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Development of Modulus of Rupture Testing Machine for the Measurement of Flexural Strength of Brittle Materials

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Abstract- Ceramics and other brittle materials like glass, plastic, wood, and concrete beams or slabs are highly valuable both for domestic and industrial applications. Most of these brittle materials fail during transportation or use when minimal force is applied. It is wise to note that careless selection of these materials could lead to significant losses in both human and material resources. Meanwhile the modulus of rupture testing machine that can be used to measure the ability of these materials to withstand stress before failure are not readily available and at the same time very expensive in Nigeria. A machine is therefore developed to measure the modulus of rupture of brittle materials. The machine is developed using rigid metallic frame, 500 N load cell, HX711 load cell amplifier, 12 V dc motor, L298N motor driving module, arduino atmega 2560 board, 20x4 I2C liquid crystal display(LCD), MicroSD card module and infrared sensor. The frame provides structural support for other units of the machine, the loading system applies a controlled force on the material to be tested, the stage holds the specimen in place, and the data acquisition system records measurements. The machine is designed such that the loading head can be changed to carry out either three point bending (3-PB) test or four point bending (4-PB) test. The machine was successfully developed and calibrated. The 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 machine was used to measure the MoR of four tile samples. The values obtained when compared to those obtained experimentally were found to be very close with average percentage error of approximately 0.50%. The statistical analysis showed that the mean modulus of rupture measured by the developed machine (24.477 MPa) was very close to that obtained experimentally (24.351 MPa). The paired t-test carried out on the results indicated that there was no statistically significant difference between the two methods at the 97 % confidence level. This signifies that the machine can perfectly be used to determine the MoR of ceramic and other brittle materials.

Keywords: brittle, force, breaks, arduino board, modulus.

I. INTRODUCTION

The concept of the modulus of rupture (MoR) which is a measure of a material's flexural strength did not emerge spontaneously. Its historical roots extend back to the foundational work of early scientists like Galileo Galilei, who explored beam bending, and Robert Hooke, who introduced Hooke’s Law and contributed significantly to the field of material mechanics (Timoshenko, 1953). Though the term “modulus of rupture” was not coined in their time, their research laid the groundwork for modern material testing methods. As industrialization progressed, the need for stronger and more reliable materials led to the formalization and standardization of mechanical property testing, including MoR. The modulus of rupture is more than a technical term. It is a fundamental concept that supports the modern world’s infrastructure and innovation. From its historical inception in classical mechanics to cutting-edge digital testing methods, MoR continues to evolve. Whether in construction, aerospace, or manufacturing, it remains a vital indicator of how materials behave under flexural stress. In a world where safety, efficiency, and durability matter more than ever, understanding and applying the modulus of rupture is not just good engineering practice but it is essential.

At its core, the modulus of rupture refers to the maximum stress a material can endure in a bending or flexural test before it fractures. Typically expressed in units like mega pascals (MPa) or pounds per square inch (psi), it provides critical insights into a material's structural performance under load (ASTM C78/C78M-18, 2018). This property is particularly important in disciplines like civil engineering, aerospace, automotive manufacturing, and construction, where structural integrity and safety are paramount.

MoR acts as a key decision-making tool for engineers and material scientists. It helps determine a material's suitability for applications that involve bending or flexural forces. A higher MoR value generally indicates a tougher, more durable material. It is an essential factor in scenarios ranging from skyscraper design to coffee mug manufacturing.

Historically, testing was conducted through manual bending experiments. Today, it has evolved to include three-point and four-point bending tests, where a specimen is supported at two points and force is applied centrally (or at two additional points in the case of four-point tests). The maximum load before failure is used to calculate the MoR (Mindess et al., 2003). Meanwhile the developed machine is designed such that it can be used for either three-point or four-point bending test by simply changing the loading anvil/roller.

Modern techniques now integrate sensors and software for greater accuracy. Advanced methods such as Digital Image Correlation (DIC) and Acoustic Emission (AE) provide real-time monitoring and microscopic insights into material behavior during stress testing (Sutton et al., 2009).

The modulus of rupture (MoR) is a material property that defines the ability of the material to withstand bending or flexural stress without breaking or failing. It is an important measure in the field of materials science and engineering, especially for materials subjected to bending forces, such as beams, panels, or structural components (Gere and Timoshenko, 1997). This property is crucial for structural materials, such as concrete, wood, and metals, which are often exposed to bending stresses in real-world applications. The modulus of rupture is often used to assess the strength of timber used in construction, including beams, planks, and other wooden structures. As wood is a natural composite material, its strength can vary based on species, grain orientation, and moisture content. In concrete, MoR is a critical factor in determining the suitability of a mix design for load-bearing applications. Concrete, while strong in compression, can be weak in tension, and the MoR helps assess how it behaves under flexural forces. For metals, polymers, and composite materials, MoR is similarly important for understanding the performance of these materials in structural applications where bending is a key factor (Neville, 2011).

Ceramics and Glass materials tend to be brittle, and the modulus of rupture is used to quantify their ability to resist fracture under flexural stress, helping in the design of products such as tiles, bricks, and glass panes.

The modulus of rupture serves as an essential parameter in evaluating materials for their ability to withstand bending stresses. By understanding this property, engineers can make informed decisions about the suitability of materials for various structural applications. The background and development of the modulus of rupture as a concept have been driven by the need for safe and efficient design of materials in engineering and construction. (Mindess et al., 2003)

Many MoR testing machines used in Nigerian laboratories are imported, making their acquisition and maintenance relatively expensive because of foreign exchange costs, transportation expenses, and dependence on overseas manufacturers for spare parts and technical support. Developing the machine locally can therefore reduce procurement and maintenance costs, while making the equipment more readily available to universities, polytechnics, research institutions, testing laboratories, and small-scale industries.

II. FACTORS INFLUENCING MOR

The Modulus of Rupture is not a fixed property but rather a variable influenced by a lot of factors ranging from material composition and specimen geometry to environmental conditions and manufacturing techniques. Understanding these factors is essential for selecting appropriate materials, designing structural components, and ensuring durability and safety in engineering applications. By controlling these variables, engineers can optimize the performance and reliability of materials under flexural loads.

Material Composition: Inherent properties differ among materials, metals like steel usually exhibit higher MoR values than polymers. Additives and treatments, such as fiber reinforcements or heat

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treatments, can also affect the strength of materials (Callister & Rethwisch, 2020).

Environmental Conditions: Temperature, humidity, and chemical exposure significantly influence MoR. For example, moisture can weaken wood or concrete, making it essential to consider environmental resilience in structural applications (Neville, 2011).

III. STANDARD TEST METHODS TO DETERMINE THE MODULUS OF RUPTURE OF MATERIALS

In order to test the flexural strength of a material, its span length should be at least three times the depth. The flexural strength is expressed as the modulus of rupture (MoR) in psi or (MPa). There are two standard test methods to determine the flexural strength of a beam,

(1) 3-Point Bending Test

A 3-point bending (3PB) test balances a specimen between two lower anvils while applying force from an upper anvil centrally at the midpoint. The area of uniform stress is quite small and concentrated under the center loading point. Different testing standards may require the anvils to be fixed, rotated, or rocking. Equation 1 presents an expression with which the modulus of rupture can be obtained.

$$MoR = \frac{3FL}{2bd^2} \quad (1)$$

Where F is the loading force, L is the length of the sample, b is width and d is the thickness. (ASTM, 2022).

(2) 4-Point Bending Test

A 4-point bending (3PB) test differs from the 3-point test in that it has two upper anvils positioned equidistant from the center of the specimen. In this test, the area of uniform stress exists between the inner span loading points (typically half the length of the outer span). Again, depending on the requirements of the testing standard, the anvils may need to be fixed, rotated, or rocking. Typically, 4-point tests are used to measure modulus of elasticity in bending for brittle materials.

In this test method, half the load is applied at each third of the beam's span length. Here the flexural strength or modulus of rupture is lower than that of the modulus of rupture found in the center point loading test. In this test, the maximum stress is present over the center one-third portion of the beam.

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

Where F is the loading force, L is the length of the sample, b is width and d is the thickness.

The calculation of modulus of rupture is considered crucial in structural mechanics as it;

1. Helps in designing structural elements like beams, cantilevers, shafts, etc.
2. Aids in the study of materials and their properties.
3. Provides a parameter for development of stronger constructional materials.
4. Helps in judging the quality of structures being used for construction.
5. Is used to predict both resistance and durability of materials. (ASTM, 2023a; ASTM, 2023b).

IV. MATERIALS

The modulus of rupture testing machine is made up of a metallic frame which consists of a loading system, a stage and a sturdy base. The frame provides structural support, holds the loading system in place, supports the specimen and provides supports for sensors. Other materials used include load cell, load cell amplifier, infrared sensor, arduino board, liquid crystal display, SD card module, capacitors, resistors, switches, verobord and connecting wires.

Loading System: This system applies a controlled force to the specimen placed on the supporting anvil of the stage. The system uses bolt and nut driven by 12 V,7 A motor. One end of the bolt is firmly tightened to the loading bar and the other end has nut around it. The nut has a gear head welded one side of it so that it can be rotated by the gear head of motor. The loading bar is the part of the loading system that can move up or down to apply the force depending on direction of rotation of the motor. One end of the load cell is directly attached to the loading bar and the other end can be attached to either three-point bending (3-PB) or four-point bending (4-PB) anvil.

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The Stage: This part holds the specimen in place during testing. It consists of two support rollers or anvils that allow the specimen to bend freely. The supports are made of metal and rubber covers to ensure proper contact with the specimen. Figure 3 shows the diagram of the frame.

The machine was constructed within base area of 0.24 m × 0.21 m, with a total height of 0.28 m. These dimensions make the machine relatively portable and suitable for laboratory use. The base serves as the foundation of the entire MOR testing machine. It was constructed in a rectangular form with a length of 0.24 m and a width of 0.21 m. The base was designed to provide sufficient strength and stability for the testing operation. The vertical height of the base of approximately 0.28 m provides space for housing some of the electrical and electronic components of the machine. It also supports the upper testing assembly. A stable base is essential because any displacement or deformation of the machine during testing may affect the accuracy of the load measurement.

An upper platform was mounted on the base to support the loading and specimen support assembly. The platform provides the working surface on which the test specimen is positioned. The effective length of the testing section is approximately 0.21 m. This dimension was selected to provide adequate space for the arrangement of the specimen supports and the central loading point. The upper platform was firmly connected to the vertical support members to ensure that it remained stable during the bending test.

The machine incorporates vertical cylindrical columns for supporting and guiding the loading assembly. Each major cylindrical column has a diameter of 40 mm. The columns were selected with this diameter to provide adequate mechanical strength and rigidity. The columns support the upper loading structure and help to maintain the vertical alignment of the loading head. The cylindrical columns were securely fixed to the upper and lower sections of the machine. Their arrangement ensures that the loading mechanism moves in the correct direction during testing and reduces the possibility of lateral movement.

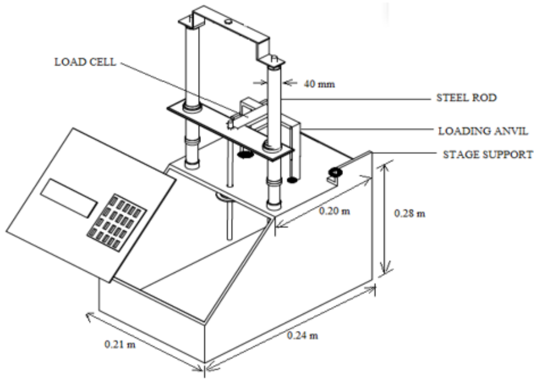

Figure 3. The Frame of MoR Testing Machine

(1) Load cells
They are precision instruments engineered to measure weight, force, and pressure by converting mechanical energy into readable electrical signals. A 50 kg load cell is utilized in the development of the machine.

Figure 4. Load Cell

(2) Load cell amplifiers
Load cell amplifiers are crucial components in force measurement systems, responsible for amplifying the low-level electrical signals generated by load cells, particularly strain gauge types. These signals, typically in the millivolt range, require amplification and conditioning to be processed by the microcontrollers, or data acquisition systems.

HX711 load cell amplifier was interfaced with the load cell for force accquisition. The primary role of the amplifier is to boost this signal to a usable level (typically 0–5V or ±10V), with minimal distortion, drift, or noise.

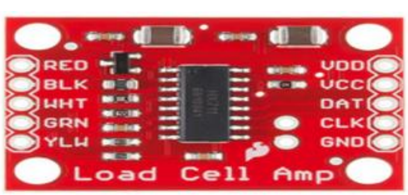

Figure 5. Load Cell Amplifiers

(3) Infrared Sensor
An active infrared sensor emits its own infrared (IR) light, unlike a passive sensor which detects existing IR radiation. The sensor is used to detect the breakage of the brittle material on the stage and hence stops the downward movement of the movable loading anvil.

Figure 6. Infrared Sensor

4 Arduino AtMega
Arduino ATmega2560 is used as the controlling unit. The Arduino Mega is a microcontroller board based on the. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller. Other units like load cell amplifier, infrared sensor, switches, motor driver, LCD and SD card module are interfaced with the board.

Figure 7. Arduino Board

5 Liquid Crystal Display
A Liquid Crystal Display (LCD) is a type of flat-panel electronic display that uses the light-modulating properties of liquid crystals to display images. By applying an electric field, the alignment of liquid crystal molecules can be controlled, which then alters the polarization of light passing through them. This modulated light, combined with polarizers and a backlight, creates the visual patterns and images seen

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on the display. A 16x4 LCD is employed in the development of the machine.

Figure 8. 20x4 Liquid Crystal Display

6 Micro SD Card
The Micro SD Card Memory Module is a compact and efficient solution for adding storage capabilities to your microcontroller or development board projects. It allows you to read from and write to SD cards, making it ideal for data logging, file storage, and other applications requiring large amounts of memory. The module supports various SD card formats and interfaces seamlessly with popular microcontrollers like Arduino, Raspberry Pi, and others

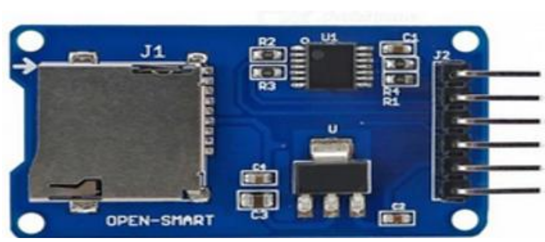

Figure 9. SD Card Module

V. METHOD

The metallic frame of the machine was constructed by a cutting 4 mm thick metallic plate and 40 mm diameter steel rod into appropriate sizes as earlier discussed. The pieces of metal were joined together to form the frame. The load cell to which an anvil is connected is attached to the movable crossbar. The block and circuit diagrams of the control unit of the machine are shown in figures 10 and 11 respectively. The crossbar is be made to move up or down using UP and DOWN control buttons. When in operation, the crossbar moves downwards until the loading/movable anvil touches the specimen on the stage when DOWN button is pressed. The downward movement continues until the specimen breaks and the movement stops automatically. The stoppage is facilitated by the infrared sensor strategically positioned between the stage anvils. The force required to break the specimen is measured using the load cell. The force is therefore used to calculate the modulus of rupture of the specimen based on the program uploaded into the arduino board. The calculated modulus of rupture is displayed on the liquid crystal display and at the same time store on the SD card module. The UP button is used to control the upward movement of the loading anvil to a reasonable or convenient height and the machine is ready for another cycle of measurement.

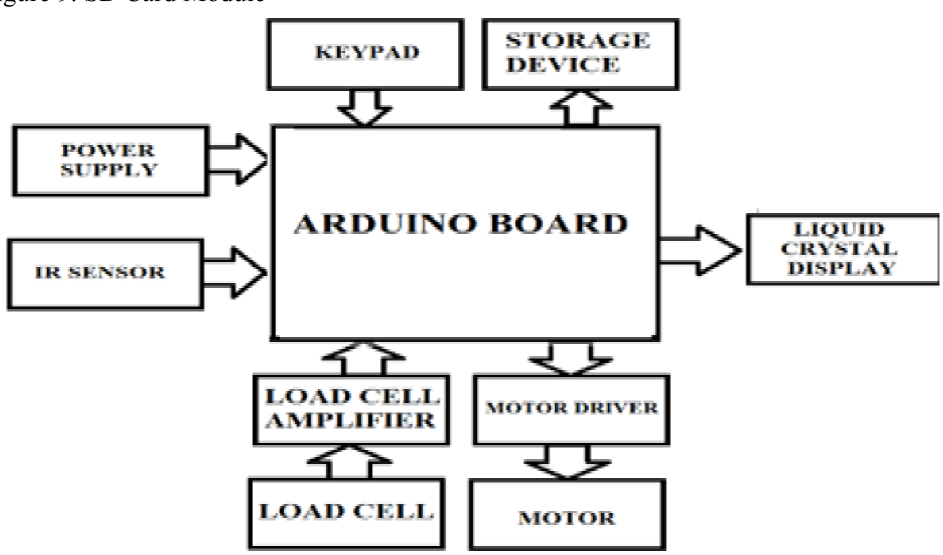

Figure 10. The Block diagram of the machine

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The circuit diagram of the machine is shown in figure 4. The circuit diagram shows the interconnectivity of different electronic components used in the development of the machine.

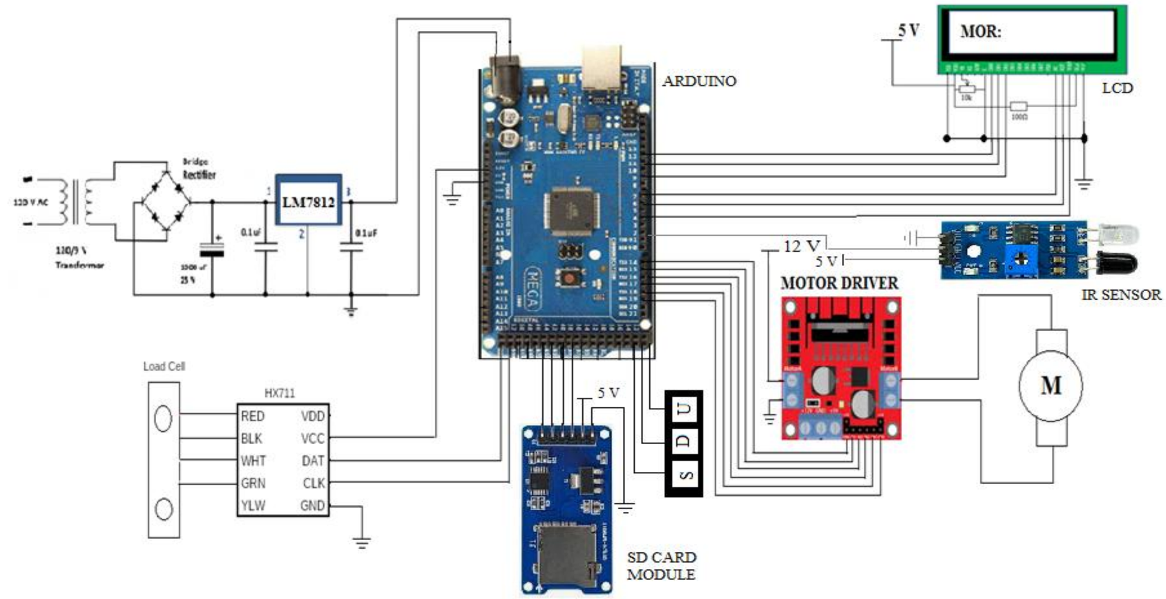

Figure 11. The Circuit Diagram of the Machine Operation

The material of a measured thickness whose modulus of rupture is to be determined must be sized into a dimension of 21.00 cm x 1.65 cm. Switching on the machine and then enter the thickness of the material. Place it properly 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. Therefore, the force required to break the material and its modulus of rupture would be displayed on the liquid crystal display. The values would also be stored on the memory card inserted into micro SD card module at the same time. The set button can be pressed to get the machine ready for another measurement.

Calibration

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 (0.1 kg, 0.2 kg, 0.5 kg, 2.0 kg, and 5.0 kg) were applied individually and the displayed force was compared to the expected value (mass × 9.807).

VI. TESTING AND RESULTS

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)	Error (N)	Error (%)
0.100	0.981	0.979	- 0.002	- 0.20

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0.200	1.961	1.965	+ 0.004	+ 0.20
0.500	4.904	4.898	- 0.006	- 0.12
1.000	9.807	9.807	- 0.000	0.00
2.00	19.613	19.628	+ 0.015	+ 0.08
5.00	49.035	49.071	+ 0.036	+0.07

The maximum measured error across the range 0.1-5.0 kg was 0.20%, occurring at the lowest applied mass (0.1 kg) where the relative impact of the load cell (HX711) noise is greatest. The calibration reference point of 1.000 kg produced an exact agreement between the expected and displayed values (9.807 N), resulting in zero error (0.00%). This confirms that the calibration procedure was correctly referenced at this point and validates the accuracy of the calibration process. At higher loads, the deviations remain very small. For 2.000 kg, the load cell overestimated the force by 0.015 N (0.08%), while at the maximum calibration load of 5.000 kg, the error increased slightly to 0.036 N (0.07%). Although the absolute error increases marginally with load, the percentage error actually decreases, indicating excellent proportional accuracy across the operating range.

The percentage errors vary between −0.20% and +0.20%, which is significantly below the commonly accepted calibration tolerance of ±1% for many engineering measurement systems. The absence of large deviations or abrupt changes in error demonstrates that the load cell possesses good linearity, repeatability, and measurement stability.

After calibration of the machine using standard weights, four different tile samples of the slightly varying thicknesses from different manufacturers were cut into the same appropriate sizes and placed on the machine in turn to determine their moduli of rupture. The samples are labeled A, B, C and D. Two sets of samples of each of the tiles were obtained from each product. Each set contains three samples of each of the tiles. The moduli of rupture of one of the sets of the samples were manually obtained as explained in the literatures while the remaining set of the tiles were tested using the machine. Table below shows the results of the tests. Three point bending test method was employed in both cases.

Table 1. Results of the Tests.

SAMPLES OF TILES	THICKNESS (m)	MODULUS OF RUPTURE(MPa)		PERCENTAGE ERROR(%)
		MACHINE	EXPERIMENT	
A	0.0074	17.656	17.572	0.48
B	0.0072	17.862	17.788	0.42
C	0.0092	28.891	28.812	0.27
D	0.0098	33.500	33.230	0.81

The results obtained are pictorially presented in the bar chart below.

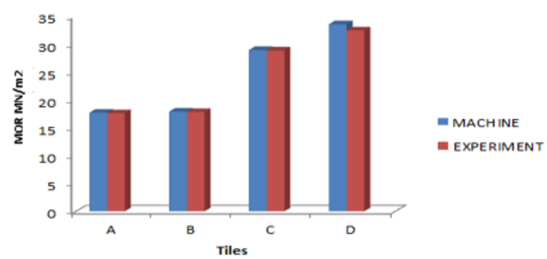

Figure 12. Bar Chart Showing the Relationship between Machine and Experimental Values

VII. CONCLUSION

The modulus of rupture (MOR) testing machine was successfully developed, fabricated, and assembled to provide a simple and reliable means of determining the flexural strength of test specimens. The machine incorporates essential components including a load cell, loading anvil, steel rods, stage supports, and a digital load display, as shown in the developed design. The fabricated structure has overall dimensions of approximately 0.24 m × 0.21 m × 0.28 m, with a 40 mm steel rod used in the loading mechanism. The successful integration of the mechanical and electronic components demonstrates that the machine is capable of applying load to a specimen in a controlled manner while measuring the applied force through the load cell and hence modulus of rupture.

The compact construction also makes the machine suitable for laboratory use, particularly where access to expensive commercial MOR testing equipment may be limited. The machine provides a functional, compact, and locally fabricated alternative for MOR testing, with potential for use in educational institutions, research laboratories, and materials testing applications in Nigeria. Its development also demonstrates the feasibility of producing locally sourced testing equipment that can reduce dependence on imported machines and support materials research and quality control.

The developed Modulus of Rupture (MOR) testing machine is primarily designed for testing brittle materials with relatively low modulus of rupture values, not exceeding approximately 500 MPa. Within this operating range, the machine is expected to provide adequate loading and measurement capability for the intended test specimens. The present design therefore provides a suitable and economical solution for laboratory testing of materials whose flexural strength falls within the specified capacity. Consequently, increasing the load-cell capacity, enlarging the stage area, strengthening the supporting structure, and incorporating improved instrumentation would significantly enhance the versatility of the developed MOR machine. These modifications would make it possible to test a wider range of brittle materials with higher modulus of rupture values, thereby increasing the usefulness of the machine for research, educational, industrial, and quality-control applications.

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