Measurement of Modulus of Rupture (MoR) of Some Locally Available Tile Samples in Nigeria using a Developed MoR Testing Machine

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ABSTRACT

Measurement of modulus of rupture (MoR) of brittle materials is one of the important tasks that must be carried out on the materials in order to predict their likelihood to fail under an applied load or force. Accurate determination of this property requires reliable and well-calibrated testing machines. Meanwhile, the machines with which MoR of materials can be measured are not readily available in our institutions and research laboratories in Nigeria. This paper therefore presents the design, construction, calibration, and performance evaluation of a Modulus of Rupture (MOR) testing machine intended to be used for measuring the flexural strength of some tile samples available locally in Nigeria. The developed machine comprises of sturdy metallic framework, arduino board (Atmega 328), a motorized loading system incorporated with standard load cell, load cell amplifier, dc motor, dc motor controlling unit, IR sensor, a 20x4 I2C liquid crystal display (LCD), switches, veroboard, connecting wires and automatic data acquisition unit. The constructed machine was tested, calibrated and used to measure the modulus of rupture of six different samples of tiles. Calibration results demonstrated excellent measurement accuracy, with a maximum percentage error of only ±0.20%**,** indicating that the load cell and force measurement system provide reliable and precise load measurements over the operating range of 500N. The measured modulus of rupture of the tile samples ranges from 32.13 MPa to 44.93 MPa for 3-point bending test method and 22.55 MPa to 29.00 for 4-point bending test method. The results of the measurements using 3-point bending test method are higher than those obtained using 4-point bending test method. The differences agree with the literatures on the relationship between the two methods. The successful construction of the modulus of rupture machine provides an affordable alternative for educational institutions and small-scale laboratories, facilitating effective material strength testing and research applications.

Keywords: modulus, rupture, strength, machine, calibration, bending, tiles.

INTRODUCTION

Historically, the determination of the modulus of rupture (MoR) relied on relatively simple manual bending experiments in which specimens were gradually loaded until fracture occurred. Although these early methods provided a basic understanding of the flexural behaviour of materials, they were limited by low measurement accuracy and poor repeatability. Advances in material testing technology have led to the adoption of standardized flexural testing procedures, particularly the three-point and four-point bending tests specified by international standards. In the three-point bending (3PB) test, the test specimen is supported at two ends while a concentrated load is applied at the midpoint. Four-point bending (4PB) test involves applying two equal loads between the supports, creating a constant bending moment over a larger portion of the specimen. The maximum

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load sustained before failure is subsequently used to calculate the modulus of rupture of the material (Mindess, Young, & Darwin, 2003; ASTM International, 2018).

Recent developments in materials testing have significantly improved the precision and reliability of flexural strength measurements. Modern testing systems are now equipped with digital load cells, displacement transducers, optical extensometers, computerized data acquisition systems, and automated control software that enable continuous monitoring of specimen deformation and failure behaviour. These technologies reduce measurement uncertainties, improve repeatability, and facilitate accurate characterization of material properties for engineering applications (Callister & Rethwisch, 2020; Hinge, Johnson, & Henriksen, 2021). Such innovations have expanded the application of modulus of rupture testing in both research laboratories and industrial quality control.

The modulus of rupture (MoR), commonly referred to as flexural strength, is defined as the maximum stress a material can withstand under bending before fracture occurs. It is one of the most important mechanical properties used to evaluate the structural integrity and service performance of engineering materials subjected to flexural loading. Usually expressed in megapascals (MPa) or pounds per square inch (psi), the modulus of rupture provides valuable information regarding the load-carrying capacity, durability, and safety of structural components (ASTM International, 2018; Callister & Rethwisch, 2020). In contemporary engineering practice, where structural safety, reliability, and sustainability are of paramount importance, accurate determination of the modulus of rupture has become indispensable for material selection, design optimization, and structural performance evaluation.

The modulus of rupture has extensive applications across civil engineering, mechanical engineering, materials science, wood technology, and ceramic engineering. It is particularly important for brittle materials such as concrete, ceramics, bricks, glass, tiles, and composite materials, which exhibit relatively low tensile strength and fail suddenly under bending loads. Since these materials are widely used in construction and manufacturing, determining their flexural strength is essential for predicting structural behaviour and preventing premature failure (Neville, 2011; Lupercio et al., 2021). Recent studies have also demonstrated the importance of flexural strength evaluation in advanced engineering ceramics and additively manufactured materials, where MoR serves as a critical quality indicator for structural applications (Zandinejad et al., 2022; Hajjaj et al., 2024; Zenthöfer et al., 2024).

Although closely related to tensile and compressive strengths, the modulus of rupture specifically measures a material's resistance to bending stresses. Tensile strength quantifies resistance to axial pulling forces, whereas compressive strength evaluates resistance to crushing loads. In contrast, the modulus of rupture accounts for the combined tensile and compressive stresses generated during flexural loading, thereby providing a more realistic assessment of the behaviour of beams, slabs, panels, and other structural members subjected primarily to bending moments (Gere & Goodno, 2018). Consequently, the modulus of rupture is frequently adopted as a design parameter in structural engineering and materials development.

Several factors influence the modulus of rupture of engineering materials. These include material composition, density, moisture content, curing conditions, loading rate, temperature, specimen dimensions, fibre orientation in composite materials, and manufacturing defects such as cracks, voids, inclusions, and inconsistent density distribution. Environmental exposure and ageing may also alter the microstructure of materials, thereby affecting their flexural performance. Consequently, standardized testing procedures and properly calibrated testing equipment are required to obtain reliable and reproducible results (ASTM International, 2018; Callister & Rethwisch, 2020).

Despite the importance of modulus of rupture testing, commercially available testing machines remain expensive, sophisticated, and highly dependent on periodic calibration and specialized maintenance. These

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

challenges are particularly pronounced in many developing countries, including Nigeria, where inadequate research funding, foreign exchange constraints, and restrictive importation policies have limited access to modern materials testing equipment. Furthermore, many existing testing machines in tertiary institutions and research laboratories have exceeded their service life and frequently suffer mechanical failures due to inadequate maintenance and the scarcity of proprietary replacement components. These constraints considerably hinder teaching, research, quality assurance, and the development of innovative construction materials.

The increasing demand for sustainable construction materials and locally sourced engineering products has further highlighted the need for affordable and accessible testing facilities. Researchers involved in developing improved building materials require reliable equipment for determining mechanical properties such as flexural strength before recommending such materials for structural applications. Recognizing this challenge, several researchers have advocated the development of low-cost indigenous testing systems capable of delivering results comparable to commercial equipment (Echezona et al., 2011; Hinge et al., 2021). The fabrication of locally produced testing machines not only reduces procurement costs but also promotes indigenous technology development, facilitates equipment maintenance, and improves the availability of testing facilities for educational institutions and research laboratories.

Against this background, this study focuses on the development and performance evaluation of a locally fabricated modulus of rupture testing machine. The study seeks to determine the accuracy, precision, operational efficiency, and reliability of the developed equipment by comparing its performance with established standard testing procedures. The successful development of such a machine is expected to provide a cost-effective alternative to imported testing equipment, improve access to material characterization facilities, promote local technological innovation, and enhance engineering education, research, and industrial quality control in Nigeria and other developing economies.

Theory of Bending

The theory of bending is one of the fundamental principles in the mechanics of materials and structural engineering. It describes the behaviour of beams and other structural members when subjected to transverse loads that produce bending moments. The theory provides the basis for analyzing the distribution of stresses and strains within a beam and forms the theoretical foundation for determining the modulus of rupture (MoR) of engineering materials. A thorough understanding of bending theory is therefore essential in the design of structural members and in the development of machines used for flexural strength testing (Gere & Goodno, 2018).

When an external load is applied perpendicular to the longitudinal axis of a beam, the beam experiences bending. This bending action induces internal stresses that vary across the depth of the beam. The upper fibres of the beam are generally subjected to compressive stresses, while the lower fibres experience tensile stresses. Between these two regions lies the neutral axis, where the longitudinal stress is theoretically zero because the fibres neither elongate nor shorten during bending (Hibbeler, 2020).

The distribution of bending stresses across a beam section is explained by the classical Euler–Bernoulli beam theory, which assumes that plane cross-sections remain plane and perpendicular to the neutral axis after deformation. The theory further assumes that the material is homogeneous, isotropic, and linearly elastic, and that the beam undergoes relatively small deflections. Under these assumptions, the normal stress at any point within the beam varies linearly with the distance from the neutral axis, reaching a maximum value at the outermost fibres (Beer, Johnston, DeWolf, & Mazurek, 2020).

The relationship between bending stress, bending moment, and the geometric properties of a beam is expressed by the flexure equation:

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

$$\delta = My/I \quad (1)$$

where δ is the bending stress (MPa or N/mm²), M is bending moment (N·mm), y is the perpendicular distance from the neutral axis to the point under consideration (mm), and I is second moment of area (moment of inertia) of the beam cross-section (mm⁴).

This equation shows that bending stress increases proportionally with the applied bending moment and the distance from the neutral axis, while it decreases with increasing moment of inertia. Consequently, beam geometry plays a significant role in determining the load-carrying capacity of structural members (Gere & Goodno, 2018).

As the applied load increases, both tensile and compressive stresses increase until the material reaches its elastic limit. Within the elastic region, the beam returns to its original shape when the load is removed. However, once the applied stress exceeds the elastic limit, permanent deformation begins, and continued loading eventually leads to fracture. For brittle materials such as concrete, ceramics, glass, bricks, and some composite materials, failure generally occurs suddenly with little or no plastic deformation. In contrast, ductile materials such as structural steel and aluminium usually undergo noticeable yielding before failure (Callister & Rethwisch, 2020).

The theory of bending is directly applicable to modulus of rupture testing because the MoR represents the maximum bending stress developed in a specimen immediately before failure. During a standard three-point bending test, the specimen is simply supported at both ends while a concentrated load is applied at its centre. The maximum bending moment occurs directly beneath the applied load, making this location the most critical point for crack initiation and fracture. In a four-point bending test, two equal loads create a constant bending moment over the region between the loading points, thereby providing a larger zone of uniform stress for evaluating material behaviour (ASTM International, 2018).

For a rectangular specimen subjected to a three-point bending test, the modulus of rupture is calculated using:

$$MoR = \frac{3PL}{2bd^2} \quad (2)$$

where P is maximum applied load before failure (N), L = span length between supports (mm),

b is specimen width (mm) and d = specimen depth/height (mm).

This equation is derived from classical beam bending theory and is widely adopted in international testing standards for evaluating the flexural strength of concrete and other brittle materials (ASTM International, 2018).

Several factors influence the bending behaviour of materials, including material composition, cross-sectional geometry, loading configuration, span length, support conditions, moisture content, temperature, and the presence of defects such as cracks, pores, or voids. Variations in any of these parameters may significantly affect the measured modulus of rupture. Therefore, standardized specimen preparation, accurate loading systems, and proper calibration of testing equipment are essential for obtaining reliable and reproducible flexural strength values (Neville, 2011).

Recent advances in mechanical testing have further enhanced the practical application of bending theory through the incorporation of digital load cells, linear displacement transducers, optical extensometers, and computerized data acquisition systems.

These technologies enable continuous measurement of load, deflection, and strain during testing, thereby improving the precision and repeatability of modulus of rupture measurements. Low-cost digital instrumentation has also encouraged the development of locally fabricated testing machines capable of

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

producing results comparable to those obtained from conventional commercial equipment (Hinge, Johnson, & Henriksen, 2021).

The theory of bending therefore provides the scientific basis for the design, calibration, and operation of modulus of rupture testing machines. A sound understanding of stress distribution, bending moments, beam deformation, and failure mechanisms is indispensable for accurately evaluating the flexural strength of engineering materials. Consequently, the successful development of a locally fabricated modulus of rupture testing machine depends on strict adherence to established principles of beam bending and standardized testing procedures.

Materials

The modulus of rupture testing machine is made up of a metallic frame, a loading system and electronic controlling/instrumentation unit. The frame which is made up thick metallic plates and steel rods provides structural support for the loading system. It provides a platform or stage that holds the specimen in place during testing. It also houses the dc motor and the gear arrangement.

The loading system applies force gradually and centrally on the test materials on the stage. The electronic controlling unit of the machine manages system operations like measurements, data acquisition and recording. The unit is made up of arduino board (Atmega 328), 50 kilogram load cell, load cell amplifier, 12 V dc motor, dc motor driver module, IR sensor, liquid crystal display, switches, veroboard, connecting wires and secure (SD) card module.

METHODS

The development of the modulus of rupture machine involves the design and construction of the metallic framework, the loading system and the controlling unit.

4.1 Design and Construction of the Frame

The design plan of frame was neatly drawn and the dimensions clearly labeled. The metallic frame provides the overall structure and stability for the machine. It is made up of rigid materials like 40 mm diameter steel rods and 10 mm thick iron plates to withstand the forces applied during testing. The steel rod and the iron plates are cut into appropriate sizes and shapes based on the design.

The base of the frame is a trapezoidal box. The box houses the dc motor, gear system and control circuit. Two opposite sides of the box have trapezoidal shape. These sides are separated by a distance of 0.21 m. The height of each of the plates is 0.28 m. Each of the plates has parallel lengths of 0.24 m and 0.20 m. The bottom plate which forms the base of the box is a rectangular plate of dimensions 0.21 m by 0.24 m. The back of the box is covered with a plate of dimensions 0.28 m and 0.21 m.

The lower front plate has dimensions of 0.21 m by 0.16 m and the upper slant plate has dimensions of 0.21 by 0.14 m. The slant plate was cut and drilled to accommodate the liquid crystal display, switches and control buttons. The top cover plate has a length of 0.21 m and breadth of 0.20 m. The plate forms the stage of the machine. The supporting anvils are properly welded at the extreme ends of the plate. It equally provides support for the two vertically positioned steel rods which are firmly bolted to it.

The other ends of the steel rods are held in place by a piece of iron plate. The two rods provides a vertical pathway for the loading bar to move up and downwards. The loading bar is appropriately drilled to give room for leveling threaded rod and attachment of load cell. To the other end of the load cell, the loading anvil can be

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

attached based testing method which can either be a three-point bending test or four-point bending test. Figure 1 shows the dimensions of the frame.

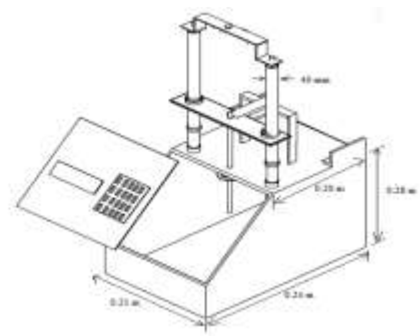

Figure 1. Block Dimensions of the Frame of the MoR Machine

4.2 Loading System

This system applies a controlled force to the specimen placed on the supporting anvil of the stage. It is a screw mechanism that moves the steel cross bar to which movable anvil and load cell are attached upward and downward. The system utilizes gear arrangement. The lower gear head is firmly welded to the rotating head of the direct current motor. The upper head has hole drilled at its center. A nut was welded at the center of the upper gear head such that the holes of the nut and that of the gear are aligned.

4.3 Support System

This system holds the specimen in place during testing. It consists of two supporting anvils placed 0.21 m apart that allow the specimen to bend freely. The supports are made of thick metal plates. They can be covered with rubber to ensure proper contact with the specimen.

4.4 Electronic Controlling Unit

This unit controls the operations of other sections of the machine. The central component of the controlling unit is the arduino board. It accepts the program which controls the activities of other electronic components. The block diagram in figure 2 shows the component units of the controlling unit.

The constituent electronic parts such as load cell, liquid crystal display, infrared sensor, power supply unit, motor driver, control switches and SD modules are connected as shown in the circuit diagram. The circuit diagram of the machine is shown in figure 3. The circuit diagram shows the interconnectivity of different electronic components used in the development of the machine.

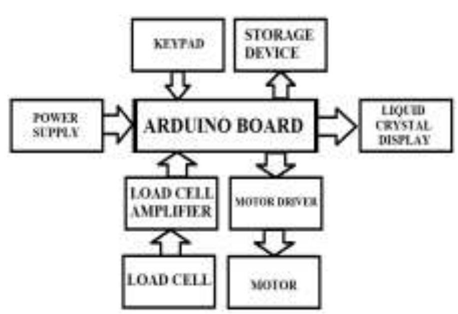

Figure 2. Block Diagram Showing the Component Units of MoR Machine

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

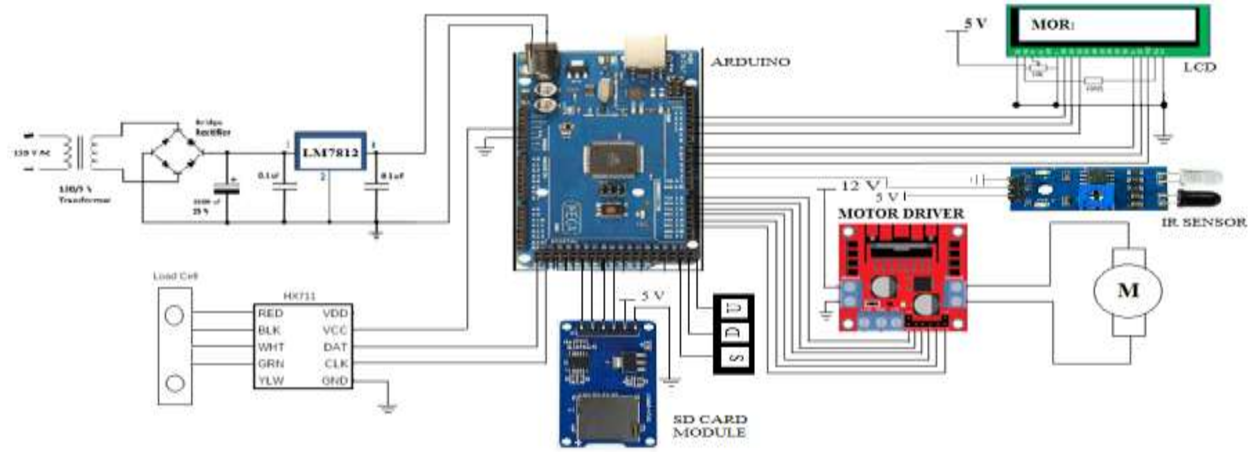

Figure 3. Circuit Diagram of the MoR Testing Machine

Operation

The material of a certain thickness whose modulus of rupture is to be determined would be sourced and sized into a dimension of 21 cm x 1.65 cm. Meanwhile, the breadth of the material can be greater than 1.65 cm. Measure and input the thickness of the material after switching on and initialization of the machine. Then place the specimen on the stage. Pressing the set button and then DOWN button facilitates the movement of the loading anvil towards the material on the stage. The anvil gradually comes in contact with the material and exerts force on it until it breaks. The infrared sensor senses the breakage and hence the downward movement of the loading system stops immediately. Therefore, the force required to break the material and its modulus of rupture would be displayed on the liquid crystal display. The values would be stored at the same time on the memory card inserted into micro SD card module. Press the set button and then UP button to move the loading anvil upwards to get the machine ready for another measurement. The diagram of the machine is shown in figure 4.

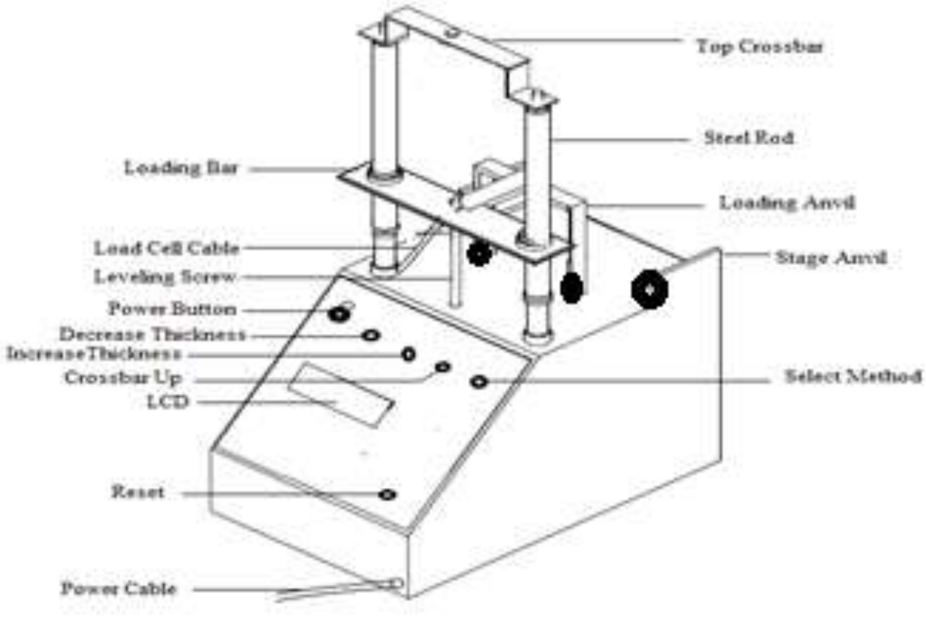

Figure 4. Diagram of the MoR Testing Machine

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XIII Issue VIII August 2026

6.0 CALIBRATION AND MEASUREMENT OF MODULUS OF RUPTURE (MOR) OF TILE SAMPLES

A known calibration mass of 1000 g was placed on the load cell to determine the calibration factor. The corresponding raw output value was recorded from the serial monitor. The calibration factor was calculated using Equation (3):

$$Calibration\ Factor = \frac{Known\ Load}{New\ Raw\ Value} \ldots\ldots\ldots\ldots\ldots (3)$$

The calculated calibration factor was then inserted into the program code using “Scale.set_scale(calibration_factor)”within the setup function. After updating the calibration factor, the system was tared again to reset the baseline. The load cell was subsequently tested using known weights, and the readings showed good agreement with the applied loads, confirming that the calibration procedure was successful and the system was operating accurately. To verify calibration linearity, five additional known masses were applied individually and the displayed force was compared to the expected value (mass × 9.807).

The developed machine was therefore used in the measurement of modulus of rupture of six different samples of tile. The samples of tile are labeled A1 – A6. The machine was used to carry out the measurements using the two methods- 3 point bending test and 4 point bending test.

RESULTS AND DISCUSSION

Table 1 shows the results of the load cell calibration with six different loads.

Table 1. Calibration Results of the Load Cell

Applied Mass (Kg)	Expected Force (N)	Displayed Force (N)
0.100	0.981	0.979
0.200	1.961	1.965
0.500	4.904	4.898
1.000	9.807	9.807
2.00	19.613	19.628
5.00	49.035	49.071

Table 2 shows the results of the measurement of moduli of rupture of the six different samples of tiles using three-point bending and four-point bending tests.

Table 2. Results of the Measurements

Tile Samples	**Name of Tiles**	**Thickness, d (m)**	**3-PB Fracture Force (N)**	**Computed 3-PB MoR (MPa)**	**4-PB Fracture Force (N)**	**Computed 4-PB MoR (MPa)**
A1	40 cm x 30 cm Marble Glazed	0.0078	102.7	32.129	106.7	22.553
A2	40 cm x 30 cm Concrete	0.0074	95.2	33.089	98.2	22.755
A3	60 cm x 60 cm	0.0099	200.4	38.917	206.9	26.780

	Porcelain					
A4	60 cm x 60 cm Super Polish	0.0101	240.8	44.929	233.2	29.007
A5	60 cm x 60 cm Rustic	0.0098	184.6	36.584	180.6	23.848
A6	60 cm x 60 cm Vitrified	0.0101	224.3	41.850	200.4	27.340

The results presented in the table 2 compare the Modulus of Rupture (MoR) of six ceramic tile samples determined using the Three-Point Bending (3PB) and Four-Point Bending (4PB) test methods. The MoR values indicate the maximum flexural stress each tile can withstand before failure and are useful for assessing the mechanical strength and quality of ceramic tiles.

The results show that the 3PB method consistently produced higher MoR values than the 4PB method for all six tile samples. This trend is expected because, in a three-point bending test, the maximum stress is concentrated directly beneath the central loading point, whereas in a four-point bending test the maximum stress is distributed over a larger region between the two loading points. Consequently, a larger portion of the specimen is subjected to the maximum tensile stress in the 4PB test, increasing the likelihood of fracture from internal flaws and resulting in lower calculated MoR values.

Among the tested samples, Sample A4 (60 cm × 60 cm Super Polish tile) exhibited the highest flexural strength, recording an MoR of 44.929 MPa under the 3PB test and 29.007 MPa under the 4PB test. These values indicate that the Super Polish tile possesses the greatest resistance to bending failure, suggesting superior material quality, higher density, lower porosity, and better manufacturing consistency.

The Porcelain tile (A3) also demonstrated high strength, with MoR values of 38.917 MPa (3PB) and 26.780 MPa (4PB). Porcelain tiles are generally known for their dense microstructure and low water absorption, which contribute to their high flexural strength.

The Vitrified tile (A6) recorded MoR values of 41.850 MPa (3PB) and 27.340 MPa (4PB), ranking among the strongest specimens. Vitrified tiles typically undergo high-temperature firing, producing a compact structure that enhances mechanical strength and durability.

The Rustic tile (A5) exhibited intermediate performance, with MoR values of 36.584 MPa (3PB) and 23.848 MPa (4PB). Although lower than those of the porcelain, vitrified, and super polish tiles, these values indicate adequate bending strength for many structural and flooring applications.

The weakest specimens were A1 (Marble Glazed tile) and A2 (Concrete tile). Sample A1 recorded MoR values of 32.129 MPa (3PB) and 22.553 MPa (4PB), while Sample A2 showed 33.089 MPa (3PB) and 22.755 MPa (4PB). Their comparatively lower flexural strength may be attributed to differences in composition, firing conditions, microstructural defects, or higher porosity.

The fracture forces generally followed the same trend as the MoR values. Samples with higher fracture loads, such as A4 and A6, also exhibited higher flexural strengths, confirming that greater resistance to applied load corresponds to improved mechanical performance. Minor differences in fracture force between the two testing methods are expected because of the different stress distributions created by the loading configurations.

CONCLUSION

The developed Modulus of Rupture (MoR) testing machine was successfully devloped, calibrated, and evaluated for determining the modulus of rupture of ceramic tiles using both three-Point Bending (3PB) and

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four-Point Bending (4PB) configurations. Calibration results demonstrated excellent measurement accuracy, with a maximum percentage error of only ±0.20%**,** indicating that the load cell and force measurement system provide reliable and precise load measurements over the operating range. The minimal calibration errors confirm that the machine is capable of producing consistent and dependable experimental data.

The measured modulus of rupture of the tile samples ranges from 32.13 MPa to 44.93 MPa for 3-point bending test method and 22.55 MPa to 29.00 for 4-point bending test method. The results of the measurements using 3-point bending test method are higher than those obtained using 4-point bending test method. The differences agree with the literatures on the relationship between the two methods. The successful development of the modulus of rupture machine provides an affordable alternative for educational institutions and small-scale laboratories, facilitating effective material strength testing and research applications.

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