decreased by approximately 22% compared to the strength at 20 mm. These findings indicate that the optimal thickness for cement mortar is around 20 mm. Similarly, for lime mortar, increasing the thickness from 13 mm to 20 mm resulted in a similar 13% increase in strength. However, when the thickness was further increased from 20 mm to 27 mm, the strength decreased by about 30%. These results clearly demonstrate that increasing the thickness does not significantly enhance strength in either type of mortar, with the optimal thickness remaining consistent at 20 mm. The designations LT13CT13, LT20CT20, and LT27CT27 represent prisms with different lime mortar thicknesses (LT) and cement mortar thicknesses (CT) in Fig. 6.

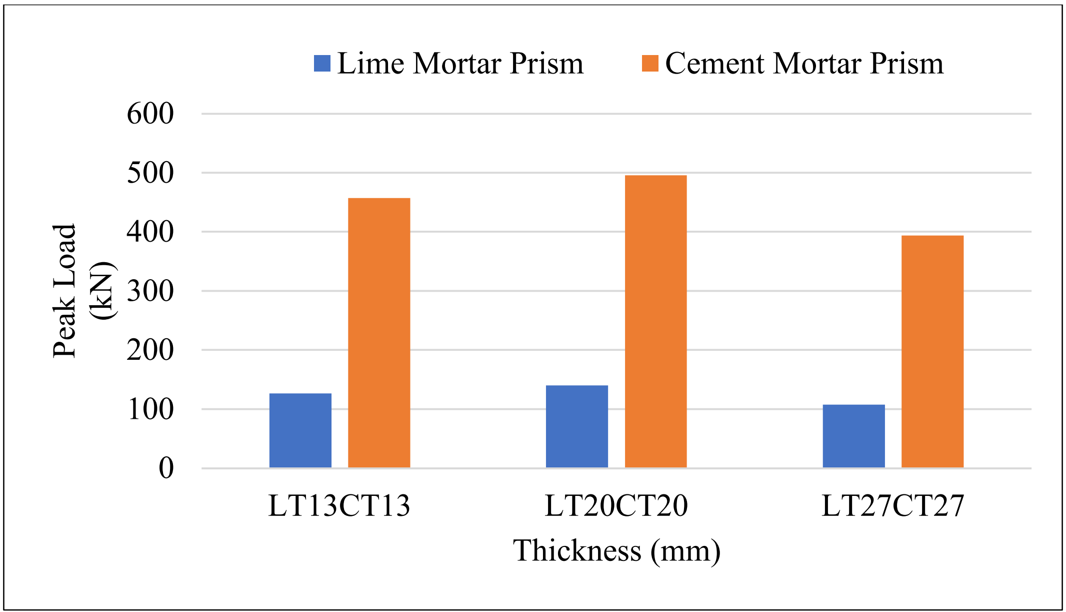

Figure 4.5. Relation between the joint thickness and the load capacity of the Prisms

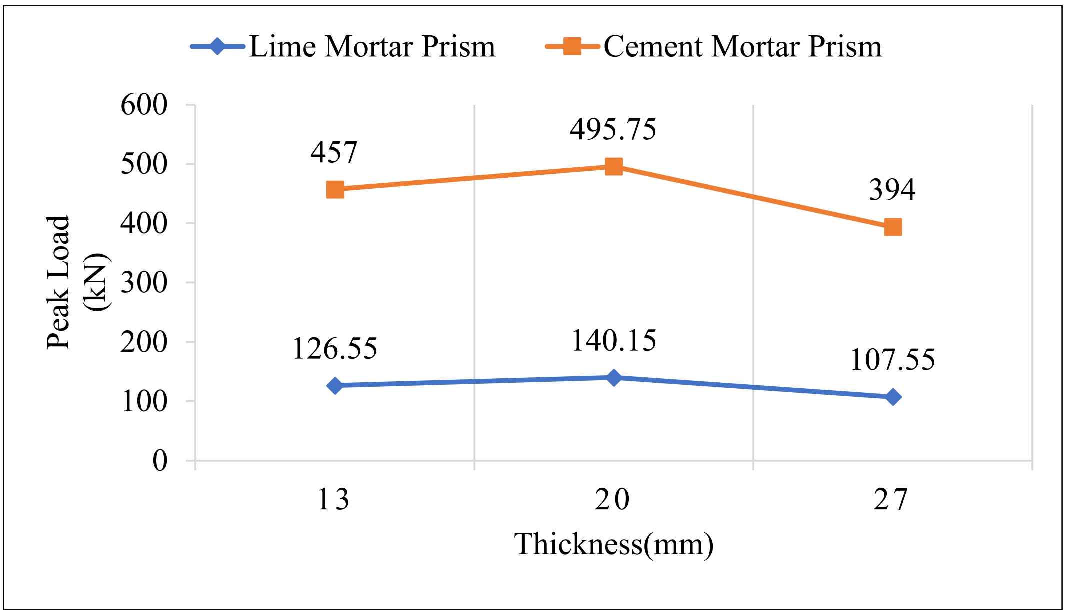

Figure 4.6. Relation between the mortar type and the load capacity of the Prisms

Fig. 4.6 illustrates the association between the joint thickness and the load capacity of the prisms, providing insights into how varying joint thickness affects the load-bearing capability. On the other hand, Fig. 4.6 depicts the relationship between the mortar type and the load carrying capability of the prisms, shedding light on how different mortar types impact the load-bearing capability of the prisms.

4.3.6. Significance of the Result

The significance of these results lies in the understanding of the relationship between joint thickness and load capacity in prisms, as well as the impact of different mortar types on load capacity. The findings indicate that there is an optimal joint thickness for both cement mortar and lime mortar, beyond which increasing the thickness does not lead to significant improvements in strength.

Additionally, these results provide insights into the behavior of different mortar types. For cement mortar, the strength increase with thickness is limited, suggesting that factors other than thickness might play a more prominent role in determining load capacity. In the case of lime mortar, increasing the thickness initially results in a similar strength increase, but beyond a certain point, the strength starts to decline. Understanding these trends allows for more informed decision-making when selecting mortar types for specific applications.

Overall, these findings contribute to the knowledge base surrounding the design and construction of masonry structures, helping to optimize structural performance, ensure safety, and inform material selection decisions.

4.3.7. Mode of Failure of Masonry Prism

The failure mechanism observed in the masonry prisms primarily involved the development of vertical cracks that extended across all sides of the specimens, resulting in masonry failure. Research indicates that joints have a tendency to undergo greater lateral expansion compared to bricks due to their relatively less rigid nature. This phenomenon arises from the use of sturdier and harder bricks in constructing the prisms. However, the presence of bricks restricts the lateral movement of the mortar, leading to the generation of shear stresses and an internal stress state characterized by triaxial compression within the mortar and bilateral tension combined with axial compression within the bricks.

The significant tensile stresses experienced by the bricks give rise to vertical splitting cracks, ultimately contributing to the failure of the masonry prisms. The propagation of cracks typically initiates from the top of the prism and progresses downwards, influenced by the type and thickness of the mortar employed. In cases where the mortar possesses high strength, a crushing failure pattern may also occur, characterized by the failure of the bricks due to the excessive strength of the mortar. Conversely, insufficient mortar strength can lead to shear failure at the interface between the mortar and brick, resulting in a bond failure scenario within the prism. These observations highlight the intricate interplay between the mechanical behavior of the bricks and mortar, the role of lateral expansion in the joints, and the subsequent failure modes observed in the masonry prisms.

The effect of mortar thickness and mortar strength on the failure mode of masonry prisms can be significant.

1. Mortar Thickness

Thicker Mortar: Increasing the thickness of the mortar joints can influence the failure mode. Thicker mortar joints provide a larger volume of mortar, allowing for greater lateral expansion. This can result in increased shear stresses and a higher likelihood of vertical splitting cracks occurring in the bricks, leading to a failure mode dominated by brick cracking and masonry failure.

Thinner Mortar: Conversely, using thinner mortar joints can restrict lateral expansion, reducing the magnitude of shear stresses. This can result in a more favourable failure mode, where the load is primarily carried by the bricks, and the failure is dominated by compressive crushing of the bricks or bond failure between the mortar and bricks.

2. Mortar Strength

Higher Mortar Strength: Employing mortar with higher strength can affect the failure mode of masonry prisms. Stronger mortar can result in higher shear strength at the mortar-brick interface, leading to a greater resistance to shear stresses and bond failure. This can promote a failure mode dominated by brick cracking or compressive crushing of the bricks.

Lower Mortar Strength: Using mortar with lower strength may lead to reduced shear strength at the mortar-brick interface. This can increase the likelihood of bond failure, where the mortar separates from the bricks, resulting in a failure mode characterized by weakened structural integrity and masonry prism failure.

In summary, the mortar thickness and strength can influence the failure mode of masonry prisms. Thicker mortar joints can promote vertical splitting cracks and masonry failure, while thinner joints can lead to compressive brick crushing or bond failure. Higher mortar strength enhances shear strength and can lead to more favourable failure modes, while lower-strength mortar increases the risk of bond failure and weakened structural integrity. Understanding the relationship between mortar characteristics and failure modes is crucial for optimizing masonry design and construction practices.

4.4. TRIPLET TEST

In this study, the brick triplet test for shear strength was performed on specimens after 28 days of curing. Table 4.12 presents the results obtained for each specimen with two different mortars. The purpose of the test was to determine the shear strength of the bricks and the effect of mortar type on the shear bond strength of the brick triplets.

4.4.1. Peak Load Carrying by Triplets for Different Mortars

Table 4.12. Peak Load Carrying by Triplets for Different Mortars

Mortar		Dimensions(mm*mm*mm)	Peak Load(kN)
Lime Mortar	1	220*110*220	10.40
	2	220*110*220	5.50
	3	220*110*220	7.80
Avg. Value			**7.90**
Cement Mortar	1	220*110*220	31.5
	2	220*110*220	26.8
	3	220*110*220	25.7
Avg. Value			**28.0**

Table 4.12 provides data on the peak load values obtained from the tests conducted on specimens using both lime mortar and cement mortar. The average peak load serves as a representative measure of the maximum load capacity exhibited by the specimens. The significantly higher average peak load observed for cement mortar (28 kN) compared to lime mortar (7.9 kN) indicates that cement mortar exhibits a substantially greater load-bearing capacity. These results emphasize the superior strength and performance of cement mortar in terms of supporting higher loads and its potential suitability for applications where greater structural integrity and load resistance are required.

4.4.2. Calculation of Shear Strength of Triplets for Different Mortar

To calculate the binding strength of a triplet, use Equation (4.3). Brick triplet shear strength is evaluated by measuring the size of the bricks and progressively increasing the force until failure occurs. The maximal force exerted just before to failure is recorded. The shear strength values obtained for various brick triplets are shown in Table 4.13.

Table 4.13. Shear Strength of Triplets for Different Mortar

Mortar	Specimen Size (mm)	Avg. Peak load (P) (kN)	Shear Bond Strength (MPa)
Lime Mortar	220*110*220	7.90	0.163
Cement Mortar	220*110*220	28.00	0.578

4.4.3. Impact of Mortar Strength on Shear Strength of Triplets

The study findings indicate a clear relationship between the compressive strength of the mortar and the corresponding shear bond strength values. Considering the difference in mortar strength is approximately 270%, it is noteworthy that the calculated peak load carrying capacity by triplets reveals a difference of around 255% between lime mortar and cement mortar. Additionally, the disparity in shear bond strength between these two mortars aligns with the difference observed in peak load capacity. These findings provide valuable insights into the relationship between mortar strength, peak load capacity, and shear bond strength, indicating that the variations in mortar strength significantly influence the overall structural performance and load-bearing capabilities of masonry elements.

4.4.4. Significance of the result

The significance of these results lies in the understanding of the relationship between mortar strength, peak load-carrying capacity, and shear bond strength of brick triplets. The findings demonstrate that the difference in mortar strength, which is approximately 270%, has a substantial impact on the peak load-carrying capacity of prisms. The observed difference of around 255% in peak load-carrying capacity between lime mortar and cement mortar highlights the significant influence of mortar type on the overall load-bearing capabilities of masonry structures. Understanding this relationship enables better decision-making in terms of selecting the most suitable mortar type for specific structural applications, considering both load-carrying capacity and shear bond strength requirements.

4.4.5. Peak Load Carrying by Triplets for Different Thickness

Table 4.14 and Table 4.15 present the data on peak load-carrying capacities of brick triplets, categorized by different thicknesses for each mortar type. For each thickness, three separate specimens were constructed and tested to determine the peak load-carrying capacity. The values obtained from these tests were averaged to calculate the shear bond strength.

These tables provide essential information on the performance and load-bearing capabilities of brick triplets with varying thicknesses and different mortar types. The average peak load values obtained from multiple specimens help to obtain more reliable and representative data for calculating shear bond strength. This approach enables a more accurate assessment of the mortar's ability to bond with the bricks and withstand applied loads. The data presented in these tables contribute to the understanding of the relationship between thickness, mortar type, and the resulting peak load-carrying capacities and shear bond strength of masonry structures.

Table 4.14. The peak load on Lime Triplet Specimens

Thickness/ Specimens		Dimensions(mm*mm*mm)	Peak Load(kN)
13 ± 3 mm	1	220*110*220	10.40
	2	220*110*220	5.50
	3	220*110*220	7.80
Avg. Value			**7.90**
20 ± 3 mm	1	220*110*220	6.30
	2	220*110*220	5.20
	3	220*110*220	5.90
Avg. Value			**5.80**
27 ± 3 mm	1	220*110*220	5.40
	2	220*110*220	4.30
	3	220*110*220	4.10
Avg. Value			**4.60**

Table 4.15. The peak load on Cement Triplet Specimens

Thickness/Specimens		Dimensions(mm*mm*mm)	Peak Load(kN)
13 ± 3 mm	1	220*110*220	31.5
	2	220*110*220	26.8
	3	220*110*220	25.7
Avg. Value			**28.00**
20 ± 3 mm	1	220*110*220	23
	2	220*110*220	20.4
	3	220*110*220	18.85
Avg. Value			**20.75**
27 ± 3 mm	1	220*110*220	13.3
	2	220*110*220	9.70
	3	220*110*220	10.60
Avg. Value			**11.20**

4.4.6. Calculation of Shear Strength of Brick Triplets

Equation (4.3) was used to compute the binding strength of a triplet. The shear strength of brick triplets is evaluated by measuring the dimensions of the bricks and applying a gradually increasing force until failure occurs. The maximum force applied just before failure is recorded. Tables 4.16 and 4.17 present the shear strength values obtained for different brick triplets. These tables provide a comprehensive overview of the shear strength performance of the brick triplets under the applied testing conditions.

Shear Bond Strength = $\frac{P}{2LB}$ .... (4.3)

Where, L= 220 mm

B = 110 mm

Table 4.16. Shear Bond Strength of Cement Mortar Triplets

Thickness (mm)	Specimen Size (mm)	Avg. Peak load (P) (kN)	Shear Bond Strength (MPa)
CT13±3	220*110*220	28.00	0.578
CT20±3	220*110*220	20.75	0.429
CT27±3	220*110*220	11.20	0.231

Table 4.17. Shear Bond Strength of Lime Mortar Triplets

Thickness (mm)	Specimen Size (mm)	Avg. Peak load (P) (kN)	Shear Bond Strength (MPa)
LT13±3	220*110*220	7.90	0.163
LT20±3	220*110*220	5.80	0.120
LT27±3	220*110*220	4.60	0.095

The data analysis reveals that the shear strength for both cement mortar and lime mortar reach its peak at a thickness of 13 mm. Subsequently, as the thickness increases from 13 mm to 20 mm, the shear strength decreases by approximately 34% for cement mortar and 35% for lime mortar. This suggests that increasing the thickness beyond 13 mm has a detrimental effect on shear strength.

Interestingly, when the thickness is further increased to 27 mm, the shear strength experiences different degrees of reduction. For cement mortar, the shear strength decreases by a substantial 85%. In contrast, for lime mortar, the shear strength only decreases by 26% at this thickness. These findings highlight the distinct behavior of cement mortar and lime mortar regarding shear strength degradation with increasing thickness.

Understanding the relationship between thickness and shear strength is vital in masonry design, as it aids in selecting appropriate thicknesses for optimal shear performance. Interestingly, the decrease in shear bond strength was found to be less frequent when increasing the depth of the mortar. This observation can be attributed to the utilization of a low-quality binder in the construction of the brickwork structures, as it adversely affects the bond strength.

Fig. 4.7 provides a graphical representation of how the load capacity of the triplets varies with different mortar types. It visually demonstrates the differences in load capacity between mortar types, allowing for a direct comparison of their performance. The result provides valuable insights into the influence of mortar type on the load-bearing capabilities of the triplets, aiding in the selection of the most suitable mortar type for specific applications. On the other hand, Fig. 4.8 presents a graphical depiction of the relationship between joint thickness and the load capacity of the triplets. It illustrates how the load capacity changes as the joint thickness is varied. This information is crucial in understanding the effect of joint thickness on the load-carrying capabilities of masonry structures. By analyzing this relationship, engineers and designers can determine the optimal joint thickness to achieve desired load capacities and structural performance.

Both Fig. 4.7 and Fig. 4.8 contribute to a comprehensive understanding of the factors influencing the load capacity of triplets in masonry construction. The Fig. 4.8 and Fig. 4.9 provide visual representations of the relationships between mortar type, joint thickness, and load capacity, facilitating informed decision-making during the design and construction processes.

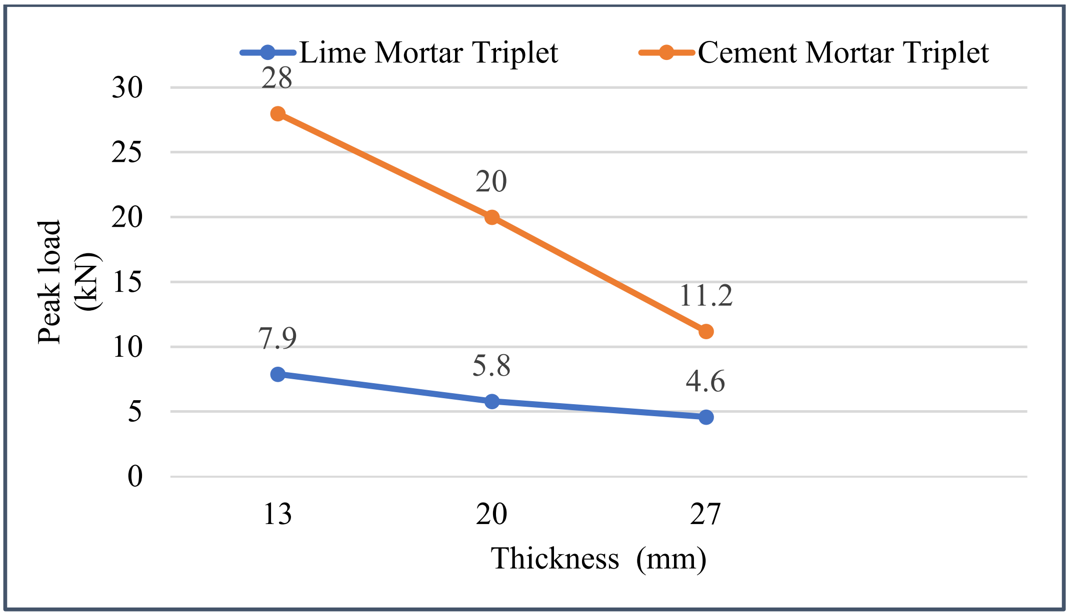

Figure 4.7. Relation between the mortar type and the load capacity of the Triplets

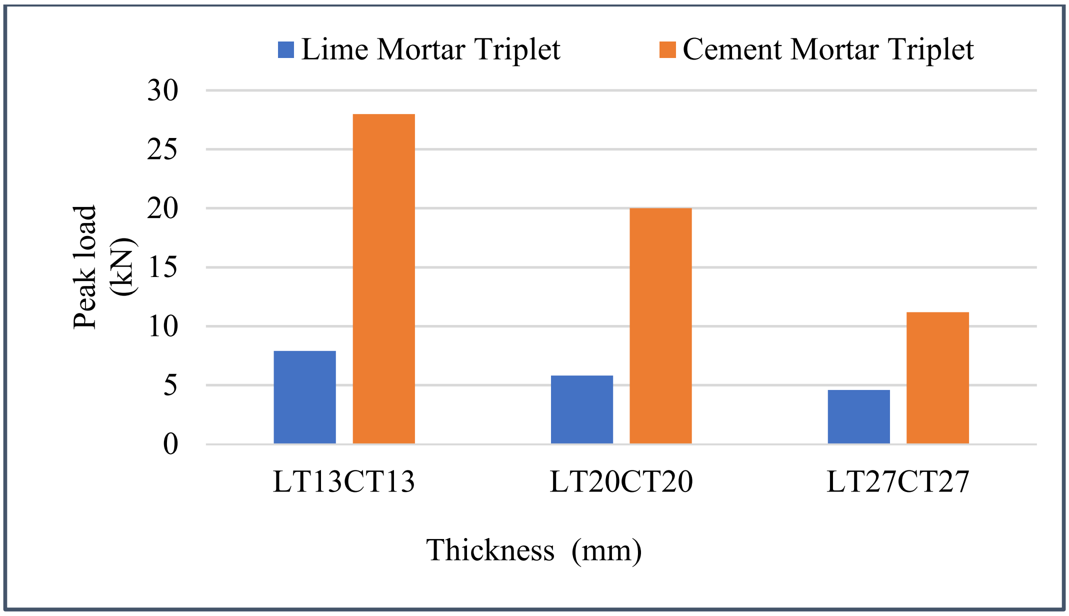

Figure 4.8. Relation between the joint thickness and the load capacity of the Triplets

4.4.7. Significance of the Result

These findings suggest that the bond strength of brickwork is primarily affected by the strength of the mortar, whereas the thickness of the mortar has a relatively minor impact. Varying the thickness of the mortar layer among the specimens can affect stress distribution and crack propagation during testing, consequently influencing the measured mechanical properties. Similarly, employing different mortar compositions can alter the bonding strength between the specimens and the mortar, thereby affecting the measured properties.

4.4.8. Mode of Failure of Brick Triplets

This particular test can be conducted using two distinct protocols, denoted as Protocol A and Protocol B, which can be performed with or without lateral pre-compression. Fig. 4.9 illustrates the anticipated failure modes for this test. The first two modes, labelled as A/1 and A/2, involve failure due to the separation of the mortar from the brick, attributed to poor contact between these two components. Failure occurs within the mortar layer, referred to as mode B when a low-strength mortar is utilized for constructing the bed joints. Conversely, if a high-strength mortar with strong adhesive characteristics is employed, the specimen is prone to failure through the occurrence of fractures running through one or both bricks, represented by modes C and D, as documented by Alecci et al. in 2013[16]. These failure modes highlight the influence of mortar quality and adhesion strength on the performance of the tested specimens.

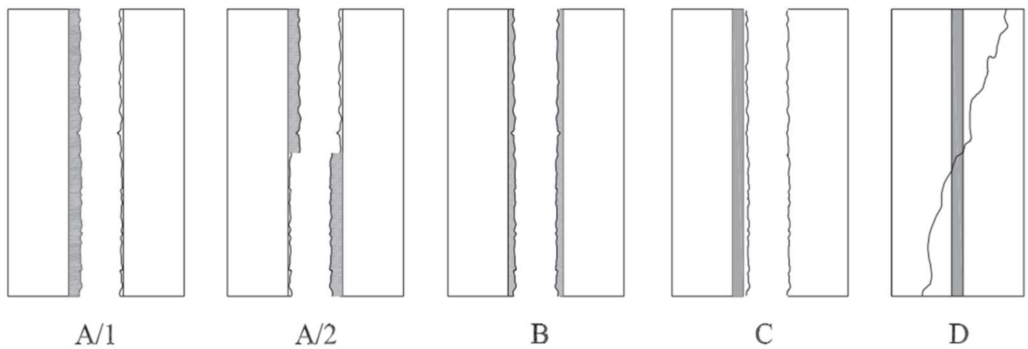

Figure 4.9. Failure mechanisms of triplet tests[16]

In the current study, the predominant failure mode observed was A/1, with some cases also exhibiting A/2 and B failure modes. This implies that the failure occurred primarily due to mortar separation from the brick, indicating inadequate contact between the two components. Additionally, in certain instances, failure within the mortar layer (mode B) was also observed. These findings align with the expected failure possibilities discussed earlier. It should be noted that the specific failure modes observed in this study were influenced by factors such as the mortar quality, adhesive characteristics, and the construction techniques employed. These results further highlight the importance of considering the quality of the mortar and ensuring proper bonding between the mortar and bricks to prevent failure in brick masonry applications.

The strength of the mortar influences the bonding and load-carrying capacity, leading to different failure modes such as mortar separation or fractures in the bricks. The thickness of the mortar joints affects the stress distribution and load transfer, which can also impact the failure mode observed. It is important to select an appropriate mortar strength and thickness to ensure optimal bonding, structural integrity, and resistance to failure in brick masonry structures.

4.5. DIAGONAL TENSION TEST / SHEAR STRENGTH TEST

In the literature[16], several interpretations of diagonal compression test results for predicting shear strength can be found. The diagonal tension test, as outlined in ASTM E519-07, involves subjecting a specimen to a diagonal tensile load to determine its shear strength. The test begins with the preparation of the specimen according to specified dimensions and surface conditions. The specimen is then securely placed within the testing apparatus, ensuring proper alignment. A diagonal tensile load is applied gradually to the specimen, typically at a specified angle and magnitude, until failure occurs. During the test, the applied load and resulting deformation are continuously measured and recorded. The shear strength of the specimen is calculated based on the peak load achieved just before failure. The testing process follows standardized guidelines to ensure consistent and reliable results for assessing the material's ability to resist diagonal tensile forces. The standard interpretation of the test [ASTM E519-07] assumes that the stress-state at the diagonal specimen's centre is pure shear and that the average shear stress equals the principal tensile stress. Using equation 4.4, the shear stress of brickwork at an applied load P was estimated for this experiment based on this assumption.

$$\tau = 0.707\frac{P}{An} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.4)$$

Where-

$An = \left(\frac{w+h}{2}\right)t$ = Net area (mm^2)

w = width, h = height, and t = thickness

P = Peak Load

4.5.1. Calculation of Shear Stress

Table 4.18 and Table 4.19 present comprehensive data regarding the direct tension testing of walls. These tables specifically illustrate the peak forces recorded during the tests and the corresponding shear strength values, calculated using Equation 4.4. The peak forces represent the maximum applied load experienced by the walls before failure occurred. By utilizing Equation 4.4, the shear strength values were determined, providing valuable insights into the walls' resistance to shear stresses.

Table 4.18. Diagonal Tension Value for Lime Mortar Specimens

Thickness/Specimens		Dimensions(mm*mm*mm)	Peak Load(kN)	τ MPa
13 ± 3 mm	1	690*690*75	20.0	0.273
	2	690*690*75	16.6	0.227
	3	690*690*75	22.7	0.310
Avg. Value				**0.270**

Table 4.19. Diagonal Tension value for Cement Mortar Specimens

Thickness/Specimens		Dimensions(mm*mm*mm)	Peak Load(kN)	τ MPa
13 ± 3 mm	1	690*690*75	65.8	0.899
	2	690*690*75	70.2	0.959
	3	690*690*75	71.8	0.981
Avg. Value				**0.946**

The results of the diagonal tension test indicated that the cement mortar exhibited a significantly higher diagonal tension strength of 0.946 compared to the lime mortar's strength of 0.27. This corresponds to a notable strength difference, with the cement mortar demonstrating approximately 250.37% higher strength than the lime mortar. It is significant to note that the maximum strength in the triplet test was obtained for a mortar thickness of 13 mm, and thus, only that thickness was considered for the diagonal tension test to maintain consistency. By focusing on the 13 mm thickness, the comparison between lime mortar and cement mortar under similar conditions allowed for a direct evaluation of their respective resistance to diagonal tension forces. The results highlight the significant impact of mortar composition on the masonry's ability to withstand diagonal tension, with the cement mortar demonstrating superior performance in this regard.

4.5.2. Failure Mode

When masonry panels were exposed to diagonal compression testing, two unique failure scenarios emerged. The first mode involved the development of cracks along the load direction, which is expected in a diagonal compression test. The applied load led to stress concentration along the diagonal axis, resulting in crack propagation in that direction.

In the second mode, cracks developed along a non-diagonal direction. This type of failure occurred when the load exceeded the tensile strength of the mortar used for the joints. The insufficient tensile strength of the mortar led to cracks forming in a direction other than the expected diagonal direction of compression.

It is important to note that the stress distribution prior to failure may have played a role in determining the specific failure mode observed. The interaction between the applied load, the properties of the masonry components, and the stress distribution within the panel influenced the failure behavior. Further analysis is necessary to fully understand the stress distribution patterns and their impact on the observed failure modes in the masonry panels subjected to diagonal compression testing.

4.6. CONCLUDING REMARKS

Chapter 4 presents the comprehensive testing results of various materials, including bricks, mortar, prisms, triplets, and the diagonal tension test. The obtained results were thoroughly discussed, interpreted, and analysed to gain insights into the mechanical properties and behaviour of the tested specimens.

The interpretation of the results focused on factors such as mortar thickness, mortar strength, and their influence on the compressive strength, shear bond strength, diagonal tension strength, and overall failure mode of the masonry elements.

The discussion encompassed the observed failure modes, stress distributions, crack propagation, and the effects of different variables on the performance of the masonry components. By analysing and interpreting these results, valuable information was gained regarding the behaviour and structural integrity of the tested materials and systems, contributing to a deeper understanding of their performance in practical applications.

CHAPTER 5

CONCLUSIONS & FUTURE WORK

5.1. SUMMARY

The objectives were established following an extensive review of the available literature on mortar thickness, mortar strength, and their impact on brick masonry. This comprehensive literature review served as the foundation for identifying gaps and limitations in previous studies pertaining to brick masonry. Chapter 2 of this thesis provides a detailed explanation of the relevant literature, organized into various sections. The inclusion of these literature sources contributes to the overall knowledge base and theoretical framework supporting this research work.

A series of experimental tests on brick assemblies and their constituent materials were performed in this work to assess different attributes such as dimensions, water absorption (WA), density, compressive strength, and shear bond strength. The test specimens were prepared using two types of mortars, lime and cement, and three distinct mortar thicknesses: 13 mm, 20 mm, and 27 mm. The experimental design includes information about the raw materials utilised, the preparation of test specimens, the equipment used, and the techniques performed during the experiment, all of which are thoroughly discussed in Chapter 3 of this Thesis. These experimental details lay the groundwork for further analysis and interpretation of the data.

Chapter 4 of this thesis provides a detailed description of the tests conducted on the specimens, aiming to evaluate the influence of mortar thickness and strength on the compressive strength of brick masonry. The tests included the determination of compressive strength of masonry prisms. Additionally, shear strength tests were performed on triplets to examine the effect of mortar thickness and strength. Furthermore, a diagonal tension test was conducted on a masonry wall to investigate the behavior of masonry under shear forces. These tests were essential in understanding the relationship between mortar characteristics, such as thickness and strength, and the overall performance of brick masonry in terms of compressive and shear strength. The results of these tests provide valuable insights into the behavior and structural properties of masonry construction.

5.2. CONCLUSIONS

The various conclusions drawn from the above studies are given below:

- The difference in compressive strength between lime mortar and cement mortar is approximately 270%, and this difference in compressive strength of mortars helped in identifying the impact of mortar strength on masonry prism and brick triplets.
- The compressive strength of cement mortar prisms is approximately 253% higher than that of lime mortar prisms, demonstrating the substantial influence of mortar strength on the compressive strength of brick masonry. It can be conclude that the compressive strength of brick masonry is proportional to the compressive strength of the mortar used.
- The shear strength of triplets with cement mortar is approximately 255% higher compared to lime mortar triplets. This finding reveals that the compressive strength of the mortar significantly impacts the shear strength of brick masonry.
- When the thickness of the mortar was increased from 13 mm to 20 mm and then 27 mm, the compressive strength in both mortar specimens exhibited an approximate increase of 13% in first case and compressive strength of the masonry prism decreased by approximately 21% for cement mortar and 26% for lime mortar in later case. These findings suggest that while an increase in thickness initially contributes to improved compressive strength, exceeding the optimal thickness threshold leads to a subsequent decline in the compressive strength of the masonry prism. This suggests that there is an optimal range for mortar thickness that maximizes the compressive strength of masonry prisms.
- With an increase in mortar thickness from 13 mm to 20 mm and then 27 mm, the shear strength of both lime mortar and cement mortar triplets decreased by approximately 35% first then the shear strength of cement mortar triplets experienced a substantial decrease of approximately 85%, while in the case of lime mortar, the shear strength decreased by approximately 26%. These findings demonstrate that as the thickness of mortar increases beyond a certain

point, there is a significant reduction in shear strength for both mortar types, albeit to a greater extent in cement mortar.

- The diagonal tension test was conducted on both lime mortar and cement mortar with a mortar thickness of 13 mm. Specifically, the shear stress recorded for the cement mortar wall was approximately 250% higher than that of the lime mortar. These findings indicate that in the case of 13 mm mortar thickness, cement mortar demonstrates significantly greater shear strength compared to lime mortar.
- Increased diagonal tension strength helps to enhance the overall stability and structural integrity of brick masonry. It improves the ability of the masonry structure to resist lateral forces, such as wind loads or seismic forces.

The above studies have led to several significant conclusions, which are summarized below:

1. Effect of Mortar Thickness: The investigations on the influence of mortar thickness on the performance of brick masonry revealed that an optimal thickness of 20 mm is favorable for both lime and cement mortar. Beyond this thickness, the strength properties tend to decrease. This indicates that increasing the mortar thickness beyond the optimum range does not provide significant benefits in terms of strength enhancement.

2. Influence of Mortar Strength: The experimental tests conducted on the specimens demonstrated a clear relationship between mortar strength and the load-carrying capacity of the masonry. It was observed that cement mortar exhibits approximately 3.5 times higher load-bearing capacity compared to lime mortar. This highlights the importance of selecting mortar with adequate strength to ensure the structural integrity and stability of the masonry construction.

3. Shear Bond Strength: The evaluation of bond strength between the mortar and bricks provided valuable insights into the behavior of masonry under shear forces. The results indicated that shear strength is directly influenced by the type and strength of mortar. The substantial difference in shear bond strength between lime and cement mortar corresponds to the observed disparities in peak load-carrying capacity. Higher diagonal tension strength in brick masonry contributes to a more robust and reliable structural system with improved performance in terms of stability, crack resistance, load-carrying capacity, durability, and design flexibility.

4. Optimum Mortar Characteristics: The findings consistently point towards an optimum mortar thickness of 20 mm for both lime and cement mortar. This suggests that utilizing a mortar thickness within this range can ensure satisfactory strength properties and performance of the masonry. It is crucial to consider the mortar type and strength when designing and constructing brick masonry structures.

These conclusions highlight the critical role of mortar thickness and strength in determining the structural behavior and load-carrying capacity of brick masonry. They provide practical insights for optimizing mortar characteristics to enhance the performance and durability of masonry constructions.

5.3. FUTURE SCOPE

The future scope of research in the field of masonry structures presents exciting opportunities for further advancements and knowledge expansion. This section highlights potential areas that can be explored to address current limitations and contribute to the development of innovative solutions. Future research can focus on various aspects such as:

i. A statistical multiple regression analysis may be used to construct a mathematical model for evaluating the compression capacity of brick prisms. This model should account for a variety of elements, such as the volume fractions of masonry units and mortar, as well as the height-to-thickness ratio.
ii. When evaluating the compression capacity of brick prisms, the volume fractions of masonry units and mortar, as well as the height-to-thickness ratio, can be taken into account. These variables have a large impact on the overall strength and behavior of the masonry assemblage.
iii. Further experimental and analytical research is required to inspect the performance of components in masonry constructions. This study is critical for establishing new techniques and tactics for reinforcing existing masonry buildings, increasing load carrying capacity, and overall performance.

iv. The mechanical properties of the masonry specimens, such as stress, strain, and modulus can include in the study. These properties are vital for understanding the behavior and response of the masonry under various loading conditions.

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India

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