Comparison of Uniaxial Compressive Strength Between Experimental Testing and Finite Element Method (FEM) Simulation

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Abstract

This study focuses on comparing the Uniaxial Compressive Strength (UCS) of rock between laboratory experimental testing and Finite Element Method (FEM) simulation to understand the relationship between experimental results and simulation outcomes. UCS tests were conducted on controlled rock samples, measuring compressive strength under defined loading conditions. Simultaneously, FEM simulations were implemented to analyze the behavior of the rock under similar conditions. The research findings suggest a reasonable level of agreement between the experimental results and the simulation outputs, indicating that FEM has potential in approximating UCS values under controlled conditions. This highlights the potential of using FEM as a supplementary tool for studying and analyzing the properties of rock materials accurately and reliably.

Keywords: Uniaxial Compressive Strength (UCS), Finite Element Method (FEM), rock mechanics, laboratory testing, simulation, predictive analysis.

1. Introduction

Rock mechanics plays a fundamental role in geotechnical, civil, and mining engineering, as understanding rock behavior is crucial for the design and construction of structures such as tunnels, slopes, and foundations. One of the key parameters in rock mechanics is Uniaxial Compressive Strength (UCS), which represents the maximum axial stress a rock can withstand before failure. Accurately determining UCS is essential for evaluating rock stability and ensuring the safety and efficiency of engineering projects.

Traditionally, UCS is determined through standardized laboratory tests, following guidelines set by organizations such as ASTM and ISRM. These tests provide reliable engineering data but also have certain limitations, including high costs, time-consuming procedures, and the need for high-quality rock samples. As a result, alternative methods for UCS estimation have gained interest, particularly numerical modeling approaches such as the Finite Element Method (FEM).

This study examines the limitations of conventional UCS testing and explores the potential of FEM simulations as an alternative approach. By comparing experimental UCS results with FEM predictions, this research aims to assess the accuracy and applicability of FEM in rock strength estimation. The findings will contribute to improving the reliability of UCS determination.

2. Methodology

2.1 Test methods for predicting UCS of rocks

The first series of UCS were conducted according to the ASTM D7012-04 (2004) standard [1]. This standard requires that test specimens have a cylindrical shape with a length-to-diameter ratio (L_0/D) between 2 and 2.5 millimeters (mm.). Additionally, the specimen diameter must be greater than ten times the maximum grain size. Table 1.

Table 1 Dimension of the specimens the ASTM standard

Specimen	Length, L_0 (mm.)	Diameter, D (mm.)	L_0/D (mm.)
S1	112	45	2.48
S2	112	45	2.48
S3	112	45	2.48
S4	112	45	2.48
S5	112	45	2.48
S6	112	45	2.48

Andesite is an intermediate rock type characterized by its dense, fine-grained to medium-grained texture, with a color ranging from grayish green to dark gray. Based on tests conducted on volcanic rocks, 24 block samples were collected from the study area, comprising four basalt samples, six tuff samples, and fourteen andesite samples. The unit weight of the samples ranged from 18.28 to 25.13 kN/m³, while their UCS values varied between 38.48 and 112.7 MPa. Additionally, the elastic modulus values fluctuated between 7.79 and 18.25 GPa. [2]

2.2 Finite Element Method simulations

Finite Element Method (FEM) is one of the most widely used numerical techniques in both research and industrial applications. It is particularly effective in solving solid mechanical problems within a continuum domain, making it a powerful tool for analyzing stress and deformation behavior in materials. In this study, FEM was not intended to replace laboratory testing but rather to provide a supplementary perspective that helps in understanding the mechanical response of rock specimens under uniaxial loading. The simulation aims to replicate experimental conditions to evaluate how closely FEM predictions align with actual test results. [3],[4]

In this study, FEM was used to model cylindrical rock specimens with a diameter of 45 mm. and a height of 112 mm., following the ASTM standard for UCS testing. The RS2 v8.0 software (Rocscience Inc., 2020b) was employed to conduct simulations. The model utilized six-node uniform triangular elements, with a total of 500 elements in the mesh.

The Mohr-Coulomb failure criterion with an elastic material model was used. Therefore, FEM is utilized in this context to explore its potential as a supportive analytical method that can complement laboratory testing in UCS evaluation, especially in preliminary studies or in cases where physical testing is limited.

3. Results

This study employs both experimental testing and numerical simulation to evaluate the UCS of rock specimens. The methodology is divided into two main parts: (1) ASTM standards to obtain UCS values from laboratory experiments and (2) FEM simulations to model and analyze the stress-strain behavior of the rock specimens. The comparison between experimental and FEM results aims to assess the accuracy and applicability of numerical modeling for UCS estimation.

3.1 Field tests of the Uniaxial compressive strength

The UCS tests were conducted on six rock samples in accordance with ASTM standards. Each cylindrical specimen had a diameter of 45 mm. and a height of 112 mm. Fig. 1 The samples were subjected to uniaxial loading until failure, with the stress-strain response continuously recorded. The peak stress (σ_c) at failure was taken as the UCS value.

The tests were performed using a Universal Testing Machine (UTM) under a controlled loading rate, ensuring precise measurement of the rock's mechanical properties.[5] This standardized procedure allows for an accurate evaluation of the UCS, providing essential data for further numerical analysis.

The UCS is calculated according to Equation (1)

$$UCS=\frac{P_{peak}}{A} \quad (1)$$

Where:

UCS = Uniaxial Compressive Strength (MPa.)

P_{peak} = Maximum applied load at failure (N)

A = Cross-sectional area of the cylindrical specimen (mm^2)

(a) (b)

Fig 1. (a) Field tests of the UCS at ASTM D7012-04 (2004) standard. (b) Specimen failure during the UCS test.

3.2 Finite Element Model (FEM) Analysis

The analysis focused on determining the major principal stress (σ_1) and vertical displacement of rock specimens under uniaxial loading. To evaluate the rock's deformation and failure behavior, a 2D axisymmetric finite element model was developed in RS2 v8.0 (Rocscience Inc., 2020b), conforming to ASTM test dimensions (diameter = 45 mm, height = 112 mm). The mesh used six-node uniform triangular elements with a total of 500 elements and an average mesh size of approximately 5 mm, as shown in Fig. 2.

The model assumes the rock behaves as a homogeneous isotropic elastic material, governed by the Mohr-Coulomb failure criterion. Table 2. Properties used as material inputs for FEM modelled platens lists the material parameters used in the FEM analysis. However, parameters for the Mohr-Coulomb model, including cohesion (c) and internal friction angle (ϕ), were not presented in the original manuscript. These are essential and have now been added in the table below.[7]

Table 2. Properties used as material inputs for FEM modelled platens [8]

Parameter	Value
Unit weight	22.53 kN/m^3
Young's modulus	13.62 Gpa
Poisson's ratio	0.2 v

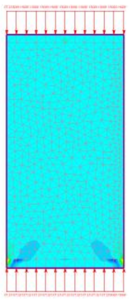

Fig 2. General 2D FEM model

3.3 Comparison Between ASTM and FEM

This section examines the limitations of conventional UCS testing and evaluates the potential of FEM simulations as an alternative approach. By comparing experimental UCS results obtained following ASTM standards with FEM predictions, this study aims to assess the accuracy and applicability of FEM in rock strength estimation.

The comparison focuses on the relationship between UCS (MPa) and displacement (mm.) using a 2D FEM model, with particular emphasis on peak UCS values.

3.3.1 Identifying the Peak UCS Points

In this study, the relationship between displacement and uniaxial compressive strength (UCS) at peak points was investigated, rather than the full stress-strain behavior throughout the loading process. The comparison focuses on the relationship between UCS (MPa) and displacement (mm.) using a 2D FEM model, with particular emphasis on peak UCS values.

The peak UCS values for both ASTM and FEM simulations occur at an approximate displacement of 0.000725 mm.

The FEM model (represented by a red line with red circles) exhibits a slightly higher peak UCS compared to the ASTM experimental results (represented by a black line with black squares).

This difference suggests that while FEM simulations closely follow the experimental trend, some discrepancies exist in the predicted strength values.

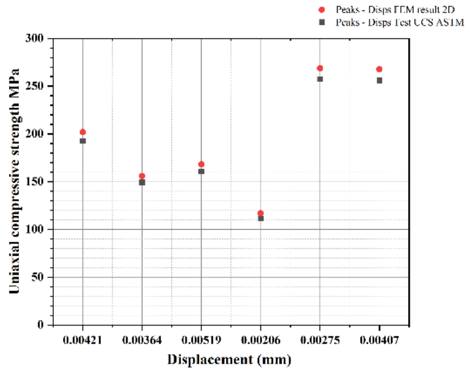

Fig 3. Relationship between displacement and UCS (peak points only) obtained from experimental test and FEM simulation. Full stress-strain curves were not considered in this comparison.

3.3.2 Clarification on Peak Stress Discrepancy

Although the same set of material parameters was applied in all simulations, differences in predicted peak UCS values compared to lab results are observed due to:

Idealized material modeling: FEM assumes uniform, defect-free rock, whereas actual specimens may contain heterogeneity, pores, or microfractures.

Simplified boundary conditions: Physical test setups introduce friction and stress concentration at platen-specimen interfaces, while simulations assume uniform load.

Mesh resolution: While 500 elements were used with ~5 mm mesh size, local stress concentrations and element distortions could subtly affect results.

Absence of nonlinear behavior: FEM does not simulate crack initiation or propagation, which influences stress redistribution in real specimens.

3.3.3 Accuracy of FEM in UCS Simulation

Despite the slight deviation in peak UCS values, the overall trend observed in FEM simulations is consistent with ASTM test results. This indicates that FEM is an effective tool for predicting the mechanical behavior of materials under uniaxial compression. To further improve the accuracy of FEM predictions, additional refinements could include:

Implementing Fracture Mechanics: Simulating crack initiation and propagation can provide a more realistic representation of material behavior under stress.

Enhancing Boundary Conditions Improving the representation of experimental setups in simulations, such as accounting for frictional contact conditions between specimens and plates, can lead to more accurate results.

4. Conclusions

This study compared the Uniaxial Compressive Strength (UCS) of rock specimens obtained through laboratory experiments and Finite Element Method (FEM) simulations.

The results showed that FEM simulations closely followed the experimental UCS values, though FEM tended to predict slightly higher strength values.

4.1 Correlation Between UCS and FEM Predictions

FEM simulation results showed a stress-strain trend similar to that of the laboratory experiments. However, the predicted UCS from FEM was slightly higher. This can be attributed to the idealized nature of the FEM model, which assumes homogeneity and linear elastic behavior until failure.

4.2 Discrepancies in Peak Deformation Values

The deformation at peak stress from FEM was approximately 0.000725 mm, which is significantly lower than the deformation observed during experimental testing. This underestimation reflects the limitations of elastic-only models that do not simulate progressive damage or nonlinear behavior prior to failure.

4.3 Clarification on Peak UCS Differences Using Same Parameters

Although identical material parameters were used, differences in predicted peak stress values occurred due to modeling assumptions, absence of microcracking mechanisms, boundary friction, and mesh-induced stress concentrations.

4.4 Potential for FEM Improvement:

Enhancing FEM models by incorporating fracture mechanics, nonlinear material behavior, and refined contact boundary conditions could significantly improve the predictive accuracy of UCS values and deformation characteristics.

4.5 Overall Implications

FEM proves to be a reliable supplementary method for understanding stress distribution and estimating UCS when experimental testing is limited or impractical. However, care must be taken in interpreting FEM outputs, particularly in relation to deformation and failure mechanisms, which require further model sophistication to mirror real-world rock behavior.

While the comparison focuses on peak strength values, future work could include full stress-strain curves to better capture post-peak behavior and material ductility.

Acknowledgement

This work was supported the rock materials by Right Tunnelling Public Company Limited.

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