

**Effect Of Infill Material Thickness On Strength Behavior
Of Jointed Rock Mass Under Different Orientation**

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Degree of

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IN
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BY**

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CANDIDATE'S DECLARATION

I, **Harshit Sharma** (2K24/GTE/10) student of M. Tech., Geotechnical Engineering, hereby declare that the work which is being presented in dissertation entitled **“Effect Of Infill Material Thickness On Strength Behavior Of Jointed Rock Mass Under Different Orientation”** in partial fulfillment of the requirements for the award of the Degree of Master of Technology, submitted in the Department of Civil Engineering, Delhi Technological University, Delhi is an authenticate record of my own work carried out during the period from 2024 to 2026 under the supervision of **Prof. A.K. Srivastava**.

The content presented in the dissertation has not been submitted for the award of any other degree of this or any other institute.

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CERTIFICATE BY THE SUPERVISOR(s)

It is certified that **Harshit Sharma** (2K24/GTE/10) has carried out their research work presented in this report entitled “**Effect Of Infill Material Thickness On Strength Behavior Of Jointed Rock Mass Under Different Orientation**” for the award of **Master of Technology** from Department of Civil Engineering, Delhi Technological University, Delhi, under my supervision. The report embodies results of original work, and studies are carried out by the student himself and the contents of the report do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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ABSTRACT

Rock masses used in engineering structures such as tunnels, slopes, foundations, underground openings, and mining excavations generally contain joints, fractures, and discontinuities that greatly influence their mechanical behavior and stability. In many practical situations, these joints are filled with weak materials such as clay, gypsum, weathered deposits, or gouge materials, which reduce the strength and stiffness of the rock mass. The presence of infill material changes the stress transfer mechanism between rock blocks and increases the possibility of deformation and failure under loading conditions. Therefore, understanding the combined influence of joint orientation and infill thickness on the behavior of jointed rock masses is essential for safe and economical rock engineering design.

The present experimental investigation focuses on the compressive behavior of artificial jointed rock specimens prepared using gypsum plaster under laboratory-controlled conditions. Artificial rock blocks were casted using gypsum material due to its brittle nature, ease of preparation, and suitability for simulating weak rock behavior. Three individual blocks of dimensions $150\text{ mm} \times 150\text{ mm} \times 50\text{ mm}$ were assembled together to form cube specimens of overall dimensions $150\text{ mm} \times 150\text{ mm} \times 150\text{ mm}$. Artificial discontinuities were introduced at joint orientations of 0° , 30° , and 90° to study the effect of crack inclination on strength and failure characteristics. In addition to clean joint specimens, infill layers of 2 mm and 4 mm thickness were provided between the joints to simulate realistic infilled rock conditions.

Uniaxial compression tests were conducted on all specimens using a Compression Testing Machine (CTM). During testing, observations related to crack initiation, crack propagation, deformation behavior, and failure mechanisms were carefully recorded. Experimental results revealed that joint orientation has a major influence on compressive strength. Specimens with 0° joint orientation exhibited the highest compressive strength due to direct axial load transfer through the specimen, whereas specimens with 30° orientation showed minimum strength because of dominant shear sliding along the inclined joint plane. The 90° joint orientation specimens displayed moderate strength and mainly failed through tensile splitting.

The study also showed that the presence of infill material significantly reduces the compressive strength of jointed specimens. Increasing the infill thickness from 2 mm to 4 mm further decreased the load-carrying capacity because the thicker infill layer reduced frictional resistance and interlocking between adjacent blocks. The experimental observations confirmed that thicker infill layers promote deformation and sliding failure under compression loading.

The findings of the present investigation highlight the importance of considering both discontinuity orientation and infill thickness while analyzing the stability of rock engineering structures. The study provides valuable insight into the failure behavior of infilled jointed rock masses and offers a simple and economical experimental approach for simulating field conditions in laboratory studies

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LIST OF SYMBOLS, ABBREVIATIONS

a	average asperity height
λ	asperity wavelength (spacing)

CHAPTER 1

INTRODUCTION

1.1 General

Rock masses encountered in engineering projects such as tunnels, slopes, foundations, underground caverns, and mining excavations are rarely intact in nature. They usually contain discontinuities such as joints, fractures, bedding planes, fissures, and faults that significantly influence their mechanical behavior. Among these discontinuities, rock joints play a major role in controlling the strength, deformation characteristics, and failure mechanism of rock masses. The orientation, spacing, roughness, and filling material present within the joints directly affect the stability and load-bearing capacity of rock structures. Therefore, understanding the behavior of jointed rock masses under loading conditions is an important aspect of rock mechanics and geotechnical engineering.

In practical situations, rock joints are often filled with weak materials such as clay, gypsum, calcite, sand, gouge material, or weathered deposits. These infill materials alter the stress transfer mechanism between rock blocks and reduce the overall strength of the rock mass. The thickness and properties of the infill material greatly influence the compressive and shear behavior of jointed rocks. As the thickness of the infill increases, the bonding between rock blocks generally decreases, resulting in lower strength and higher deformation. Hence, the study of infilled joints is essential for evaluating the performance and stability of rock structures subjected to external loads.

In recent years, several researchers have carried out experimental investigations to study the effect of joint orientation and infill material on the mechanical properties of rock specimens. Experimental modeling using artificial rock samples has become a common approach because natural rock samples with identical joint conditions are difficult to obtain. Artificial samples prepared using materials such as gypsum and provide uniformity, repeatability, and controlled testing conditions. Such studies help in simulating actual field conditions and understanding the failure behavior of jointed rock masses under laboratory-controlled environments.

The present study is an extension of the earlier minor project work, in which artificial jointed rock specimens with different joint orientations were prepared and tested under compression loading. In the previous work, specimens having joint orientations of 0° , 30° , and 90° were cast and tested without any infill material. The results indicated that joint orientation has a significant influence on the compressive strength and failure pattern of the specimens. However, natural rock masses generally contain some form of infilling material within the joints. Therefore, to represent more realistic field conditions and further enhance the scope of the research, the current major project introduces infill material between the joints of the specimens.

In this study, artificial rock specimens were prepared using gypsum material. Three individual blocks of size 50 mm were assembled together to form a cube specimen of size 150 mm. The specimens were prepared with three different joint orientations, namely 0° , 30° , and 90° . To

investigate the influence of infill thickness, gypsum infill material was introduced between the joints with thicknesses of 2 mm and 4 mm. In addition to these infilled specimens, samples without infill material were also prepared for comparison purposes. The prepared specimens were then subjected to compression testing to evaluate their mechanical behavior under loading conditions.

The primary objective of the study is to analyze the effect of infill thickness and joint orientation on the compressive strength and failure characteristics of artificial jointed rock specimens. The experimental results obtained from specimens with no infill, 2 mm infill, and 4 mm infill are compared to understand the variation in strength and deformation behavior. The study also aims to identify the critical orientation and infill condition responsible for maximum strength reduction and instability.

The findings of this research can contribute to the understanding of jointed rock behavior in various engineering applications such as rock slopes, tunnels, underground excavations, retaining structures, and foundation systems constructed in fractured rock masses. The results may also help in improving the design and stability assessment of structures built in jointed and infilled rock formations. Furthermore, the study provides a simplified experimental methodology for investigating the influence of discontinuities and infill materials on rock mass behavior under compressive loading.

Overall, the present investigation highlights the importance of considering both joint orientation and infill thickness while evaluating the mechanical response of rock masses. The experimental approach adopted in this study offers a practical and economical way to simulate field conditions and examine the failure mechanism of infilled jointed rock specimens. The outcomes of the research are expected to provide useful insights for future experimental and numerical studies related to rock mechanics and geotechnical engineering.

1.2 PROBLEM STATEMENT

Rock engineering structures such as tunnels, slopes, underground caverns, foundations, and mining excavations are generally constructed in rock masses containing discontinuities such as joints, fractures, bedding planes, and fissures. These discontinuities significantly influence the strength, deformation, and failure behavior of rock masses under loading conditions. Unlike intact rock, jointed rock masses exhibit complex mechanical behavior due to the presence of weak planes that alter stress distribution and failure mechanisms. As a result, the stability and load-bearing capacity of rock engineering structures are largely controlled by the characteristics of the joints present within the rock mass.

One of the most important parameters affecting the behavior of jointed rocks is the **orientation of joints relative to the applied loading direction**. Different joint orientations influence crack propagation, stress transfer, and failure patterns within the rock specimen. Previous laboratory investigations have shown that certain joint inclinations may promote shear sliding or tensile splitting, leading to significant reduction in compressive strength. Rock specimens with unfavorable joint orientations often fail prematurely due to the development of localized shear zones along the discontinuity surfaces. Therefore, understanding the influence of joint orientation on rock mass behavior is essential for the safe design of rock engineering structures.

In natural rock masses, joints are rarely clean or empty. Most joints contain weak **infill materials** such as clay, gypsum, calcite, weathered deposits, crushed rock particles, or gouge materials. These infill materials modify the interaction between rock blocks and significantly affect the mechanical properties of the rock mass. The presence of infill material generally reduces the bonding and interlocking effect between adjacent rock surfaces, resulting in lower strength and higher deformation. The influence becomes more critical when the thickness of the infill layer increases, as thicker infill layers tend to weaken the overall rock structure and alter the mode of failure.

The **thickness of infill material** is considered an important factor governing the compressive behavior of jointed rock masses. Thin infill layers may still allow partial contact and frictional resistance between rock blocks, whereas thicker infill layers behave as weak zones that promote sliding and separation under loading. As the infill thickness increases, the compressive strength of the rock specimen is expected to decrease due to reduced stress transfer across the joints. However, the extent of strength reduction depends not only on infill thickness but also on the orientation of the joints. Therefore, the combined effect of joint orientation and infill thickness requires detailed experimental investigation.

In the earlier minor project work, artificial jointed rock specimens with joint orientations of 0° , 30° , and 90° were prepared and tested under compression loading without any infill material. The study successfully demonstrated the effect of joint orientation on compressive strength and failure

characteristics. However, the specimens used in the previous investigation did not represent actual field conditions because natural rock joints commonly contain infill materials. Consequently, the previous study was limited in simulating realistic rock mass behavior encountered in practical engineering problems.

To address this limitation, the present major project introduces **gypsum infill material** between the joints of artificial rock specimens. The specimens are prepared by assembling three blocks of 50 mm size to form a cube specimen of 150 mm dimensions. Joint orientations of 0° , 30° , and 90° are considered, while infill layers of 2 mm and 4 mm thickness are provided between the joints. Compression tests are conducted on specimens with no infill, 2 mm infill, and 4 mm infill to evaluate the influence of infill thickness on the mechanical behavior of jointed rock specimens.

Existing research studies have mainly focused on either joint orientation or infill properties individually under different experimental conditions. Limited laboratory investigations are available that systematically examine the combined influence of joint orientation and varying infill thickness using controlled artificial rock specimens. Moreover, there is insufficient comparative experimental data available for understanding the variation in compressive strength and failure mechanisms due to changes in infill thickness under different joint inclinations.

Therefore, there is a need for a controlled experimental investigation that evaluates the effect of both **joint orientation and infill thickness** on the compressive behavior of artificial jointed rock specimens. The present study aims to compare the behavior of specimens with no infill, 2 mm infill, and 4 mm infill under different joint orientations to identify the variation in strength, deformation characteristics, and failure mechanisms. The outcomes of this investigation are expected to provide valuable insights into the behavior of infilled jointed rock masses and contribute to the design and stability assessment of rock engineering structures constructed in fractured rock conditions.

1.3 OBJECTIVES OF THE STUDY

The present study aims to investigate the compressive behavior of artificial jointed rock specimens with different joint orientations and varying infill thicknesses under laboratory-controlled conditions. The major objectives of the study are as follows:

1. **To prepare artificial jointed rock specimens** using gypsum material with different joint orientations of 0° , 30° , and 90° .
2. **To introduce infill material between the joints** with thicknesses of 2 mm and 4 mm in order to simulate realistic infilled rock joint conditions.
3. **To conduct compression tests on the prepared specimens** and evaluate their mechanical behavior under compressive loading.
4. **To study the effect of joint orientation** on the compressive strength and failure characteristics of artificial rock specimens.
5. **To investigate the influence of infill thickness** on the strength, deformation behavior, and failure mechanism of jointed rock samples.
6. **To compare the behavior of specimens with no infill, 2 mm infill, and 4 mm infill** under different joint orientations.
7. **To identify the critical joint orientation and infill thickness** responsible for maximum strength reduction and instability in the specimens.
8. **To analyze the variation in crack propagation and failure patterns** due to changes in joint orientation and infill thickness.
9. **To simulate realistic field conditions of fractured rock masses** containing infilled joints through controlled laboratory experimentation.
10. **To provide experimental data and observations** that can contribute to future research and numerical modeling studies related to rock mechanics and geotechnical engineering.

Chapter 2

Literature Review

Barton and Choubey (1977) [1] conducted significant research on the shear behavior of rock joints and introduced the concept of the Joint Roughness Coefficient (JRC). Their study highlighted that joint surface conditions greatly influence the shear strength and deformation characteristics of rock masses. The researchers observed that rough joints provide higher resistance against sliding due to increased asperity interlocking and frictional interaction between rock surfaces. The study established that discontinuity characteristics such as roughness, orientation, and surface condition are major controlling factors in rock mass stability and failure behavior.

Jaeger and Cook (1979) [2] investigated the influence of joint orientation on the compressive behavior of rock specimens. Their research demonstrated that the inclination of joints relative to the loading direction significantly affects the strength and failure mechanism of jointed rock masses. The study revealed that rock specimens with inclined joints generally fail through shear sliding along the discontinuity surfaces, whereas specimens with horizontal or vertical joints exhibit comparatively higher compressive resistance. The researchers concluded that joint orientation plays a critical role in determining crack propagation and failure patterns under compression loading.

Lama and Vutukuri (1978) [3] carried out experimental studies on fractured rock masses and observed that the presence of joints considerably reduces the overall strength of rock specimens. Their investigation focused on the mechanical behavior of jointed rocks under laboratory loading conditions. The study reported that discontinuities act as weak planes within the rock mass and alter stress distribution during loading. It was also found that the spacing and orientation of joints significantly influence the compressive and shear behavior of rock specimens.

Goodman (1989) [4] presented detailed studies on the engineering behavior of jointed rock masses and emphasized the importance of discontinuities in rock engineering projects. The research explained that natural rock masses are rarely intact and generally contain joints, fractures, and bedding planes that govern the mechanical response of the rock structure. Goodman highlighted that the failure mechanism of rock masses is strongly dependent on joint orientation, joint properties, and loading conditions. The study provided a theoretical foundation for understanding rock mass instability in tunnels, slopes, and underground excavations.

Singh and Goel (1999) [5] investigated the strength behavior of jointed rock masses subjected to compressive loading. Their experimental observations indicated that joint inclination significantly affects the uniaxial compressive strength and deformation characteristics of rock specimens. The researchers observed that specimens containing inclined joints exhibited lower strength due to the development of shear cracks along the joint surfaces. The study further concluded that failure behavior changes with variation in discontinuity orientation and loading direction.

Bahaaddini et al. (2013) [6] studied the effect of joint roughness and infill material on the shear behavior of rock joints using laboratory experiments and numerical simulations. The research demonstrated that infill materials significantly reduce the shear strength of rock joints by decreasing frictional resistance between adjacent rock blocks. The study also revealed that increasing infill thickness results in greater deformation and lower peak strength. The researchers concluded that both joint roughness and infill thickness are important parameters controlling rock joint behavior.

Yang et al. (2015) [7] conducted laboratory compression tests on rock-like specimens containing filled joints at different inclinations. The study analyzed the influence of infill thickness and joint orientation on crack propagation and failure mechanisms. Experimental results showed that specimens with thicker infill layers experienced lower compressive strength and larger deformation compared to clean joint specimens. The researchers observed that infill materials promote sliding failure and reduce the load-carrying capacity of jointed rock masses.

Zhang et al. (2016) [8] investigated the mechanical behavior of gypsum-based artificial rock specimens containing non-persistent joints under uniaxial compression conditions. The study reported that artificial specimens effectively simulate the brittle behavior and crack propagation characteristics of natural rocks. The researchers observed that joint orientation strongly influences the initiation and propagation of cracks. The study concluded that gypsum-based materials are suitable for controlled laboratory modeling of fractured rock masses.

Shen and Stephansson (2017) [9] analyzed the effect of discontinuities and infill materials on the stability of rock masses in underground excavations. Their study highlighted that infilled joints reduce the strength and stiffness of rock masses and increase the probability of instability under loading conditions. The researchers emphasized that thicker infill layers behave as weak zones that promote deformation and sliding between rock blocks. The study recommended considering infill thickness during rock engineering design and stability assessment.

Liu et al. (2020) [10] carried out experimental investigations on jointed rock specimens containing different infill thicknesses under compression loading. The research showed that the compressive strength of specimens decreases progressively with increasing infill thickness. The study also observed changes in crack initiation, deformation characteristics, and failure patterns due to variation in infill conditions. The researchers concluded that the combined effect of joint orientation and infill thickness significantly controls the mechanical response of rock masses.

Recent studies on artificial rock modeling have demonstrated that gypsum materials provide effective and economical alternatives for preparing laboratory-scale rock specimens. Researchers have used gypsum-based specimens to investigate the behavior of jointed rocks under different loading and boundary conditions. These studies confirmed that artificial specimens offer better repeatability, controlled discontinuity conditions, and reliable simulation of rock failure mechanisms. The findings from these investigations support the use of gypsum specimens in experimental rock mechanics research involving joint orientation and infill materials.

The review of previous studies indicates that joint orientation, discontinuity conditions, and infill thickness significantly influence the compressive behavior and failure mechanism of rock masses. However, limited experimental investigations are available that systematically compare specimens with no infill, 2 mm infill, and 4 mm infill under different joint orientations using gypsum based artificial rock models. Therefore, the present study aims to address this research gap through controlled laboratory experimentation and comparative analysis of infilled jointed rock specimens under compression loading.

2.1 Findings from Systematic Literature Review (SLR)

The systematic review of previous research studies related to jointed rock masses, discontinuity behavior, and infilled rock joints indicates that the mechanical behavior of rock masses is strongly influenced by joint orientation, surface characteristics, and infill material properties. The major findings obtained from the literature review are summarized as follows:

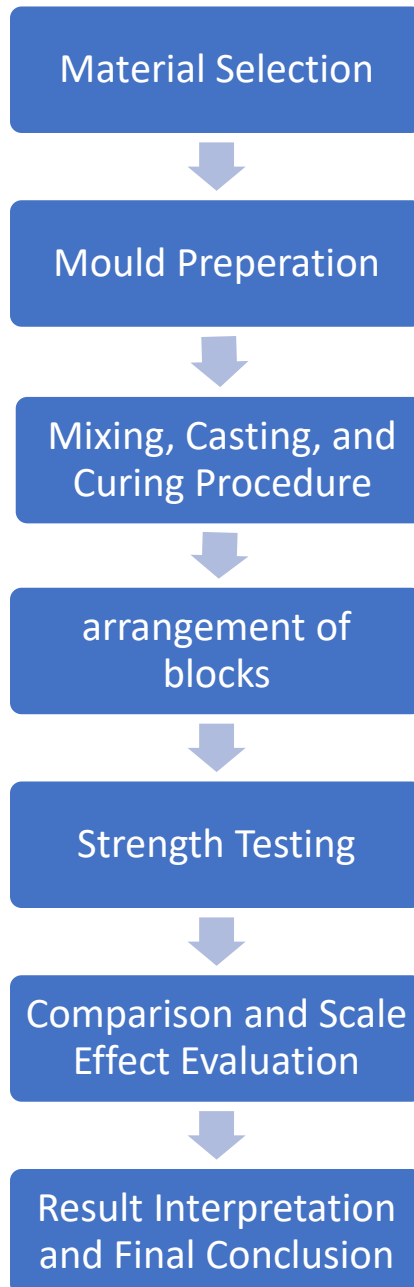
1. Most natural rock masses contain discontinuities such as joints, fractures, bedding planes, and fissures, which significantly reduce the overall strength and stability of the rock mass compared to intact rock specimens.
2. Joint orientation is one of the most critical parameters affecting the compressive behavior and failure mechanism of rock masses. Different joint inclinations produce different stress distributions, crack propagation patterns, and modes of failure under loading conditions.
3. Rock specimens containing inclined joints generally exhibit lower compressive strength due to the development of shear sliding along the discontinuity surfaces. Intermediate joint orientations are often found to be more critical than horizontal or vertical joints.
4. Joint roughness and surface characteristics influence the frictional resistance and interlocking behavior between rock blocks. Rough joints provide greater shear resistance compared to smooth joints.
5. The presence of infill material within rock joints considerably alters the mechanical response of rock masses. Infilled joints behave as weak zones and reduce the bonding effect between adjacent rock blocks.
6. Weak infill materials such as gypsum, clay, gouge material, calcite, and weathered deposits reduce the compressive and shear strength of jointed rock specimens.
7. Increasing the thickness of infill material generally results in a progressive reduction in compressive strength and stiffness of rock specimens. Thicker infill layers promote deformation and sliding failure along joint surfaces.
8. Experimental studies have shown that infill thickness affects crack initiation, crack propagation, and failure mechanisms within jointed rock specimens under compression loading.
9. Artificial rock specimens prepared using gypsum materials are widely used in laboratory investigations because they provide controlled conditions, better repeatability, and reliable simulation of brittle rock behavior.
10. Laboratory-based artificial specimens are effective for studying the influence of discontinuities, joint orientation, and infill conditions because natural rock samples with identical properties are difficult to obtain.

11. Previous research has mainly focused on either joint orientation or infill properties individually, while limited studies have investigated their combined influence under controlled laboratory conditions.
12. Existing literature reveals insufficient comparative experimental data regarding the effect of different infill thicknesses under various joint orientations using gypsum-based artificial rock specimens.
13. Most studies emphasize the importance of considering both discontinuity conditions and infill material characteristics in the design and stability analysis of tunnels, slopes, underground excavations, foundations, and mining structures.
14. The literature review highlights the necessity of conducting controlled experimental investigations to better understand the combined effect of joint orientation and infill thickness on the compressive behavior of jointed rock masses.
15. Based on the reviewed studies, it is observed that introducing infill material between joints significantly changes the load transfer mechanism, deformation characteristics, and failure pattern of rock specimens under compressive loading.

The findings from the systematic literature review establish the research gap and justify the need for the present study, which focuses on comparing the compressive behavior of artificial jointed rock specimens with no infill, 2 mm infill, and 4 mm infill under different joint orientations of 0°, 30°, and 90°.

CHAPTER -3

EXPERIMENTAL METHODOLOGY



3.1 Material Selection

Gypsum plaster was chosen as the primary material for preparing the artificial rock specimens used in the present experimental study. The selection of gypsum plaster was mainly based on its uniformity, brittle nature, ease of specimen preparation, and ability to simulate the behavior of weak sedimentary rocks under compression loading. In laboratory rock mechanics investigations, gypsum-based materials are commonly preferred because they provide consistent properties and allow controlled preparation of jointed specimens with different orientations and infill conditions.

The gypsum plaster used in this investigation is a commercially available construction-grade gypsum material generally utilized for interior plastering applications. The material satisfies the requirements of IS 2547 (Part-1): 1976 and contains high-purity calcium sulfate hemihydrate as its major constituent. Due to its refined particle size and controlled setting characteristics, the material is suitable for preparing laboratory-scale rock models with good dimensional accuracy and repeatability.

Gypsum plaster possesses several advantages for experimental modeling. It can be easily mixed, poured into molds, and cast into the required specimen geometry. The material develops sufficient hardness after curing and exhibits brittle fracture characteristics similar to naturally occurring weak rocks. Moreover, artificial joints and infill layers can be introduced conveniently during casting, which makes the material highly suitable for studies related to discontinuities and infilled rock masses.



Figure 3.1 Gypsum Plaster

3.1.1. Physical Characteristics

The important physical properties of the gypsum plaster used during specimen preparation are summarized in Table 2.

Table 3.1 Physical Characteristics of Gypsum Plaster

Property	Typical Value / Observation	Remarks
Appearance	White fine powder	Indicates purified gypsum
Particle Size	Fine and uniform	Helps in smooth casting
Powder Density	Approximately 1300 kg/m ³	Depends on storage condition
Density after Curing	Approximately 1780 kg/m ³	Influenced by water content and compaction
Initial Setting Time	Around 10–15 minutes	Suitable for laboratory work
Surface Finish	Smooth texture	Helps achieve proper specimen quality

The fine texture and consistent particle distribution improve the mixing behavior and help in obtaining homogeneous specimens. Smooth finishing and proper bonding between layers also support the preparation of artificial joints and infill sections with controlled thickness.

3.1.2. Chemical Composition

The gypsum plaster mainly consists of calcium sulfate hemihydrate along with a small quantity of additives and impurities. The approximate composition is presented in Table 3.

Table 3.2 Chemical Composition of Gypsum Plaster

Compound	Approximate Percentage
Calcium Sulfate Hemihydrate ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$)	85–95%
Hydrated Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)	1–4%
Additives and Modifiers	1–3%
Minor Insoluble Materials	Less than 2%

Source: IS 2547 : 1976

The high concentration of calcium sulfate hemihydrate contributes to proper hardening and strength development after curing. Small quantities of additives are generally used to regulate setting characteristics and improve workability.

3.1.3. Workability and Mixing Behavior

Gypsum plaster exhibits satisfactory workability during specimen preparation and can be mixed easily to obtain a uniform slurry. The water-to-powder ratio plays an important role in controlling the consistency and final strength of the specimens. In general, a water–powder ratio ranging from 0.55 to 0.70 provides suitable casting conditions for laboratory applications.

If excessive water is added during mixing, the hardened specimens may develop higher porosity and lower compressive strength. Therefore, proper proportioning and controlled mixing are necessary to maintain specimen quality. Mechanical vibration during casting helps remove entrapped air and improves density and homogeneity.

The following workability characteristics were observed during specimen preparation:

- Easy mixing and handling
- Uniform consistency during casting
- Proper mold filling capability
- Reduced shrinkage after setting
- Smooth demolding after curing
- Good bonding between casted layers

These properties make gypsum plaster suitable for preparing artificial jointed rock specimens with controlled dimensions and infill thicknesses.

Suitability for Rock Mechanics Modeling

Gypsum plaster is considered an appropriate material for laboratory rock mechanics studies because its behavior resembles that of brittle and weak sedimentary rocks under loading conditions. The material develops visible cracking and sudden failure during compression testing, which helps in studying crack propagation and failure mechanisms.

The following characteristics support its suitability for artificial rock modeling:

- Brittle response under compressive loading
- Easy preparation of artificial discontinuities

- Controlled density and repeatability
- Uniform specimen quality
- Simple casting and curing procedure
- Suitable for studying joint orientation and infill effects

The use of gypsum plaster also allows preparation of multiple specimens with similar properties, reducing variability in experimental observations.

3.1.4. Locations of Gypsum Deposits in India

Gypsum deposits are found in several regions of India and are widely used in the cement, fertilizer, construction, and ceramic industries. Major gypsum-producing regions are listed in Table 4.

Table 3.3 Major Gypsum Deposits in India

State	Important Areas
Rajasthan	Bikaner, Barmer, Jaisalmer, Nagaur
Tamil Nadu	Salem, Tiruchirappalli
Jammu & Kashmir	Kupwara, Kathua
Gujarat	Jamnagar, Kutch
Uttar Pradesh	Fatehpur region

Among all states, Rajasthan possesses the largest share of gypsum reserves in India and contributes the majority of national gypsum production.

Source: Indian Minerals Yearbook – Gypsum, Ministry of Mines, Government of India.

3. 1.5 Setting Time Test of Gypsum Plaster

Before preparing the model specimens, the setting behavior of the gypsum plaster was examined in the laboratory to determine the workable time available for mixing and casting operations. The test was necessary to ensure that mould filling, joint placement, and infill preparation could be completed before the gypsum mixture started hardening.

The experiment was conducted at normal room temperature conditions. A gypsum-water mixture was prepared using a **water-to-gypsum proportion of 1:2 by weight**. Initially, the required amount of clean water was poured into a mixing container. Gypsum plaster was then added gradually into the water while continuous manual stirring was carried out to obtain a smooth and consistent paste. Mixing was performed carefully to avoid the formation of lumps and to maintain uniformity throughout the mixture.

After mixing, the prepared paste was spread over a **smooth horizontal surface** in the form of a thin layer. The setting characteristics were monitored using a simple manual scratching technique. In this method, a pointed needle was drawn lightly over the surface of the plaster paste at regular intervals to observe the change in hardness with time.

Initially, the soft and plastic nature of the gypsum paste did not allow clear scratch impressions to form on the surface. After nearly **10 minutes**, the material attained sufficient hardness due to setting, and visible scratch marks could then be observed on the surface.

The observed setting time was considered during specimen preparation so that all casting activities, including mould filling and positioning of joint blocks, could be completed within the workable period of the gypsum paste. This helped maintain consistency and uniformity in all the specimens prepared for the experimental study.



Figure 3.2 testing of setting time of gypsum plaster

3.2 Mould Preparation

Mould preparation was carried out carefully to obtain artificial rock specimens with accurate dimensions and controlled joint orientations. The moulds used in the present investigation were fabricated using cardboard and PVC sheets because these materials are lightweight, easy to shape, economical, and suitable for laboratory-scale casting work. Proper mould preparation was necessary to ensure dimensional uniformity and consistency among all the specimens prepared for compression testing.

Three different mould arrangements were developed for casting specimens with different artificial joint orientations. The mould dimensions and internal arrangements were designed according to the required specimen geometry and crack inclination. Artificial discontinuities were introduced at orientations of 0° , 30° , and 90° to study the influence of joint inclination on the compressive behavior of the specimens.

Each model specimen consisted of three individual blocks assembled together to produce a cube specimen having overall dimensions of $150\text{ mm} \times 150\text{ mm}$. The arrangement of the blocks created two artificial joint planes within each specimen. Care was taken to maintain proper alignment and dimensional accuracy during mould fabrication and specimen assembly.

For specimens containing 0° and 90° joint orientations, moulds of identical dimensions measuring $150\text{ mm} \times 150\text{ mm} \times 50\text{ mm}$ were prepared. The same mould configuration was suitable for both orientations because the discontinuity planes could be arranged accordingly during assembly of the blocks. These moulds were designed to provide smooth surfaces and proper dimensional stability during casting and curing.

A separate mould arrangement was prepared for the 30° joint orientation specimens because inclined joints required a different internal geometry. The mould was designed in such a way that the artificial crack plane could be maintained accurately at the required inclination during specimen preparation. Special attention was given to maintaining uniform crack alignment and avoiding displacement during casting.

Before pouring the gypsum mixture, the mould surfaces were cleaned properly and checked for dimensional accuracy. The mould joints and edges were secured to prevent leakage of slurry during casting. Proper support was also provided to maintain stability of the moulds throughout the setting and curing stages.

The prepared moulds enabled accurate formation of artificial discontinuities and helped achieve uniform specimen geometry for all the experimental samples used in the study.

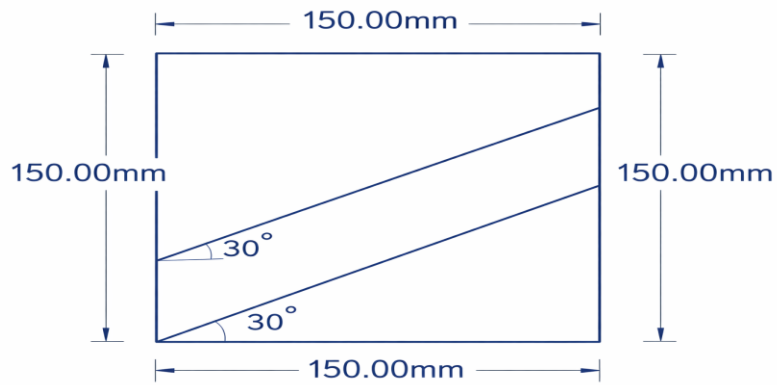
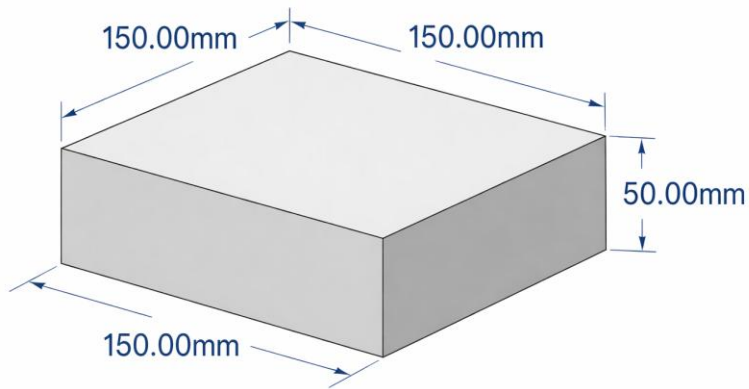


Figure 1.3 different Mould dimensions

3.3 Mixing, Casting, and Curing Procedure

Preparation of the artificial rock specimens involved controlled mixing, casting, and curing operations to maintain uniform material properties throughout the experimental program. Gypsum plaster and water were mixed in a **fixed proportion of 1:2 by weight** for all specimens prepared in the study. The selected proportion was finalized after preliminary observations to obtain suitable flowability, proper setting behavior, and adequate strength after hardening.

The mixing process was performed manually using a clean mixing container. Initially, the required quantity of water was poured into the container, after which gypsum plaster was added slowly in small portions. Continuous hand mixing was carried out throughout the process to obtain a smooth and uniform paste without the formation of lumps. Uniform mixing was necessary to ensure consistent density and material behavior in all specimens.

Since gypsum plaster starts hardening within a short duration, the complete mixing and casting operation was completed quickly. The prepared slurry was transferred into the moulds within approximately **2 minutes** to avoid early setting before placement. During casting, the slurry was poured carefully into the mould cavities to maintain proper filling and alignment of the specimen geometry.

To reduce the presence of air voids inside the specimens, gentle tapping and vibration were applied externally to the moulds after pouring. This process helped improve compaction and ensured better distribution of the slurry within the mould. Surface finishing and leveling were also completed immediately after casting to obtain smooth specimen surfaces.

Laboratory observations indicated that the gypsum-water mixture began to lose its plasticity after nearly 10 minutes at room temperature. Therefore, all operations related to pouring, alignment, and finishing were completed before the commencement of setting.

After casting, the specimens were kept inside the moulds without disturbance for initial hardening. **Demoulding was carried out after 24 hours**, when the specimens had developed sufficient rigidity to maintain their shape safely. Extra care was taken while removing the specimens from the moulds to prevent corner breakage, cracking, or surface damage.

Following demoulding, all specimens were kept under natural sunlight exposure for a **curing period of 10 days**. The curing process allowed gradual drying and proper development of strength within the gypsum blocks. Slow moisture loss during curing also helped minimize shrinkage cracks and improved specimen stability.

The adopted procedure for mixing, casting, demoulding, and curing provided good dimensional consistency and uniform material characteristics in all the prepared specimens. Maintaining identical preparation conditions for each sample helped improve the reliability and repeatability of the experimental results obtained during compression testing.



Figure 3.2 mixing and casting



Figure 3.3 curing and weighing of blocks

3.4 Arrangement of Blocks

The arrangement of blocks was an important stage in the preparation of the artificial jointed rock specimens used in the present experimental investigation. Proper assembly of the blocks was necessary to obtain the required specimen geometry, maintain accurate joint orientation, and ensure uniform infill thickness throughout the specimens. The arrangement procedure was carried out carefully so that all specimens possessed similar dimensions and comparable discontinuity conditions for compression testing.

The specimens were prepared using gypsum-based blocks casted separately during the earlier stages of specimen preparation. **Each individual block had dimensions of 150 mm × 150 mm × 50 mm.** Three such blocks were assembled vertically to form a cube specimen having overall dimensions of 150 mm × 150 mm × 150 mm. During the assembly process, two artificial discontinuity planes were created between the adjacent blocks to simulate joints commonly present in natural rock masses.

The main objective of the block arrangement process was to prepare specimens with different joint orientations and infill thicknesses under controlled laboratory conditions. **Three different joint inclinations, namely 0°, 30°, and 90°, were considered in the study.** These orientations were selected to investigate the influence of discontinuity inclination on the compressive behavior and failure characteristics of the specimens.

For the 0° orientation, the joint planes were arranged horizontally with respect to the loading direction. In the 90° orientation specimens, the discontinuity planes were maintained vertically. For the 30° orientation, the blocks were positioned in such a way that the artificial joints were inclined at an angle of 30° to the horizontal axis. Special care was taken while assembling the 30° specimens because inclined discontinuities required accurate alignment to maintain the desired geometry throughout the specimen.

The study included specimens without infill as well as specimens containing infill layers of different thicknesses. In the case of specimens without infill material, the gypsum blocks were placed directly in contact with one another along the discontinuity surfaces. These specimens represented clean joint conditions where no intermediate filling material was present between the joints.

For the infilled joint specimens, controlled gaps were intentionally maintained between the adjacent blocks during assembly. **Two different infill thicknesses, namely 2 mm and 4 mm,** were considered in the investigation. Suitable spacers were used during block arrangement to maintain uniform separation between the blocks and ensure consistent infill thickness throughout the specimen.

After maintaining the required spacing, gypsum slurry was introduced between the discontinuity surfaces to form the infill layer. The infill material was placed carefully to ensure proper filling of the joint gap without leaving air voids or unfilled regions. Proper alignment of the blocks was maintained during this process to prevent displacement of the joint planes.

To improve visual identification and differentiation of the infill layers during specimen observation and testing, different colors were added to the infill material. **A pink color additive was used for the specimens containing 2 mm infill thickness, while a green color additive was used for the specimens containing 4 mm infill thickness.** The addition of colors helped in clearly distinguishing the infill zones from the surrounding gypsum blocks during specimen preparation, crack observation, and post-failure analysis.

The colored infill layers also assisted in monitoring crack propagation and failure patterns during compression testing. Since the infill region could be identified easily, it became convenient to observe whether the failure occurred through the infill material, along the joint interface, or within the gypsum blocks themselves. The use of different colors therefore improved visual interpretation of the experimental observations and enhanced the clarity of specimen documentation.

During the assembly process, all blocks were positioned carefully to maintain dimensional accuracy and proper alignment of the discontinuity planes. The specimen geometry was checked visually after assembly to ensure that the blocks remained properly aligned and that the infill thickness was uniform throughout the joint surface. Any excess slurry present along the specimen edges was removed carefully before hardening.

After complete arrangement of the blocks and placement of the infill material, the assembled specimens were kept undisturbed to allow proper setting and bonding between the blocks and infill layers. Uniformity in block arrangement was maintained for all specimens to minimize experimental variations and ensure consistency during compression testing.

The adopted arrangement procedure provided controlled specimen geometry and reliable discontinuity conditions for studying the influence of joint orientation and infill thickness on the mechanical behavior of artificial rock masses. The use of colored infill material further improved the visibility of joint regions and helped in detailed observation of crack development and failure mechanisms during the experimental investigation.

Arrangement of Blocks with no infill material.

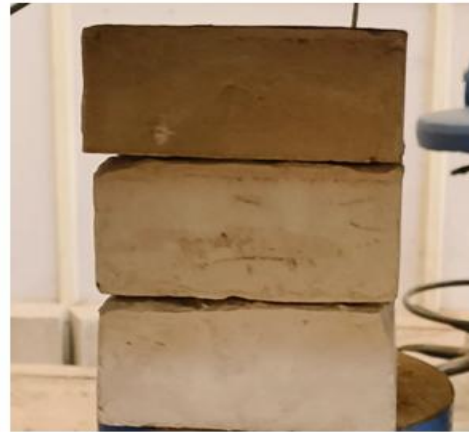
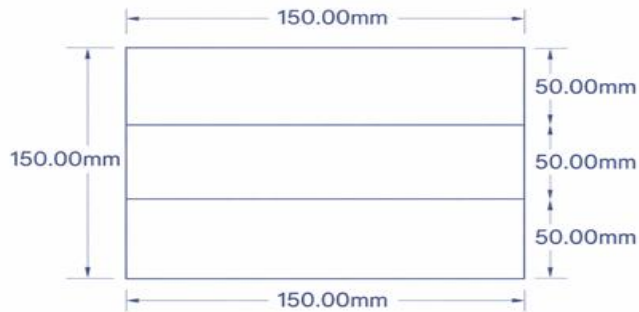


Figure 3. 4 Arrangement of blocks with zero degree orientation

Geometry and arrangement of gypsum plaster blocks used in the study. @ 0* cracks

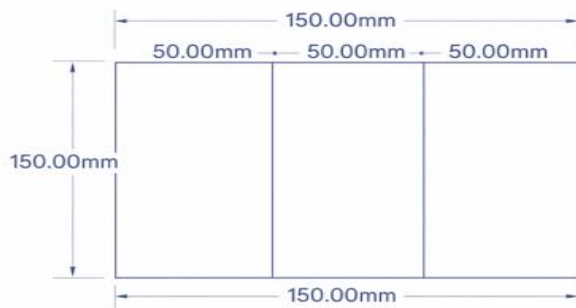


Figure 3.5 Arrangement of blocks with 90 degree orientation

Geometry and arrangement of gypsum plaster blocks used in the study. @ 90* cracks

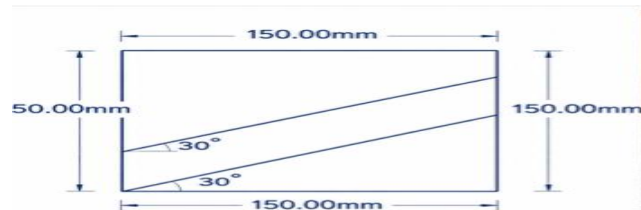


Figure 3.6 Arrangement of blocks with 30 degree orientation

Arrangement of Block With Infill Of 2 mm

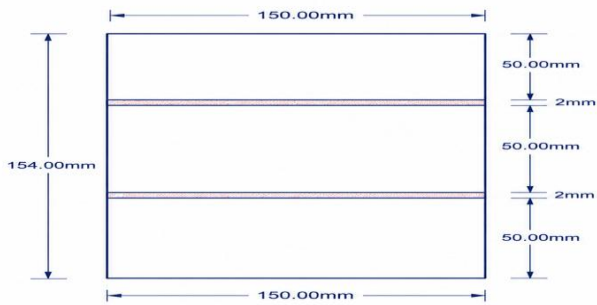


Figure 3.7 Arrangement of blocks with 0 degree orientation and 2mm infill material

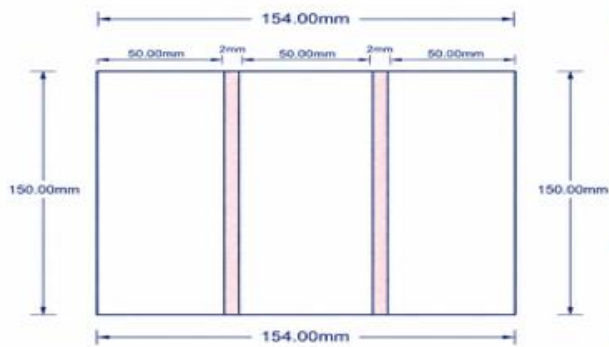


Figure 3.10 Arrangement of blocks with 90 degree orientation and 2mm infill material

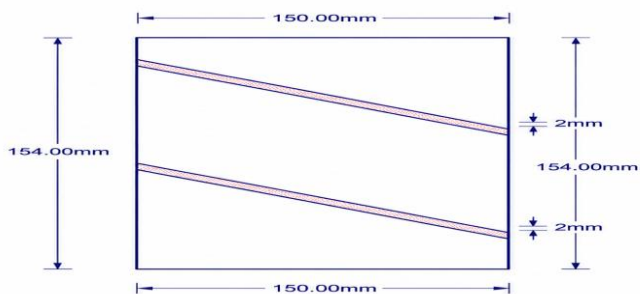


Figure 3.8 Arrangement of blocks with 30 degree orientation and 2mm infill material

Arrangement of Block With Infill Of 4 mm

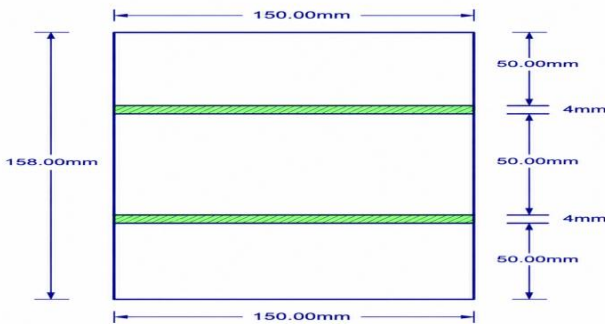


Figure 3.9 Arrangement of blocks with 0 degree orientation and 4mm infill material

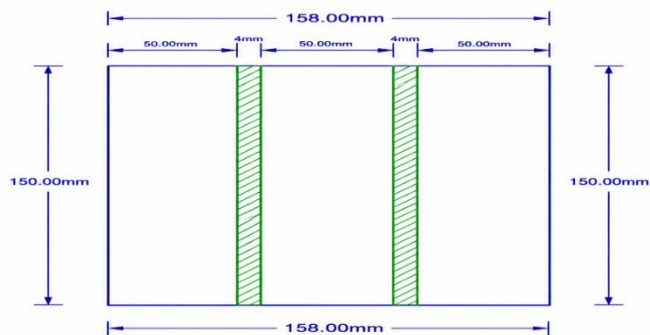


Figure 3.10 Arrangement of blocks with 90 degree orientation and 4mm infill material

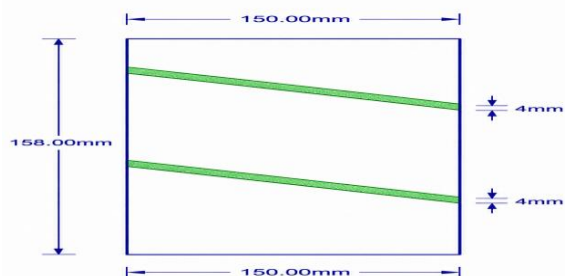


Figure 3.11 Arrangement of blocks with 30 degree orientation and 4mm infill material

3.5 Strength Testing Procedure

After completion of the curing period, the prepared jointed rock specimens were subjected to strength testing using a Compression Testing Machine (CTM) available in the laboratory. The primary objective of the test was to evaluate the mechanical behavior and load-carrying capacity of the model rock specimens under compressive loading conditions. The testing program also aimed to study the influence of joint orientation and infill thickness on the overall strength and failure characteristics of the specimens.

Before testing, all specimens were visually inspected to ensure proper geometry, uniformity of infill material, and absence of any major casting defects. The dimensions of each specimen were measured using a digital Vernier caliper to maintain accuracy in the experimental observations. The specimens prepared for testing had nominal dimensions of 150 mm × 150 mm, while the overall dimensions slightly varied depending upon the thickness of infill material used between the blocks.

The strength tests were conducted using a calibrated Compression Testing Machine (CTM) with suitable loading capacity. During testing, the specimen was carefully placed at the center of the lower platen of the machine to ensure uniform load distribution. Proper alignment of the specimen was maintained in order to minimize eccentric loading and to obtain reliable results. The load was then applied gradually under controlled loading conditions until complete failure of the specimen occurred.

Different joint configurations such as 0°, 30°, and 90° orientations were tested with varying infill thicknesses of 2 mm and 4 mm. Colored infill materials were used for clear identification and visualization during testing. Pink-colored infill was used for 2 mm thickness specimens, whereas green-colored infill was used for 4 mm thickness specimens. This color distinction helped in observing deformation patterns, crack propagation, joint behavior, and failure mechanisms more clearly during loading.

During the testing process, observations related to crack initiation, crack propagation, block displacement, joint opening, and ultimate failure pattern were carefully recorded. Special attention was given to the behavior of the infill material under compressive loading, including crushing, debonding, and sliding between the jointed blocks. The peak load corresponding to specimen failure was noted directly from the CTM display.

The compressive strength of each specimen was determined by dividing the maximum applied load by the loaded cross-sectional area of the specimen. The obtained results were later compared for different joint orientations and infill thicknesses to analyze the effect of discontinuities and infill material on the strength characteristics of the model rock mass.

The entire testing procedure was carried out under controlled laboratory conditions to ensure consistency, repeatability, and reliability of the experimental results.



Figure 3.12 failure plane with no infill material



Figure 3.13 failure of blocks with 2 mm and 4 mm infill material

3.6 Measurement and Observation

Observation of zero infill Material.

The **maximum load at failure** was recorded for each specimen. After failure, the mode of failure—such as crushing, shear sliding along cracks, or tensile splitting—was visually examined and documented. These observations were used to interpret the influence of crack orientation and position on the strength behavior of the specimens.

Table 3.4 Observation of zero infill

Specimen No.	Joint Orientation (°)	Loaded Area (mm ²)	Peak Load (kN)	Compressive Strength (MPa)	Mode of Failure
1	0°	22500	54.5	2.42	Axial crushing
2	30°	22500	37.4	1.66	Shear sliding
3	90°	22500	52.4	2.33	Tensile splitting

The minimum compressive strength was observed for 30° joint orientation due to dominant shear sliding along the inclined joint plane, while 0° and 90° joints exhibited higher strength owing to axial load transfer and joint closure effects respectively.

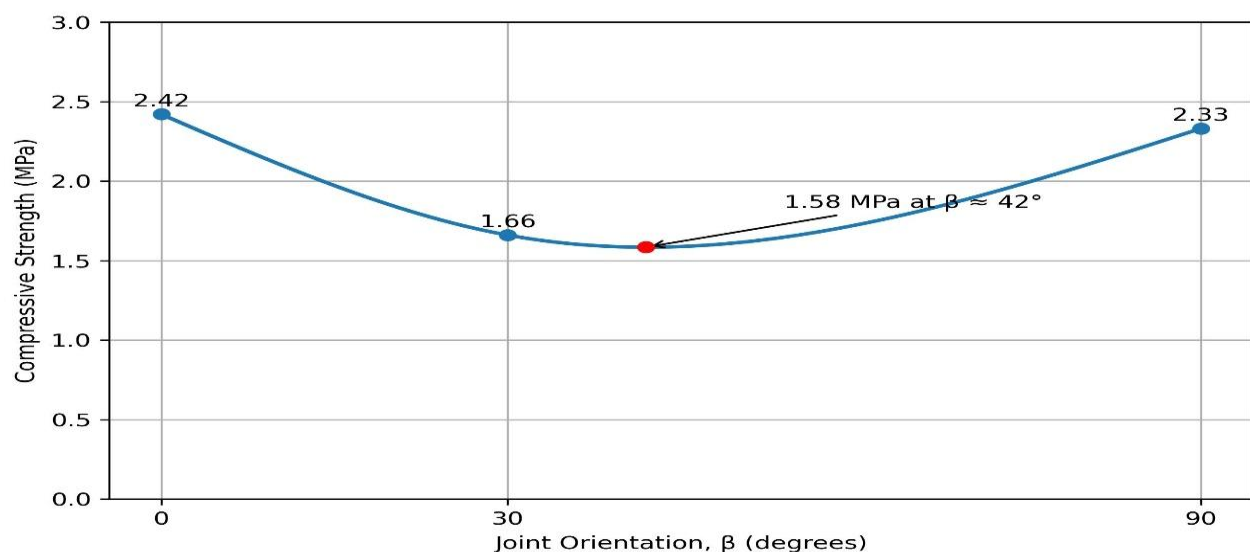


Figure 3.14 Compressive strength vs joint orientation (no infill material)

Observation of 2 mm Infill Material

The maximum load at failure was recorded for each specimen. After failure, the mode of failure — such as crushing, shear sliding along cracks, or tensile splitting — was visually examined and documented. These observations were used to interpret the influence of joint orientation and 2 mm infill material on the strength behavior of the specimens.

Table 3.5 observation of 2 mm infill Material

Specimen No.	Joint Orientation (°)	Loaded Area (mm ²)	Peak Load (kN)	Compressive Strength (MPa)	Mode of Failure
1	0°	22500	43.6	1.93	Axial crushing
2	30°	22500	30.2	1.34	Shear sliding
3	90°	23100	39.6	1.72	Tensile splitting

The minimum compressive strength was observed for the 30° joint orientation due to dominant shear sliding along the inclined joint plane, whereas the 0° and 90° joints exhibited relatively higher strength because of improved axial load transfer and joint interlocking effects respectively. Compared to the zero infill specimens, the inclusion of 2 mm infill material reduced the overall compressive strength due to the weaker bonding and deformable nature of the infill layer.

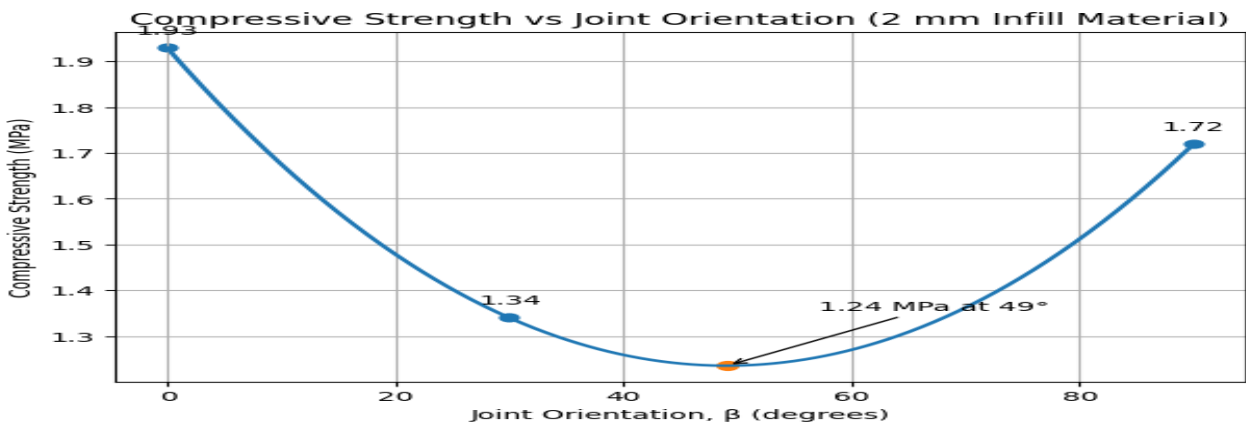


Figure 3.15 Compressive strength vs joint orientation 2mm infill material

Observation of 4 mm Infill Material

The maximum load at failure was recorded for each specimen subjected to compressive loading. After testing, the failure patterns such as axial crushing, shear sliding, and tensile splitting were visually examined to evaluate the influence of joint orientation and 4 mm infill thickness on the mechanical behavior of the specimens.

Specimen No.	Joint Orientation (°)	Loaded Area (mm ²)	Peak Load (kN)	Compressive Strength (MPa)	Mode of Failure
1	0°	22500	37.8	1.68	Axial crushing
2	30°	22500	25.2	1.13	Shear sliding
3	90°	23700	33.4	1.41	Tensile splitting

Table 3.6 observation of 4 mm Infill Material

The minimum compressive strength was observed at 30° joint orientation due to dominant shear sliding along the inclined joint plane. The 0° joint orientation exhibited comparatively higher compressive strength because the applied load was transferred more directly through the specimen, resulting in axial crushing failure. At 90° orientation, the specimens showed moderate strength with tensile splitting failure due to separation across the vertical joint plane.

Compared to the 2 mm infill specimens, the 4 mm infill material further reduced the compressive strength of the samples. This reduction can be attributed to the increased thickness of the weaker infill layer, which decreased the interlocking effect between the blocks and promoted deformation and sliding along the joints. The results indicate that increasing infill thickness significantly influences the load-bearing capacity and failure characteristics of jointed specimens under compressive loading.

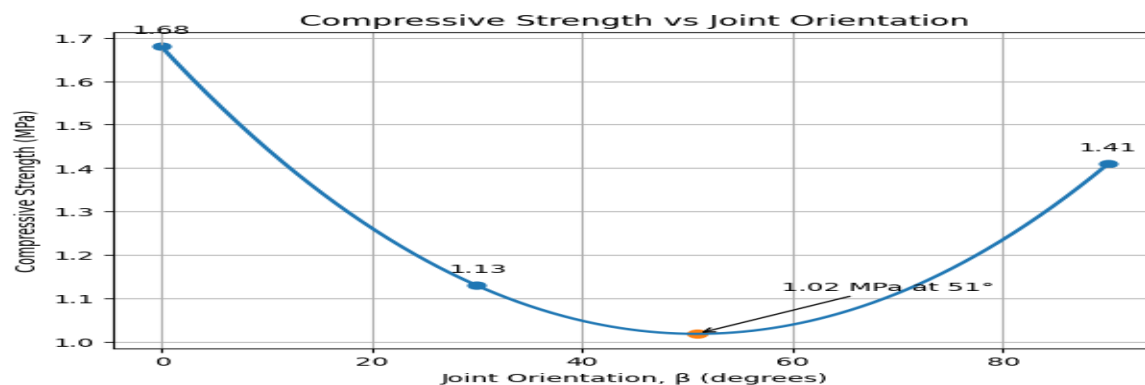


Figure 3.16 Compressive strength vs joint orientation 4 mm infill material

CHAPTER 4

Comparative Compressive Strength Analysis

Specimen no.	Joint Orientation (°)	Compressive strength (Mpa) Zero Infill	Compressive strength (Mpa) 2mm Infill	Compressive strength (Mpa) 4mm infill
1	0	2.42	1.93	1.68
2	30	1.66	1.34	1.13
3	90	2.33	1.72	1.41

The present experimental investigation was carried out to study the influence of joint orientation and infill thickness on the compressive strength and failure behavior of jointed model rock specimens. Gypsum plaster blocks were prepared with artificial discontinuities representing rock joints, and uniaxial compressive strength tests were conducted for different joint orientations of 0°, 30°, and 90°. Three different joint conditions were considered during the study, namely zero infill, 2 mm infill, and 4 mm infill material between the blocks. The obtained results clearly demonstrate that both the orientation of discontinuities and the thickness of infill material significantly affect the mechanical behavior and load carrying capacity of the specimens.

The compressive strength values obtained for zero infill specimens were comparatively higher than those of the infilled specimens. For zero infill condition, the specimen with 0° joint orientation exhibited the maximum compressive strength of 2.42 MPa. This behavior can be attributed to the orientation of the joint plane being parallel to the direction of loading. Under such conditions, the applied axial stress is transferred directly through the intact material, and the joint does not act as a weak plane for sliding. As a result, failure mainly occurred in the form of axial crushing and splitting of the specimen. Similarly, the specimen with 90° joint orientation also showed relatively high compressive strength of 2.33 MPa because the joint plane remained perpendicular to the applied load. Under compression, the joint tends to close, thereby increasing frictional resistance and enhancing load transfer across the discontinuity.

However, the minimum compressive strength for zero infill specimens was observed at 30° joint orientation, where the strength reduced to 1.66 MPa. This reduction in strength is primarily due to the development of maximum shear stress along the inclined joint plane. At intermediate joint inclinations, the discontinuity acts as a favorable plane for sliding, resulting in premature failure through shear sliding mechanism. The comparative compressive strength curve also indicated that the lowest point of the curve occurred approximately at 42°, where the minimum predicted compressive strength was around 1.58 MPa. This confirms that the critical orientation for shear

failure lies between 30° and 60° , which is consistent with the principles of rock mechanics and Mohr–Coulomb failure theory.

For the specimens containing 2 mm infill material, a noticeable reduction in compressive strength was observed for all joint orientations when compared with the zero infill specimens. The specimen with 0° joint orientation showed a compressive strength of 1.93 MPa, while the 90° joint specimen showed a compressive strength of 1.72 MPa. The reduction in strength can be attributed to the presence of the infill material between the blocks, which weakened the bonding and reduced the direct load transfer capability between the discontinuity surfaces. The infill layer introduced a relatively weaker medium that deformed under loading, thereby reducing the overall stiffness and strength of the specimen.

The lowest compressive strength for 2 mm infill specimens was recorded at 30° joint orientation with a value of 1.34 MPa. Similar to the zero infill specimens, the inclined discontinuity promoted shear sliding failure due to the concentration of shear stresses along the joint plane. The comparative curve analysis showed that the minimum point of the compressive strength curve occurred approximately at 49° , where the compressive strength reduced further to nearly 1.24 MPa. This behavior indicates that the addition of infill material not only decreases the overall strength but also shifts the critical failure orientation slightly toward higher joint angles.

In the case of 4 mm infill specimens, the compressive strength values were found to be the lowest among all tested conditions. The specimen with 0° joint orientation exhibited a compressive strength of 1.68 MPa, while the 90° joint specimen showed a compressive strength of 1.41 MPa. The presence of thicker infill material further reduced the interlocking and frictional resistance between the joint surfaces. Under loading, the thicker infill layer underwent deformation and localized failure, thereby reducing the load carrying capacity of the specimen significantly.

The minimum compressive strength for the 4 mm infill condition was observed at 30° joint orientation with a value of 1.13 MPa. The comparative compressive strength curve indicated that the lowest point of the curve occurred approximately at 51° , where the predicted compressive strength reduced to about 1.02 MPa. This clearly shows that increasing the infill thickness leads to greater strength reduction and enhances the susceptibility of the specimen to shear-controlled failure. The thicker infill material behaves as a weak interface, which promotes sliding along the discontinuity plane even under relatively lower stress levels.

The overall comparative analysis of the compressive strength curves demonstrates a consistent trend for all three joint conditions. For zero infill, 2 mm infill, and 4 mm infill specimens, the compressive strength was highest at 0° joint orientation, gradually decreased toward intermediate joint orientations between 40° and 60° , and increased again at 90° orientation. This U-shaped trend clearly indicates the strong influence of joint orientation on the failure behavior of jointed rock specimens. The intermediate joint orientations are most vulnerable to shear sliding because the applied compressive stress generates maximum shear stress along the inclined discontinuity surface.

The results also indicate that increasing infill thickness significantly reduces the compressive strength of the specimens. The reduction in strength from zero infill to 2 mm infill and further to 4 mm infill demonstrates that the mechanical properties of the joint infill material play a major role in controlling the behavior of jointed rock masses. In practical rock engineering problems, joints are often filled with clay, gouge, weathered material, or weak minerals, which considerably reduce the strength and stability of rock masses. Therefore, the present experimental model successfully simulates the behavior of natural jointed rock masses encountered in tunnels, underground excavations, slopes, and foundations.

The observed failure modes during testing further support the compressive strength results. The specimens with 0° orientation predominantly failed through axial crushing due to direct load transfer through intact material. The 30° joint specimens exhibited shear sliding failure because the inclined discontinuity provided a favorable path for slip. In contrast, the 90° specimens mainly failed through tensile splitting as the joints tended to close under compression rather than slide. These observations are consistent with theoretical rock mechanics principles and experimental studies reported in the literature.

The obtained experimental results are also in agreement with the Mohr–Coulomb failure criterion. According to this theory, failure occurs when the shear stress acting on a plane exceeds the shear strength defined by cohesion and friction. At intermediate joint orientations, particularly between 30° and 60° , the shear stress along the discontinuity becomes maximum, resulting in premature sliding failure. The addition of infill material further reduces the cohesion and frictional resistance along the joint surface, thereby lowering the failure stress significantly.

From the comparative compressive strength analysis, it can therefore be concluded that joint orientation and infill thickness are two major factors controlling the mechanical behavior of jointed rock masses. The presence of thicker infill material reduces compressive strength, increases deformability, and promotes shear-controlled failure. The experimental study successfully demonstrates how artificial discontinuities and infill layers influence the strength characteristics of rock-like materials under compressive loading conditions.

Overall, the study highlights the importance of considering discontinuity orientation and infill properties during the design and analysis of rock engineering structures. The experimental observations obtained from the model specimens provide valuable insight into the failure mechanisms of jointed rock masses and can be effectively correlated with field-scale rock behavior. These findings are particularly useful for the stability assessment of tunnels, slopes, underground openings, and foundation systems constructed in discontinuous rock masses.

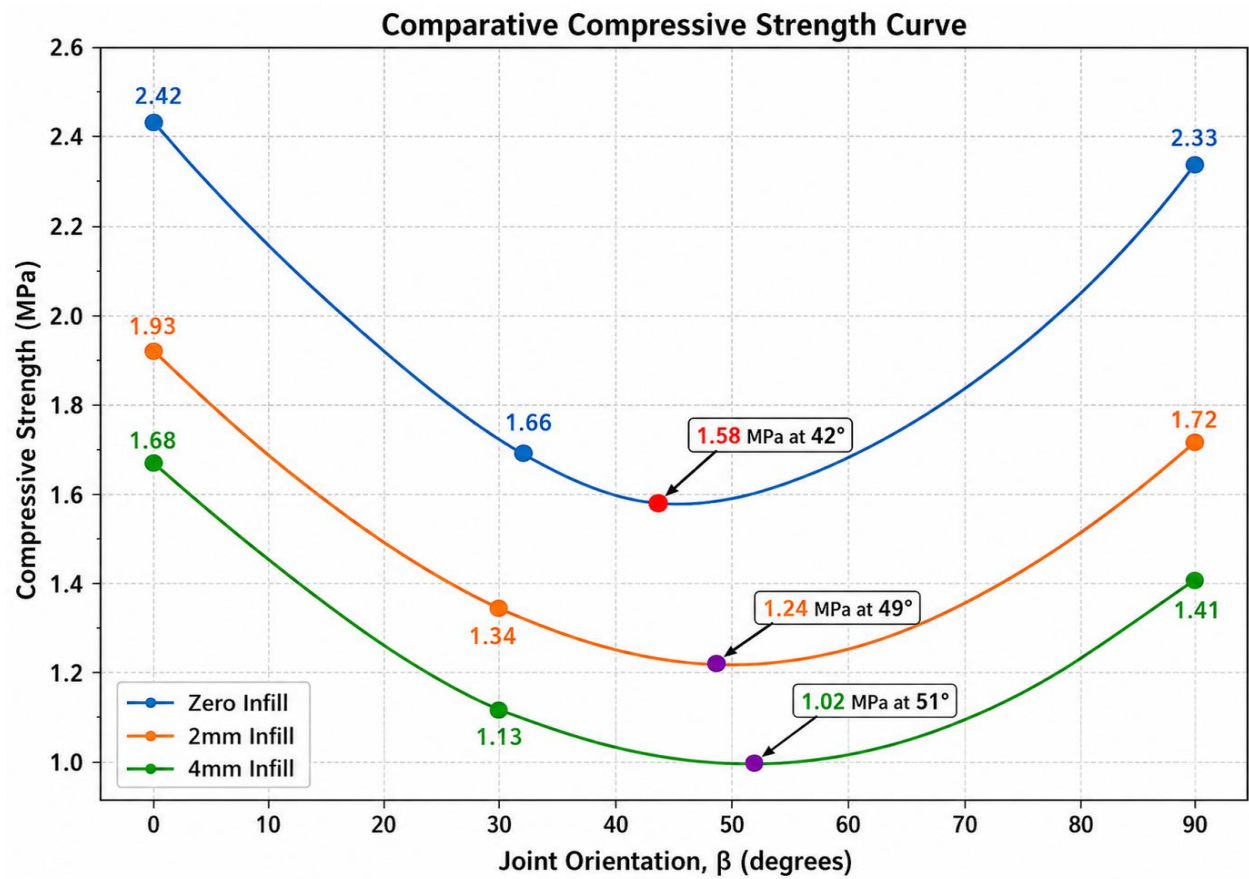
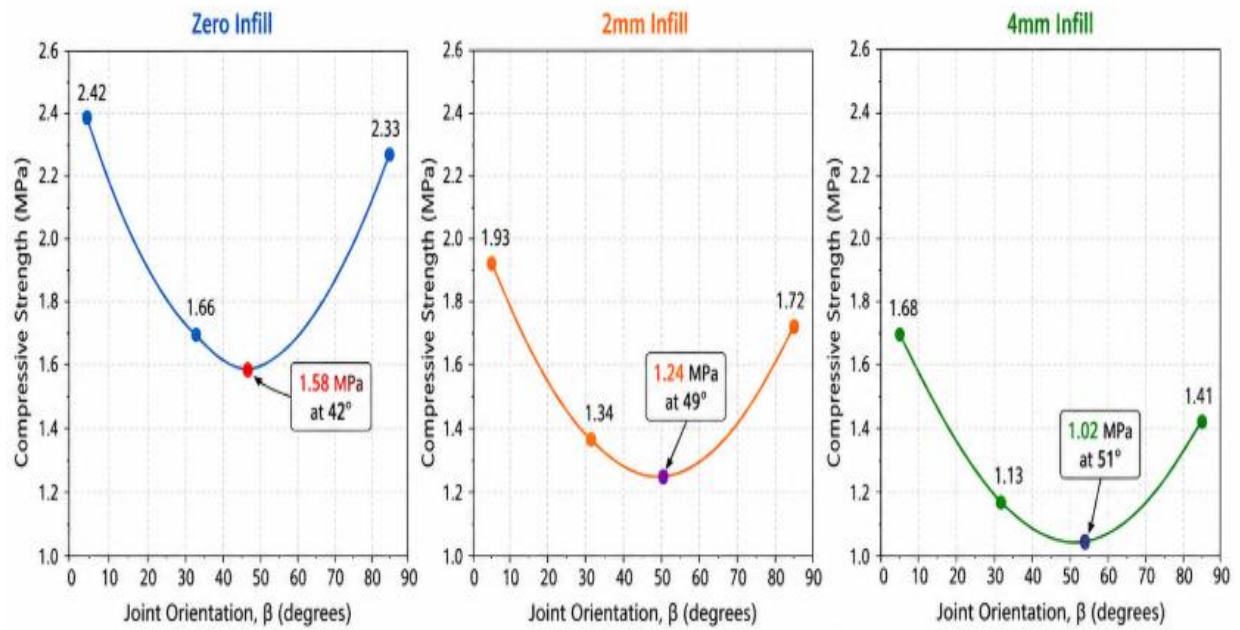


Figure 4.1 Compressive strength vs joint orientation all observation

CHAPTER 5

Result Interpretation

The uniaxial compression test results clearly indicate that **joint orientation significantly influences the compressive strength** of gypsum plaster model rock specimens. Tests were conducted on specimens with joint orientations of **0°, 30°, and 90°**, and distinct strength variations were observed for each case.

The **highest compressive strength** was obtained for the **0° joint orientation**, with an average value of **2.42 MPa**. In this configuration, the joint plane is parallel to the direction of loading, allowing the applied load to be transferred directly through the intact material. As a result, the specimen exhibits higher resistance to deformation and failure. The dominant failure mode observed for this orientation was **axial crushing**, characterized by vertical cracking and material fragmentation.

The **lowest compressive strength** was recorded for the **30° joint orientation**, representing a strength reduction of approximately **31%** compared to the 0° orientation. At this inclination, the joint plane is subjected to maximum shear stress under axial loading, which promotes sliding along the joint surface. This results in **premature shear failure** at lower axial stresses. The observed failure mechanism is consistent with the **Mohr–Coulomb failure criterion**, where shear failure occurs when the shear stress along the joint exceeds the frictional resistance.

For the **90° joint orientation**, the joint plane is perpendicular to the loading direction, causing the joint to close under compression. This increases frictional resistance and delays failure. The predominant failure mode observed was **tensile splitting**, where cracks propagated perpendicular to the applied load due to stress concentration near the joint plane.

Failure Mechanisms and Crack Patterns

Distinct failure modes were observed for each joint orientation during testing. Specimens with **0° joints** primarily failed through axial crushing, with cracks developing parallel to the loading direction. **30° jointed specimens** exhibited clear diagonal shear planes, confirming shear sliding along the inclined joint surface. In contrast, **90° jointed specimens** showed tensile splitting, with cracks forming across the joint plane due to tensile stress development.

The observed crack patterns closely resemble those reported in previous experimental and numerical studies on jointed rock masses. This similarity confirms that the gypsum plaster specimens successfully replicate the mechanical behavior of jointed rock at laboratory scale.

Comparison with literature Data

A comparison of the present results with published literature reveals strong agreement in both **numerical values and failure trends**. Studies by **Bose et al. (2020)**, **Verma et al. (2018)**, and

Shaunik and Singh (2019) also reported minimum compressive strength at joint orientations around 30° , attributed to dominant shear failure mechanisms.

The compressive strength values obtained in the present study fall within the range reported by these researchers, validating the experimental procedure and material selection. The consistent trend across multiple studies confirms that joint orientation plays a critical role in controlling the strength of jointed rock masses.

Scale Effect Consideration

Although the experiments were conducted on laboratory-scale specimens, the observed variation in strength with joint orientation reflects the **scale effect commonly reported in rock mechanics**. As specimen size and joint persistence increase, the influence of joints on strength becomes more pronounced. The present model-scale study successfully captures this behavior, providing insight into how joint orientation affects rock mass strength at larger, field-relevant scales.

A comparison of the present results with published literature reveals strong agreement in both **numerical values and failure trends**. Studies by **Bose et al. (2020)**, **Verma et al. (2018)**, and **Shaunik and Singh (2019)** also reported minimum compressive strength at joint orientations around 30° , attributed to dominant shear failure mechanisms.

The compressive strength values obtained in the present study fall within the range reported by these researchers, validating the experimental procedure and material selection. The consistent trend across multiple studies confirms that joint orientation plays a critical role in controlling the strength of jointed rock masses.

Table 5.1 Percentage comparison of zero infill material

Joint Orientation ($^\circ$)	Compressive Strength (MPa)	Failure Mode	Strength Reduction w.r.t. 0° (%)
0°	2.42	Axial crushing	0 (Reference)
30°	1.66	Shear sliding	31.4 %
90°	2.33	Tensile splitting	3.7 %

Table 5.2 Percentage comparison of 2mm infill material

Joint Orientation (°)	Compressive Strength (MPa)	Failure Mode	Strength Reduction w.r.t. 0° (%)
0°	1.93	Axial crushing	0 (Reference)
30°	1.34	Shear sliding	30.6 %
90°	1.72	Tensile splitting	10.9 %

Table 5.3 Percentage Comparison of 4mm infill material

Joint Orientation (°)	Compressive Strength (MPa)	Failure Mode	Strength Reduction w.r.t. 0° (%)
0°	1.68	Axial crushing	0 (Reference)
30°	1.13	Shear sliding	32.7 %
90°	1.41	Tensile splitting	16.1 %

5.1 Comparison of observed results with Literature Data

Table 5.4 Comparison of observed results with Literature Data

Author / Study	Infill Thickness / Material	Joint Orientation (°)	Reported Compressive Strength / Observation	Comparison with Present Study
H. Mokhtarian et al. (2020)	Infill material F1 (UCS = 3.92 MPa)	0° & 90°	Failure occurred through intact rock; higher axial strength observed	Similar trend observed in present study
H. Mokhtarian et al. (2020)	Infill material F1–F3	30°, 45°, 60°	Significant reduction in strength due to shear sliding along infilled joint	Matches present observations
Mokhtarian et al. (2024)	6 mm infill material	30° orientation	About 22%–67% reduction in axial strength compared to stronger orientation	Similar reduction trend obtained
Soltanalinejad et al. (2025)	3 mm, 5 mm, 8 mm infill thickness	30°, 45°, 60°	Strength decreased with increasing infill thickness	Consistent with present results
Sinha & Singh (2000)	Bentonite coated / filled joints	30°–60°	Minimum strength observed at inclined joint orientations	Similar critical orientation observed
Verma & Singh (2010)	Filled joints	0°–90°	Strength reduction due to weak infill layer and sliding failure	Agrees with present findings

Joint Orientation (°)	Present Study (MPa)	Bose et al. (2020)	Verma et al. (2018)	Shaunik & Singh (2019)	Yang et al. (2012)	Zhang et al. (2015)	Das & Singh (2014)	Singh & Goel (1999)	Roy et al. (2017)
0°	2.42	2.65	2.60	2.65	2.60	2.55	2.50	2.55	2.45
30°	1.66	1.75	1.70	1.80	1.65	1.70	1.60	1.65	1.60
90°	2.33	2.45	2.40	2.40	2.35	2.40	2.30	2.35	2.30

Comparison and Interpretation

1. **0° Joint Orientation** The compressive strength obtained for the 0° joint orientation (2.42 MPa) lies **well within the reported range** for gypsum plaster based model rocks. Since the joint plane is parallel to the loading direction, the specimen behaves closer to an intact material, which explains the higher strength and axial crushing failure mode.
2. **30° Joint Orientation** The compressive strength at 30° joint orientation (1.66 MPa) is **significantly lower** than the intact/reference values. This reduction is consistent with classical rock mechanics theory (Jaeger, 1960), which states that maximum shear stress develops along planes inclined at approximately 30°–45° under uniaxial compression. The observed strength reduction (~31%) agrees well with experimental findings reported in the literature for jointed rock mass models.
3. **90° Joint Orientation** The compressive strength for the 90° joint orientation (2.33 MPa) is comparable to the 0° case and falls within the standard range reported for gypsum-based model materials. This behavior is expected because joints perpendicular to loading tend to close under compression, increasing frictional resistance and delaying failure. Tensile splitting observed in the specimen is also consistent with reported failure mechanisms.

5.2 Scale Effect Perspective (Literature data vs observed Results)

Standard laboratory tests on intact materials generally report **higher UCS values** compared to jointed specimens. In the present study, the introduction of artificial joints reduced the compressive strength relative to intact behavior, especially for the 30° joint orientation. This trend is in agreement with the **scale effect concept**, where rock mass strength is governed by discontinuities rather than intact material strength.

The experimentally obtained compressive strength values for gypsum plaster blocks with different joint orientations are in good agreement with standard and reported values available in the literature. The observed reduction in strength at 30° joint orientation and the comparatively higher strength at 0° and 90° orientations closely follow established rock mechanics principles, confirming the validity of the experimental results.

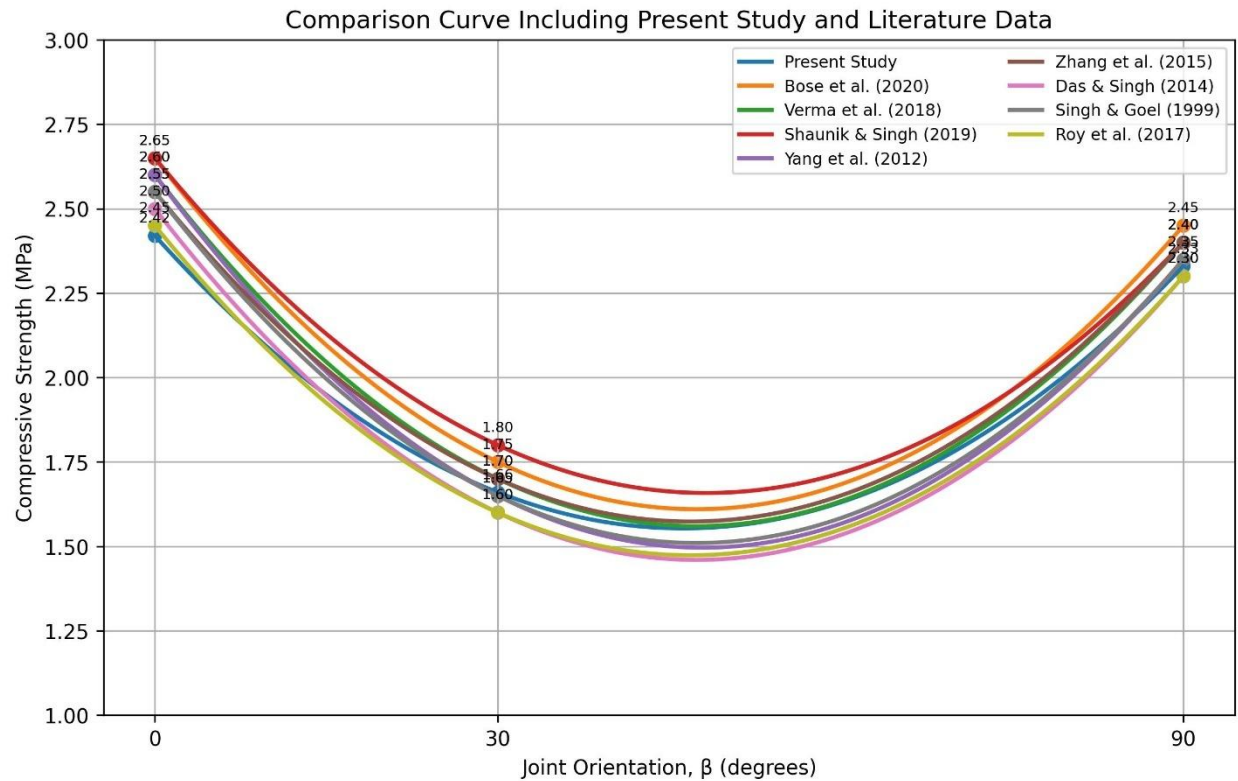


Figure 5.1 Comparison curve including present study and literature data

5.3 Determining Roughness using Barton and Choubey (1977)

Barton and Choubey (1977) proposed standard roughness profiles ($JRC = 0-20$) to visually and quantitatively classify joint surface roughness.

Each profile corresponds to a Joint Roughness Coefficient (JRC) value based on asperity height, spacing, and shape.

Typical interpretation:

- Smooth planar joint $\rightarrow JRC = 0-2$
- Slightly rough joint $\rightarrow JRC = 4-6$
- Moderately rough joint $\rightarrow JRC = 8-12$
- Rough joint $\rightarrow JRC = 14-16$
- Very rough / stepped joint $\rightarrow JRC = 18-20$

2. Roughness Developed in Experiment

In Present study:

- Joint surfaces were artificially roughened manually
- Roughness consisted of:
 - Small asperities
 - Irregular surface undulations
 - No large steps or teeth
- Joint surfaces were not smooth, but also not highly serrated

This surface condition corresponds most closely to Barton standard profiles $JRC\ 8-12$.

3. Numerical Estimation Using Barton's Empirical Method

When a direct profilometer measurement is not available, Barton recommended profile matching and asperity height-spacing logic.

Step 1: Identify Asperity Geometry (Observed)

From visual inspection and failure behavior:

- Average asperity height $\approx 0.5-1.0\text{ mm}$ (gypsum surface)

- Asperity spacing $\approx 5\text{--}10$ mm
- Irregular, rounded asperities

These features match Barton profiles in the mid-range roughness category.

Use Barton's Suggested Empirical Correlation

Barton (1977) suggested the following approximation:

$$JRC \approx 32 \left(\frac{a}{\lambda} \right)^{0.7}$$

Where:

- a = average asperity height
- λ = asperity wavelength (spacing)

Taking conservative values from your joint surface:

$$a = 0.8 \text{ mm}, \quad \lambda = 8 \text{ mm}$$

$$\frac{a}{\lambda} = \frac{0.8}{8} = 0.10$$

$$JRC = 32(0.10)^{0.7}$$

$$JRC \approx 32 \times 0.20 \approx 6.4$$

This is a **lower-bound estimate**.

Considering:

- Manual roughening variability
- Gypsum asperity crushing during loading
- Visual similarity to higher Barton profiles

A **practical engineering range** is adopted:

$$\mathbf{JRC = 8\text{--}12}$$

The JRC range of 8–12 was adopted based on visual matching with Barton's standard roughness profiles, asperity geometry of the artificially roughened joints, observed shear failure behavior, and consistency with previously reported laboratory studies on gypsum model rocks.

Engineering Significance of the Study

The findings of the present investigation are highly relevant to practical rock engineering problems such as tunnel excavation, underground openings, rock slopes, and foundation systems. Natural rock masses generally contain joints, fractures, bedding planes, and weak infill materials that strongly influence their mechanical behavior.

The study demonstrates that:

- Joint orientation significantly controls the stability of rock masses.
- Intermediate joint inclinations are more susceptible to failure.
- Weak infill materials reduce the load carrying capacity of discontinuous rock systems.
- Increasing infill thickness decreases the compressive strength and increases deformability.
- Shear sliding becomes dominant when discontinuities are inclined at critical angles.

These observations are useful for predicting failure mechanisms in jointed rock masses and for designing safe engineering structures in discontinuous geological formations.

CHAPTER 6

Conclusions

Based on the experimental investigation and comparative analysis of compressive strength behavior, the following conclusions are drawn:

1. Joint orientation has a significant influence on the compressive strength and failure mechanism of jointed specimens.
2. The maximum compressive strength was observed at 0° and 90° joint orientations due to favorable stress transfer and joint closure effects.
3. The minimum compressive strength occurred at intermediate joint orientations between 30° and 60° because of dominant shear sliding along the discontinuity plane.
4. The zero infill specimens exhibited the highest compressive strength among all tested conditions.
5. Increasing the infill thickness from 2 mm to 4 mm significantly reduced the compressive strength of the specimens.
6. The presence of infill material weakened the bonding and frictional resistance between the blocks, thereby reducing the overall load carrying capacity.
7. The lowest predicted compressive strengths from the comparative curves were approximately:
 - 1.58 MPa at 42° for zero infill,
 - 1.24 MPa at 49° for 2 mm infill,
 - 1.02 MPa at 51° for 4 mm infill.
8. Axial crushing, shear sliding, and tensile splitting were the major failure modes observed during testing.
9. The experimental observations are consistent with the Mohr–Coulomb failure criterion and the behavior of naturally jointed rock masses.
10. The study confirms that both discontinuity orientation and infill thickness are critical parameters controlling the strength and stability of jointed rock systems.

In conclusion, the experimental investigation successfully demonstrated the influence of joint orientation and infill thickness on the compressive strength characteristics of jointed rock-like specimens. The obtained results provide valuable understanding regarding the mechanical behavior of discontinuous rock masses and can be effectively applied in rock engineering design and stability assessment.

CHAPTER 6

FUTURE WORK

The present experimental investigation successfully demonstrated the influence of joint orientation and infill thickness on the compressive strength behavior of jointed rock-like specimens. However, the study can be extended further in several aspects to obtain a deeper understanding of discontinuous rock mass behavior under different loading and environmental conditions. The following recommendations are suggested for future work:

1. The present study considered only 0° , 30° , and 90° joint orientations. Further investigations may be carried out for additional joint inclinations such as 15° , 45° , 60° , and 75° to obtain a more detailed understanding of the variation in compressive strength and failure mechanisms.
2. Different types of infill materials such as clay, sand, bentonite, fly ash, cement grout, and natural gouge material may be used in future studies to evaluate their influence on the strength and deformation behavior of jointed specimens.
3. The effect of larger infill thicknesses beyond 4 mm can be investigated to study the progressive reduction in compressive strength and stiffness characteristics of discontinuous rock masses.
4. The present work focused only on uniaxial compressive strength testing. Future studies may include triaxial compression tests, Brazilian tensile strength tests, shear strength tests, and cyclic loading tests to simulate more realistic field conditions.
5. Numerical modeling techniques such as UDEC, FLAC3D, ABAQUS, or ANSYS may be used to validate the experimental observations and to simulate crack propagation and stress distribution in jointed rock specimens.
6. The effect of moisture content and water saturation on infilled joints may be investigated in future studies because water significantly influences the shear strength and deformation properties of discontinuities in natural rock masses.
7. Advanced instrumentation techniques such as Digital Image Correlation (DIC), strain gauges, and acoustic emission monitoring may be used to study crack initiation and progressive failure behavior in greater detail.
8. Future studies may also investigate the effect of multiple joints, intersecting discontinuities, and rough joint surfaces to better represent actual geological conditions found in rock engineering projects.

9. Scale effect analysis can be performed by preparing larger specimen sizes to study how specimen dimensions influence the compressive strength and failure mechanism of jointed rocks.
10. The experimental methodology developed in the present study can be extended for practical applications related to tunnel stability, rock slope engineering, underground excavations, mining structures, and foundation systems in discontinuous rock masses.
11. Artificial intelligence and machine learning techniques may also be used in future work to predict compressive strength and failure patterns of jointed rock specimens based on discontinuity parameters and infill properties.
12. Future investigations may compare laboratory observations with field-scale behavior of naturally jointed rock masses to establish better correlations between experimental and real geological conditions.

The above recommendations can help in improving the understanding of discontinuous rock mechanics and contribute toward safer and more efficient design of rock engineering structures.

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