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RESEARCH ARTICLE

AUTOMATION IN THE CURING PROCESS: A CONTROL AND MONITORING SYSTEM FOR MOIST CHAMBERS IN CEMENTITIOUS COMPOSITES

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Abstract

This study presents the development of an automated system for a moist chamber designed for curing concrete and mortar specimens, adhering to the guidelines of ABNT NBR 9479:2006. The proposed system enables automated control of temperature and relative humidity throughout the curing process. An unconventional refrigeration system was employed for thermal control, specifically designed to maintain hygrometric stability through spray distribution systems, there by avoid ing losses associated with temperature adjustments. A physical prototyp e was constructed, featuring shelves for specimen accommodation and an integrated water drainage system. During testing, the prototype demonstrated satisfactory performance. The adopted climate control method effectively prevented excessive moisture removal from the environment,managing humidity through condensation and evaporation phases. The fluid temperature was maintained at approximately -4 °C, with a thermal variation (ΔT) of 4 °C, ensuring a constant relative humidity between 93% and 95% and a stabilized ambient temperature near 25 °C. The implementation of this compact moist chamber is concluded to be a viable solution for enhancing scientific research and practical activities in science and technology institutions, ensuring that cementitious matrices achieve mechanical and durability properties equivalent to those specified in structural designs through proper curing procedures.

Introduction:-

Concrete and mortar are fundamental materials in contemporary civil construction, valued for their versatility in adapting to complex geometries and diverse structural demands [1, 2, 3]. However, their mechanical and rheological properties are highly sensitive to environmental conditions during fabrication. Consequently, the application of appropriate dosing, molding, and thermal treatment techniques must be rigorously evaluated and controlled [4]. Prior to the execution of structures on construction sites, technological tests on component materials are imperative. For cementitious matrices, specimens are prepared according to project specifications to determine their mechanical properties. One of the most critical stages in the manufacturing of these samples is the curing process, routinely conducted within moist chambers [5]. This stage demands strict control over environmental variables, complying with standards such as ABNT NBR 9479:2006, which specifies temperature ranges of (23 ± 2) °C and relative humidity equal to or greater than 95%. Negligence or instability during the curing period leads to increased porosity and fragility

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of the concrete, compromising cement hydration and preventing the material from achieving its maximum potential for compressive strength and durability [4, 6]. Moist chambers function as confined microenvironments designed to simulate and standardize ideal hydration conditions. Nevertheless, conventional systems often face operational limitations, including the need for manual wetting, dehumidification due to traditional refrigeration systems, and vulnerability to local climatic seasonality. Such fluctuations hinder the development of advanced cementitious composites, which frequently incorporate supplementary cementitious materials to mitigate environmental impacts and require even more stable curing regimes. In this context, the development of reduced-scale prototypes emerges as a viable alternative to optimize the control of these variables and address the aforementioned operational bottlenecks.

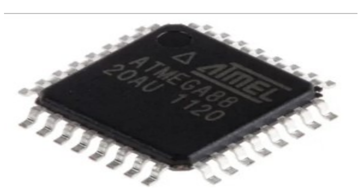
Concurrently, advancements in embedded electronics and industrial automation have transformed climate control systems [7]. These technological evolutions provide greater precision, traceability, and reliability to microclimatic control in material testing laboratories. In control engineering, process regulation can occur through sequential loops—based on successive events—or through continuous control, characterized by uninterrupted monitoring and adjustment of the system's physical variables via dedicated instrumentation. The simultaneous and efficient management of multiple physical parameters necessitates the employment of complex microprocessor architectures and robust control algorithms [8]. Given the need to overcome the limitations of manual management and ensure the homogeneity of mechanical properties in cementitious composites, this study proposes the development and implementation of a continuous and automated temperature and relative humidity control system for compact moist chambers. This device aims to safeguard the normative requirements for the conservation of cementitious matrices, thereby enabling the advancement of scientific research and experimental academic activities in science and technology institutions.

Literature Review:-

Moist Chambers and Monitoring Systems:-

The development of control and monitoring systems applied to moist chambers aims at automating experimental prototypes for evaluating and standardizing microclimatic curing processes. For this purpose, scientific literature reports the feasibility of using low-cost microcontroller architectures, such as the ATmega328P integrated circuit (Figure 1a), associated with printed circuit boards dedicated to power control (Figure 1b). These devices are responsible for acquiring environmental data and activating actuators for thermal and hygrometric regulation. Previous investigations indicate that systems based on this architecture can mitigate severe oscillations, initially operating in ranges of 20ºC to 23ºC and relative humidity between 38% and 43% RH, progressing to highly satisfactory stationary conditions with stable averages around 21ºC and 96% RH [9, 10]. This stabilization is critical to prevent premature desiccation of cementitious matrices.

Figure 1. Instrumentation and control system infrastructure: (a) ATMEGA328P Microcontroller; (b) Actuation and peripheral control board.



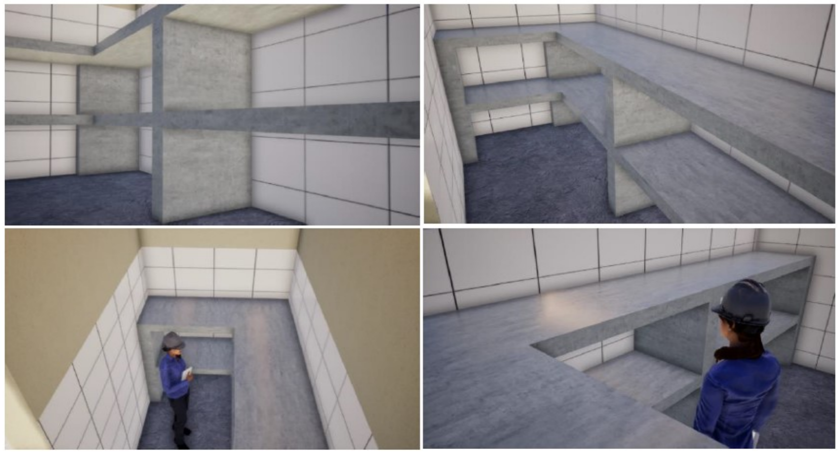
(a) **(b)**

Source: Adapted from Storino (2016) [9].

Physical modeling and the implementation of automated laboratory infrastructures corroborate the relevance of controlled curing on the mechanical performance of concrete and mortar mixtures. In practical material engineering applications, moist chamber structures demand the design of optimized layouts, including reinforced concrete shelves for sample arrangement, hydraulic distribution systems via continuous or intermittent spraying, gravity drainage networks, and chemical waterproofing of walls and boundary surfaces (Figure 2).

The consolidation of stable thermal and hygrometric environments directly benefits the reproducibility of axial compression tests, in addition to enabling the infrastructure of technological testing laboratories in technical and higher education institutions [11].

Figure 2. Volumetric conception and three-dimensional modeling of the laboratory moist chamber after study.

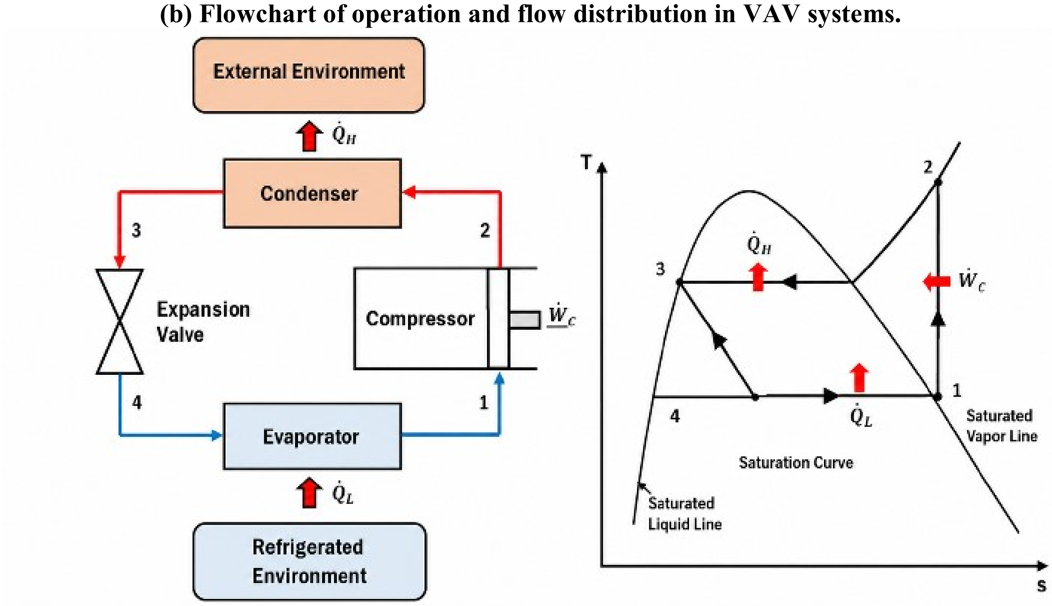


Source: Xavier and Trigo (2020) [11].

Refrigeration System and Psychrometric Analysis:-

The efficiency of climate control and environmental systems is intrinsically linked to the choice of the thermodynamic cycle and the load modulation strategy. In commercial buildings, computational simulations in software such as EnergyPlus demonstrate that Variable Air Volume (VAV) and Variable Refrigerant Flow (VRF) systems exhibit distinct energy performances depending on the imposed thermal load. The maximum coefficient of performance (COP) is typically achieved under full load conditions (Part Load Ratio – PLR = 100%), significantly reducing its efficiency in partial load regimes (PLR = 30%). This behavior highlights the need for optimization in control algorithms to mitigate energy losses [12], as illustrated in Figures 3 (a) and (b).

Figure 3. Configuration and Flowchart: (a) Schematic configuration of a variable air volume (VAV) system and (b) Flowchart of operation and flow distribution in VAV systems.



(a) **(b)**

Source: Adapted from Santos Jr & Koga (2020) [12]

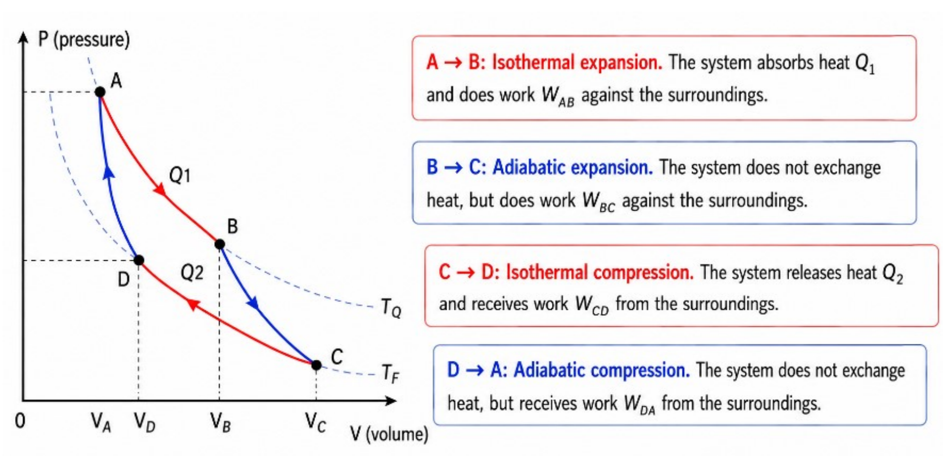
In the context of laboratory test chambers, compressor capacity control is fundamental for stabilizing hygrometric parameters and reducing energy consumption. The implementation of mechanical or electronic regulators at the suction or compressor head, such as the continuous capacity regulation system (CRII), Figure 4, acts to stabilize the evaporation pressure. This approach avoids premature wear due to the high number of start-stop cycles (cycling), resulting in greater thermal efficiency and lower electrical power demand [13], as exemplified in Figure 4.

Figure 4. Cutaway view of a commercial compressor equipped with a CRII capacity control mechanism.

Source: Rezende; Nascimento; Rosa (2022) [13].

The basic vapor compression refrigeration cycle is based on the forced circulation of a refrigerant fluid through four main components: compressor, condenser, expansion device, and evaporator (Figure 5). The fluid enters the compressor in the superheated vapor state at low pressure and temperature, being isentropically compressed until it reaches high pressures and temperatures. In the condenser, heat is rejected to the external environment, converting the fluid into saturated or subcooled liquid. Upon passing through the expansion valve, the refrigerant undergoes an irreversible expansion at constant enthalpy (enthalpization), drastically reducing its pressure and temperature before entering the evaporator. In this last heat exchanger, the fluid absorbs energy from the environment to be conditioned through its phase change (evaporation), restarting the thermodynamic cycle.

Figure 5. Representation of the theoretical Carnot cycle in temperature vs. entropy (T x s) diagrams.



Source: Adapted from Santos et al. (2020) [14].

The ideal theoretical limit applicable to these systems is governed by the Carnot Cycle (Figure 5). The First Law of Thermodynamics establishes the global energy balance in real thermal machines, as expressed in Equation (1):

$$Q_{hot} = W - (Q_{cold}) \qquad (1)$$

Where Q_{hot} represents the heat rejected to the hot source, W the work or mechanical power supplied to the system, and Q_{cold} the heat extracted from the cold source.

The thermal efficiency (η) of a thermal machine is determined by the ratio between the useful work obtained and the total thermal energy absorbed from the hot source, as per Equation (2):

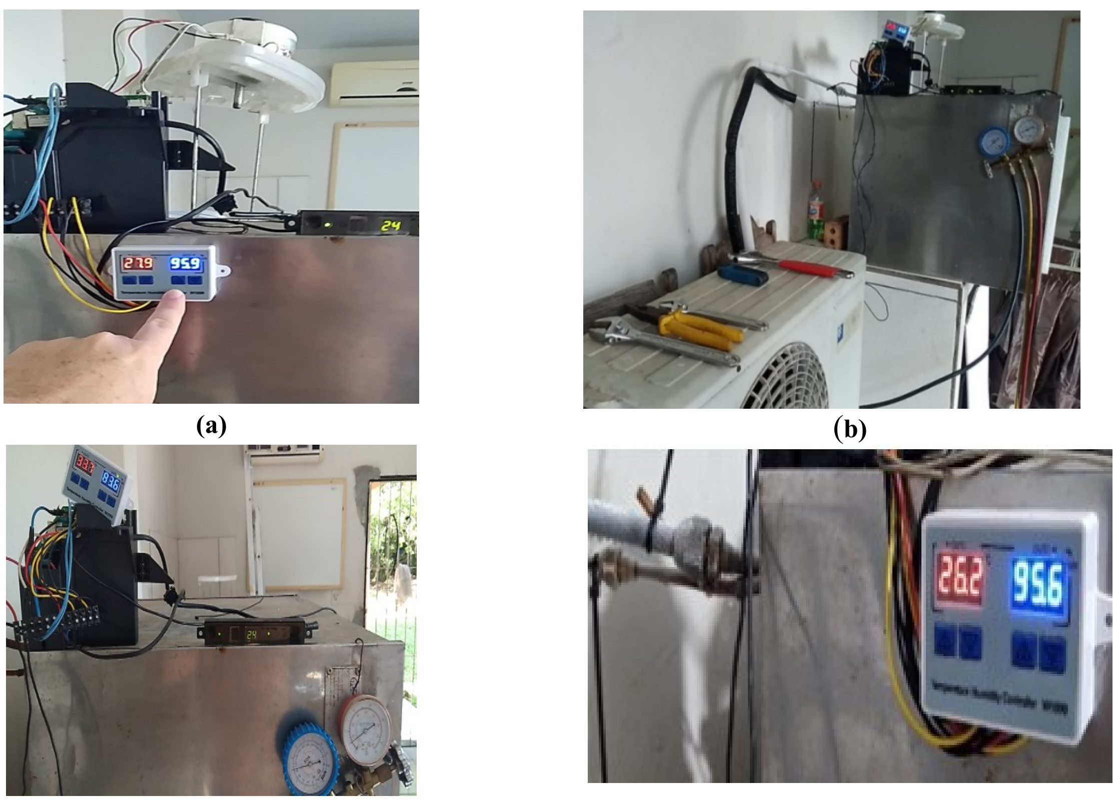
$$\eta = \frac{W}{Q_{hot}} = \frac{Q_{hot} - (Q_{cold})}{Q_{hot}} = 1 - \frac{(Q_{cold})}{Q_{hot}} \quad (2)$$

Considering the postulates of the Second Law of Thermodynamics, the integral conversion of heat into work is impossible in continuous cycles, which prevents obtaining a unitary efficiency ($\eta = 1$). Given that the rate of heat rejected to the cold source is never zero ($Q_{cold} \neq 0$), the real efficiency limit is always fractional ($0 \leq \eta < 1$). Alternative systems, such as absorption refrigeration or thermoelectric effect (Peltier effect), eliminate moving parts; however, they face significant rheological, electrical, and mechanical limitations that drastically reduce their COP when applied to rigorous microclimatic control [14, 15], making them unfeasible compared to compression systems.

Methodology:-

This section details the design, construction, and testing of the automated moist chamber system for curing cementitious composites. The methodology was structured to ensure compliance with ABNT NBR 9479:2006 standards, focusing on precise control of temperature and relative humidity (Figure 6).

Figure 6. Compilation of controller boards: (a) set point temperature and relative humidity; (b) Wet chamber simulation model; (c) Tests and checks and (d) Superheat calculation.



(a) (b) (c) (d)

System Design and Components:-

The automated system comprises several key components:-

- **Microcontroller Unit:** An ATmega328P-based microcontroller was selected for its low cost and proven reliability in environmental control applications [9]. This unit is responsible for data acquisition from sensors and controlling actuators.
- **Sensors:** High-precision temperature and humidity sensors were integrated to continuously monitor the internal conditions of the moist chamber. These sensors provide real-time feedback to the microcontroller for accurate environmental regulation.
- **Refrigeration System:** An unconventional refrigeration system was designed to maintain hygrometric stability. Unlike traditional systems that may cause dehumidification, this system utilizes spray distribution to ensure consistent humidity levels without significant temperature fluctuations. The fluid temperature was controlled around -4 °C, allowing for efficient heat exchange while maintaining the desired ambient conditions.
- **Actuators:** Peripherals controlled by the microcontroller include pumps for the spray system, a compressor for the refrigeration cycle, and fans for air circulation. These actuators work in conjunction to maintain the specified temperature and humidity ranges.
- **Physical Prototype:** A compact moist chamber prototype was constructed with internal dimensions suitable for accommodating standard concrete and mortar specimens.

The chamber features:-

◦ **Shelves:** Reinforced concrete shelves were incorporated for optimal specimen arrangement and structural integrity.
◦ **Spray Distribution System:** A continuous or intermittent spray system ensures uniform moisture distribution throughout the chamber.
◦ **Drainage System:** An integrated gravity drainage network prevents water accumulation and maintains hygiene.
◦ **Waterproofing:** Chemical waterproofing was applied to the internal surfaces to prevent moisture leakage and ensure durability.

Control Algorithm:-

The control algorithm implemented in the microcontroller operates on a continuous control loop, constantly monitoring temperature and relative humidity. The system adjusts the refrigeration and spray mechanisms based on predefined set points (23 ± 2) °C for temperature and $\geq 95\%$ for relative humidity. The algorithm is designed to minimize oscillations and maintain stable conditions, crucial for the proper hydration of cementitious materials.

Testing Procedures:-

Performance tests were conducted to evaluate the system's ability to maintain the required environmental conditions.

Key parameters monitored during testing included:

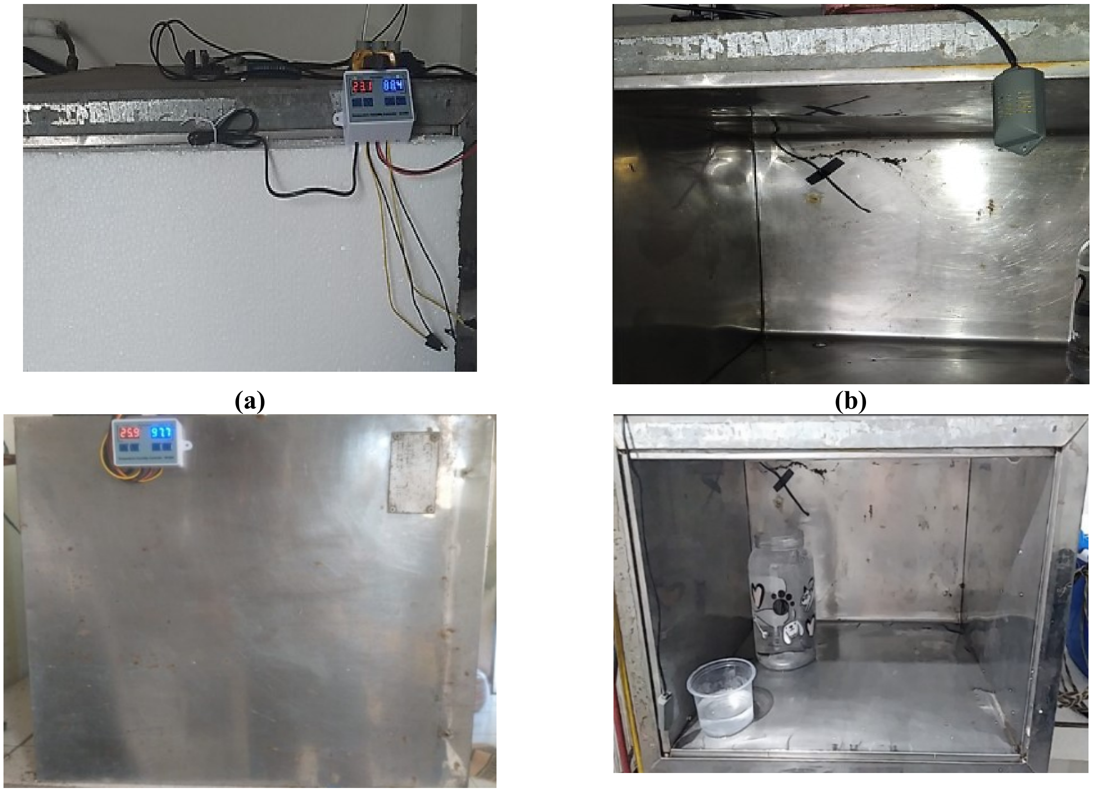
- **Temperature Stability:** The system's capacity to maintain the temperature within the (23 ± 2) °C range was assessed over extended periods.
- **Relative Humidity Consistency:** The ability to sustain relative humidity at or above 95% was a primary focus.
- **Energy Efficiency:** The energy consumption of the refrigeration and control systems was evaluated to ensure operational efficiency.
- **Specimen Curing Quality:** Concrete and mortar specimens cured within the automated chamber were subjected to mechanical tests (e.g., compressive strength) to verify that they achieved properties equivalent to those specified in structural designs, confirming the effectiveness of the curing process.

The testing phases aimed to validate the prototype's performance under various operational scenarios, ensuring its robustness and reliability for scientific research and practical applications.

Results and Discussion:-

During the testing phases, the developed prototype demonstrated satisfactory results, validating its effectiveness in controlling the critical environmental parameters for curing cementitious composites. The adopted climate control method proved particularly efficient in preventing excessive moisture removal from the environment, a common issue with conventional refrigeration systems. This was achieved by managing humidity through controlled condensation and evaporation phases (Figure 7).

Figure 7.Controlling the critical environmental parameters for curing cementitious composites: (a) first tests: temperature 23.1 ºC and relative humidity88.4 and (b) normal humidity; (c) segund test: temperature 25.9 ºC and relative humidity 97.7 and (d) normal humidity, no freezing.



(a) **(b)** **(c)** **(d)**

Specifically, the fluid temperature within the unconventional refrigeration system was consistently maintained around -4 °C, exhibiting a thermal variation (ΔT) of approximately 4 °C. This precise control over the cooling fluid directly contributed to the stability of the ambient conditions within the moist chamber. As a result, a constant relative humidity between 93% and 95% was achieved, coupled with a stabilized ambient temperature close to 25 °C. These parameters are in strict compliance with the ABNT NBR 9479:2006 standard, which mandates a temperature range of (23 ± 2) °C and a relative humidity of 95% or higher for optimal curing conditions.

The ability of the system to maintain these narrow ranges of temperature and humidity is a significant advancement over manual or less sophisticated automated systems. The continuous monitoring and adjustment facilitated by the ATmega328P microcontroller ensured that any deviations were promptly corrected, thereby minimizing fluctuations that could compromise the hydration process of the cementitious matrices. This stability is crucial for achieving the desired mechanical properties and long-term durability of concrete and mortar specimens.The integration of the physical prototype with features such as reinforced concrete shelves, a uniform spray distribution system, and an efficient gravity drainage network further enhanced the system's performance. The optimized layout ensured that all specimens were exposed to consistent curing conditions, reducing variability in test results and improving the reproducibility of experiments. The chemical waterproofing of the internal surfaces also contributed to the system's longevity and operational integrity.

This automated approach addresses several limitations of conventional moist chambers, including the labor-intensive manual wetting procedures and the susceptibility to seasonal climatic variations. By providing a stable and controlled microenvironment, the system supports the development of advanced cementitious composites, particularly those incorporating supplementary cementitious materials that demand highly stable curing regimes. The successful implementation of this compact moist chamber thus offers a viable and enhanced solution for scientific research and practical activities in science and technology institutions, ensuring that cementitious matrices attain mechanical and durability properties equivalent to those specified in structural designs.

Conclusion:-

This study successfully developed and implemented an automated control and monitoring system for a compact moist chamber, specifically designed for the curing of concrete and mortar specimens. The system effectively maintains the critical environmental parameters of temperature and relative humidity within the strict limits prescribed by ABNT NBR 9479:2006. Through the innovative use of an unconventional refrigeration system and precise microcontroller-based control, the prototype demonstrated its capability to provide a stable curing environment, characterized by a fluid temperature of approximately -4 °C, an ambient temperature near 25 °C, and a relative humidity consistently between 93% and 98%.

The findings confirm that this automated moist chamber significantly mitigates the operational challenges associated with traditional curing methods, such as manual intervention and environmental instability. The enhanced control over curing conditions ensures optimal hydration of cementitious materials, leading to improved mechanical properties and durability of concrete and mortar. This system not only streamlines experimental procedures in material science but also contributes to the reliability and reproducibility of research outcomes. Its implementation is poised to advance scientific research and practical applications in civil engineering and materials technology, ensuring high-quality cementitious composites for various structural applications.

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