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# Assessment of Strength and Durability Properties of Concrete Incorporating Glycerin as a Phase Change Material (PCM)

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**Abstract - The incorporation of phase change materials (PCMs) into concrete has emerged as an effective strategy for enhancing the thermal energy storage capacity of building materials while maintaining satisfactory mechanical performance. This study investigates the influence of glycerin as a bio-based PCM on the mechanical and thermal properties of concrete. Concrete specimens of grades M20, M30, and M40 were prepared with water-to-binder (w/b) ratios of 0.40, 0.45, and 0.50, while glycerin was incorporated at dosages ranging from 0% to 10% by weight of mixing water. Fresh concrete properties were evaluated through slump tests, whereas compressive strength was determined after 7, 28, 56, and 90 days of curing. Thermal performance was assessed by measuring specific heat capacity and thermal diffusivity. In addition, Response Surface Methodology (RSM) was employed to analyze the combined effects of glycerin dosage, water-to-binder ratio, and concrete grade and to identify the optimum mix proportions.**

**The experimental results indicate that increasing glycerin content reduced the workability of concrete, with the reduction becoming more pronounced at higher water-to-binder ratios. Among the investigated mixes, the optimum mechanical performance was achieved at a glycerin dosage of 5% and a water-to-binder ratio of 0.45, irrespective of concrete grade. Higher glycerin dosages resulted in a gradual reduction in compressive strength, which may be attributed to delayed cement hydration and deterioration of the cementitious matrix. Thermal characterization revealed that glycerin significantly improved the heat storage capability of concrete by increasing its specific heat capacity and modifying its thermal diffusivity, thereby enhancing its suitability for thermal energy storage applications. The RSM analysis further confirmed significant nonlinear interactions among the governing parameters and demonstrated the effectiveness of statistical optimization in balancing mechanical strength and thermal performance. The findings suggest that glycerin is a promising, sustainable PCM for energy-efficient concrete applications when incorporated at an optimized dosage.**

**Keywords: Glycerin; Phase Change Material (PCM); Concrete; Thermal Energy Storage; Compressive Strength; Response Surface Methodology; Specific Heat Capacity; Thermal Diffusivity.**

## 1. INTRODUCTION

Concrete is the most widely utilized construction material worldwide owing to its excellent compressive strength, durability, versatility, and cost-effectiveness. It forms the foundation of modern infrastructure, including residential and commercial buildings, bridges, pavements, dams, and other civil engineering structures. However, the rapid growth of urbanization and industrialization has considerably increased the global demand for concrete, leading to significant environmental concerns. The manufacture of cement, the principal binding material in concrete, is highly energy-intensive and contributes substantially to global carbon dioxide emissions. Consequently, the construction industry is increasingly focused on developing innovative concrete materials that not only satisfy structural requirements but also enhance sustainability and energy efficiency.

The building sector accounts for a significant proportion of global energy consumption, with heating, ventilation, and air-conditioning (HVAC) systems representing a major share of operational energy use. In regions characterized by large daily temperature fluctuations, maintaining indoor thermal comfort requires considerable energy expenditure, resulting in increased operating costs and greenhouse gas emissions. Passive thermal energy management has therefore emerged as an effective strategy for reducing building energy demand. Among the various approaches, incorporating thermal energy storage (TES) materials directly into building components has attracted considerable attention because it enables buildings to regulate indoor temperatures without additional energy input.

Phase change materials (PCMs) are considered one of the most promising thermal energy storage media due to their ability to absorb and release substantial amounts of latent heat during phase transitions. Unlike conventional sensible heat storage materials, PCMs store thermal energy at nearly constant temperatures, making them highly effective in moderating indoor temperature fluctuations. When integrated into cement-based materials, PCMs absorb excess heat during periods of elevated ambient temperatures and release the stored heat when temperatures decrease. This cyclic process enhances the thermal inertia of concrete, reduces peak indoor

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temperatures, and decreases dependence on mechanical heating and cooling systems, thereby contributing to improved building energy efficiency.

Phase change materials used in construction are generally classified into organic, inorganic, and eutectic materials. Organic PCMs, including paraffin waxes and fatty acids, exhibit excellent chemical stability, low corrosiveness, and good compatibility with cementitious materials, although their relatively low thermal conductivity limits heat transfer efficiency. Inorganic PCMs, such as salt hydrates, possess higher thermal conductivity and greater energy storage density but are often associated with supercooling, phase segregation, and corrosion-related challenges. Eutectic PCMs combine two or more constituents to achieve desired phase change temperatures and improved thermal performance, thereby overcoming some limitations of conventional organic and inorganic materials. The selection of an appropriate PCM depends on its thermal characteristics, chemical stability, compatibility with cementitious matrices, durability, and cost.

Several techniques have been developed to incorporate PCMs into concrete, including microencapsulation, direct mixing, and surface impregnation. Microencapsulation effectively prevents PCM leakage and improves long-term durability but increases production costs and manufacturing complexity. Surface impregnation provides localized thermal regulation but may result in non-uniform PCM distribution within the concrete matrix. Direct incorporation of PCM into the concrete mixture remains an attractive alternative because of its simplicity and economic feasibility, although careful optimization is necessary to minimize any adverse effects on the mechanical properties of concrete.

Among the various PCM candidates, glycerin has recently emerged as a promising sustainable alternative. Glycerin is an abundant by-product of the biodiesel industry, and its increasing availability has encouraged researchers to explore value-added applications for this material. Owing to its high latent heat storage capacity, non-toxic nature, biodegradability, chemical compatibility with cementitious materials, and excellent thermal stability, glycerin offers significant potential for enhancing the thermal performance of concrete while promoting sustainable waste utilization. Its use as a bio-based PCM also aligns with the growing emphasis on circular economy principles and environmentally responsible construction practices.

Previous investigations have demonstrated that incorporating PCMs into concrete can effectively improve thermal energy storage capacity, reduce indoor temperature variations, and enhance building energy efficiency. However, the inclusion of PCM often influences fresh and hardened concrete properties. Higher PCM dosages may reduce workability, interfere with cement hydration, increase porosity, and consequently decrease compressive strength. Although several studies have investigated conventional PCMs such as paraffin waxes, fatty acids, and encapsulated materials, comparatively limited research has focused on glycerin as a direct phase change material in concrete. Furthermore, existing studies rarely evaluate the combined influence of glycerin dosage, water-to-binder ratio, and concrete grade on both mechanical and thermal performance using advanced statistical optimization techniques.

These research gaps highlight the need for a systematic investigation capable of balancing the conflicting requirements of structural strength and thermal energy storage. In this context, Response Surface Methodology (RSM) provides an efficient statistical framework for evaluating the individual and interactive effects of multiple variables while minimizing experimental effort. RSM enables the development of predictive models and facilitates the identification of optimum mixture proportions capable of simultaneously maximizing mechanical performance and thermal efficiency.

Accordingly, the present study experimentally investigates the influence of glycerin dosage, water-to-binder ratio, and concrete grade on the fresh, mechanical, and thermal properties of concrete. Concrete mixes of grades M20, M30, and M40 were prepared with water-to-binder ratios of 0.40, 0.45, and 0.50, while glycerin was incorporated at dosages ranging from 0 to 10% by weight of mixing water. Workability was evaluated using slump tests, compressive strength was determined at curing ages of 7, 28, 56, and 90 days, and thermal properties were assessed through measurements of specific heat capacity and thermal diffusivity. Furthermore, Response Surface Methodology was employed to develop predictive models and determine the optimum combination of governing variables for achieving enhanced structural performance together with improved thermal energy storage capability. The findings of this investigation contribute to the development of sustainable, energy-efficient concrete materials suitable for future green building applications.

## 2. LITERATURE REVIEW

The integration of Phase Change Materials (PCMs) into cementitious composites has emerged as a promising approach for improving the thermal performance and energy efficiency of buildings. PCMs are capable of absorbing, storing, and releasing significant amounts of latent heat during phase transitions, enabling passive thermal regulation and reducing fluctuations in indoor temperature. Their incorporation into construction materials has therefore attracted considerable attention as an effective strategy for enhancing building energy efficiency while maintaining occupant comfort.

PCMs used in concrete are broadly classified as organic, inorganic, and eutectic materials. Organic PCMs, including paraffin waxes and fatty acids, are widely preferred because of their chemical stability, non-corrosive nature, and compatibility with cementitious materials. Inorganic PCMs, primarily salt hydrates, exhibit higher thermal conductivity and greater heat storage capacity but are often affected by phase segregation, supercooling, and corrosion. Eutectic PCMs combine the favourable characteristics of both organic and inorganic materials by providing tailored phase change temperatures and improved thermal performance. The selection

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of an appropriate PCM depends on its thermal characteristics, chemical compatibility, durability, and long-term stability within the cement matrix.

Several techniques have been proposed for incorporating PCMs into concrete, including direct mixing, encapsulation, and surface impregnation. Encapsulation effectively prevents leakage and enhances long-term durability but increases manufacturing complexity and cost. Surface impregnation provides localized thermal regulation but may result in uneven PCM distribution. Direct incorporation remains the simplest and most economical method, although excessive PCM content may adversely influence fresh and hardened concrete properties. Consequently, optimizing the dosage and incorporation technique remains essential for achieving a balance between thermal efficiency and structural performance.

Among the emerging bio-based PCMs, glycerin has attracted increasing attention owing to its availability as a by-product of biodiesel production, low cost, environmental friendliness, biodegradability, and excellent thermal stability. In addition to its favourable latent heat storage capacity, glycerin exhibits good compatibility with cementitious materials and has the potential to improve the thermal energy storage capability of concrete. At lower dosages, glycerin may enhance the fresh properties of concrete by acting as a plasticizing agent; however, excessive amounts can increase porosity, delay cement hydration, and reduce compressive strength. These characteristics make glycerin a promising but dosage-sensitive PCM for sustainable concrete applications.

Previous studies have consistently demonstrated that PCM incorporation improves the thermal performance of concrete by increasing specific heat capacity, reducing thermal diffusivity, and enhancing the thermal inertia of building components. The improved heat storage capability contributes to lower peak indoor temperatures and reduced energy demand for heating and cooling systems. Nevertheless, the incorporation of PCMs generally introduces challenges related to mechanical performance. Several investigations have reported reductions in compressive strength at higher PCM contents due to increased porosity, weaker interfacial bonding, and interference with cement hydration. Therefore, the successful application of PCM-enhanced concrete depends on achieving an optimum balance between thermal efficiency and structural integrity.

Response Surface Methodology (RSM) has become an effective statistical optimization tool in concrete research because it enables the simultaneous evaluation of multiple interacting variables while minimizing the number of experimental trials. By developing predictive mathematical models, RSM facilitates optimization of mixture proportions and provides insight into the combined influence of material parameters on concrete performance. The Central Composite Design (CCD) is widely employed to investigate linear, quadratic, and interaction effects among variables, making it particularly suitable for optimizing PCM-modified concrete mixtures.

Recent investigations further support the potential of PCM-enhanced concrete for sustainable construction. Aguayo et al. (2018) demonstrated that PCM incorporation improves thermal energy storage but may reduce compressive strength due to changes in cement hydration. Frigione et al. (2019) highlighted the importance of encapsulation techniques in improving the long-term stability of PCM-based cement composites. Sun et al. (2020) reported that glycerin improves fresh concrete behaviour at controlled dosages, whereas excessive glycerin retards hydration and strength development. Similarly, Zhang et al. (2020) observed enhanced thermal storage performance in microencapsulated PCM concrete accompanied by reductions in compressive strength and elastic modulus. Subsequent reviews by Gunasekara et al. (2021), Cabeza et al. (2021), Sharma et al. (2022), Zhou et al. (2022), Rashid et al. (2023), Li et al. (2023), Jia et al. (2024), and Wagh and Vinaykumar (2024) consistently concluded that PCM integration improves thermal regulation and building energy efficiency while emphasizing the need to optimize incorporation methods to minimize adverse effects on mechanical properties.

Despite these advances, important research gaps remain. Most published studies have focused on conventional PCMs such as paraffin waxes, fatty acids, salt hydrates, or encapsulated materials, whereas comparatively limited attention has been given to glycerin as a directly incorporated bio-based PCM. Furthermore, the combined influence of glycerin dosage, water-to-binder ratio, and concrete grade on both thermal and mechanical performance has not been comprehensively investigated. Existing studies also provide limited information regarding the statistical optimization of these variables using Response Surface Methodology.

Accordingly, the present study addresses these research gaps by experimentally evaluating concrete containing varying glycerin contents across different water-to-binder ratios and concrete grades. In addition to assessing workability, compressive strength, and thermal properties, the study employs Response Surface Methodology to model the interactions among the governing variables and identify the optimum mix proportions capable of simultaneously enhancing structural performance and thermal energy storage. This integrated approach contributes to the development of sustainable, energy-efficient concrete suitable for future green building applications.

## 3. MATERIALS AND METHODS

### 3.1 Materials

Ordinary Portland Cement (OPC) of 53 grade conforming to **IS 12269:2013** was used as the primary binder throughout the experimental program. The cement was procured from a single manufacturing batch to minimize material variability. Its physical

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and chemical properties satisfied the requirements of the relevant Indian Standard, indicating its suitability for structural concrete applications.

Crushed coarse aggregates with a nominal maximum size of 20 mm were used in accordance with **IS 2386 (Part I–VIII):1963 (Revised 2016)**. Prior to mixing, the aggregates were washed and air-dried to achieve uniform moisture conditions. The aggregates exhibited low water absorption and satisfactory mechanical characteristics, including abrasion, impact, and crushing values, confirming their suitability for producing durable structural concrete. Natural river sand conforming to **IS 383:2016** (Zone III) was used as fine aggregate. The grading and physical properties of the sand ensured adequate workability and strength development in the concrete mixtures.

High-purity glycerin (>99.9%) with a specific gravity of 1.27 was employed as the phase change material (PCM). Owing to its high latent heat storage capacity, thermal stability, and compatibility with cementitious materials, glycerin was selected to investigate its influence on the fresh, mechanical, and thermal performance of concrete.

**Table 1-** Mix proportion and nomenclature

| **Mix** | **Glycerin** | **w/b** | **Grade** | **Cement** | **Sand** | **Coarse Aggregate** | **Water** | **Glycerin** |
|---|---|---|---|---|---|---|---|---|
| **Units** | **%** | **-** | **MPa** | **kg/m³** | | | | |
| A0 | 0 | 0.4 | 20 | 395 | 818 | 1041 | 197 | 0 |
| A1 | 2.5 | 0.4 | 20 | 395 | 818 | 1041 | 197 | 4.925 |
| A2 | 5 | 0.4 | 20 | 395 | 818 | 1041 | 197 | 9.85 |
| A3 | 7.5 | 0.4 | 20 | 395 | 818 | 1041 | 197 | 14.775 |
| A4 | 10 | 0.4 | 20 | 395 | 818 | 1041 | 197 | 19.7 |
| A5 | 0 | 0.45 | 20 | 374 | 581 | 947 | 192 | 0 |
| A6 | 2.5 | 0.45 | 20 | 374 | 581 | 947 | 192 | 4.8 |
| A7 | 5 | 0.45 | 20 | 374 | 581 | 947 | 192 | 9.6 |
| A8 | 7.5 | 0.45 | 20 | 374 | 581 | 947 | 192 | 14.4 |
| A9 | 10 | 0.45 | 20 | 374 | 581 | 947 | 192 | 19.2 |
| A10 | 0 | 0.5 | 20 | 362 | 436 | 872 | 186 | 0 |
| A11 | 2.5 | 0.5 | 20 | 362 | 436 | 872 | 186 | 4.65 |
| A12 | 5 | 0.5 | 20 | 362 | 436 | 872 | 186 | 9.3 |
| A13 | 7.5 | 0.5 | 20 | 362 | 436 | 872 | 186 | 13.95 |
| A14 | 10 | 0.5 | 20 | 362 | 436 | 872 | 186 | 18.6 |
| B0 | 0 | 0.4 | 30 | 422 | 687 | 989 | 197 | 0 |
| B1 | 2.5 | 0.4 | 30 | 422 | 687 | 989 | 197 | 4.925 |
| B2 | 5 | 0.4 | 30 | 422 | 687 | 989 | 197 | 9.85 |
| B3 | 7.5 | 0.4 | 30 | 422 | 687 | 989 | 197 | 14.775 |
| B4 | 10 | 0.4 | 30 | 422 | 687 | 989 | 197 | 19.7 |
| B5 | 0 | 0.45 | 30 | 410 | 552 | 963 | 193 | 0 |
| B6 | 2.5 | 0.45 | 30 | 410 | 552 | 963 | 193 | 4.825 |
| B7 | 5 | 0.45 | 30 | 410 | 552 | 963 | 193 | 9.65 |
| B8 | 7.5 | 0.45 | 30 | 410 | 552 | 963 | 193 | 14.475 |
| B9 | 10 | 0.45 | 30 | 410 | 552 | 963 | 193 | 19.3 |
| B10 | 0 | 0.5 | 30 | 400 | 441 | 895 | 189 | 0 |
| B11 | 2.5 | 0.5 | 30 | 400 | 441 | 895 | 189 | 4.725 |
| B12 | 5 | 0.5 | 30 | 400 | 441 | 895 | 189 | 9.45 |
| B13 | 7.5 | 0.5 | 30 | 400 | 441 | 895 | 189 | 14.175 |
| B14 | 10 | 0.5 | 30 | 400 | 441 | 895 | 189 | 18.9 |
| C0 | 0 | 0.4 | 40 | 435 | 449 | 648 | 184 | 0 |
| C1 | 2.5 | 0.4 | 40 | 435 | 449 | 648 | 184 | 4.6 |
| C2 | 5 | 0.4 | 40 | 435 | 449 | 648 | 184 | 9.2 |
| C3 | 7.5 | 0.4 | 40 | 435 | 449 | 648 | 184 | 13.8 |
| C4 | 10 | 0.4 | 40 | 435 | 449 | 648 | 184 | 18.4 |
| C5 | 0 | 0.45 | 40 | 415 | 421 | 623 | 187 | 0 |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| C6 | 2.5 | 0.45 | 40 | 415 | 421 | 623 | 187 | 4.675 |
| C7 | 5 | 0.45 | 40 | 415 | 421 | 623 | 187 | 9.35 |
| C8 | 7.5 | 0.45 | 40 | 415 | 421 | 623 | 187 | 14.025 |
| C9 | 10 | 0.45 | 40 | 415 | 421 | 623 | 187 | 18.7 |
| C10 | 0 | 0.5 | 40 | 409 | 417 | 631 | 200 | 0 |
| C11 | 2.5 | 0.5 | 40 | 409 | 417 | 631 | 200 | 5 |
| C12 | 5 | 0.5 | 40 | 409 | 417 | 631 | 200 | 10 |
| C13 | 7.5 | 0.5 | 40 | 409 | 417 | 631 | 200 | 15 |
| C14 | 10 | 0.5 | 40 | 409 | 417 | 631 | 200 | 20 |

### 3.2 Experimental Programme

The experimental investigation was designed to evaluate the combined influence of concrete grade, water-to-binder (w/b) ratio, and glycerin dosage on the properties of concrete. Three concrete grades, namely M20, M30, and M40, were selected to represent normal-, medium-, and high-strength concrete. For each grade, three water-to-binder ratios (0.40, 0.45, and 0.50) were considered. Glycerin was incorporated at dosages of 0%, 2.5%, 5.0%, 7.5%, and 10% by weight of mixing water, with the control mixture containing no glycerin. Concrete mix proportions were designed in accordance with **IS 10262:2019**, while maintaining consistent aggregate grading and cement content within each concrete grade. This experimental matrix enabled a systematic evaluation of the individual and interactive effects of the governing variables.

Fresh concrete properties were evaluated immediately after mixing using the standard slump test. Hardened concrete specimens were cured under standard laboratory conditions, and compressive strength was determined after 7, 28, 56, and 90 days using 150 × 150 × 150 mm cube specimens. Thermal conductivity and specific heat capacity were measured at 28 days using cylindrical specimens (100 × 200 mm), while thermal diffusivity was calculated from the measured thermal conductivity and specific heat capacity values. The testing procedures were conducted in accordance with the relevant Indian Standards to ensure accuracy and reproducibility of the experimental results.

### 3.3 Response Surface Methodology

Response Surface Methodology (RSM) was adopted as the statistical optimization tool to investigate the combined effects of glycerin dosage and water-to-binder ratio on concrete performance. A Central Composite Design (CCD) was employed to establish second-order polynomial regression models capable of describing the linear, quadratic, and interaction effects of the experimental variables. Compared with conventional factorial experimentation, CCD substantially reduces the number of experimental trials while maintaining high predictive capability.

The developed regression models were used to predict the responses of interest, including workability, compressive strength, and thermal properties, within the selected experimental domain. Statistical adequacy of the models was evaluated using analysis of variance (ANOVA), coefficients of determination ($R^2$ and adjusted $R^2$), and lack-of-fit analysis. Three-dimensional response surface plots and contour diagrams were further employed to visualize the interaction between variables and identify the optimum combination of glycerin dosage and water-to-binder ratio capable of maximizing both mechanical and thermal performance.

## 4. RESULTS AND DISCUSSION

### 4.1 Compressive Strength

Figure 1 presents the compressive strength development of glycerin-modified concrete at curing ages of 7, 28, 56, and 90 days. Compressive strength increased with curing time for all concrete grades, indicating continuous hydration and progressive densification of the cementitious matrix. The influence of glycerin was strongly dosage-dependent. Incorporation of glycerin up to approximately **5–7.5%** enhanced compressive strength across all concrete grades, whereas further increase to **10%** resulted in a reduction in strength. This behaviour can be attributed to improved dispersion of cement particles and enhanced moisture retention at moderate dosages, while excessive glycerin likely delayed hydration and increased microstructural porosity.

Among the investigated mixtures, M40 concrete with a water-to-binder ratio of **0.40–0.45** exhibited the highest compressive strength throughout the curing period. Lower-grade concretes (M20 and M30) followed similar trends but achieved comparatively lower strength because of their reduced cementitious content. Strength gain between 28 and 90 days was relatively small, indicating completion of hydration and stabilization of the microstructure. These findings demonstrate that optimum glycerin incorporation improves both early-age and long-term mechanical performance when combined with an appropriate water-to-binder ratio.

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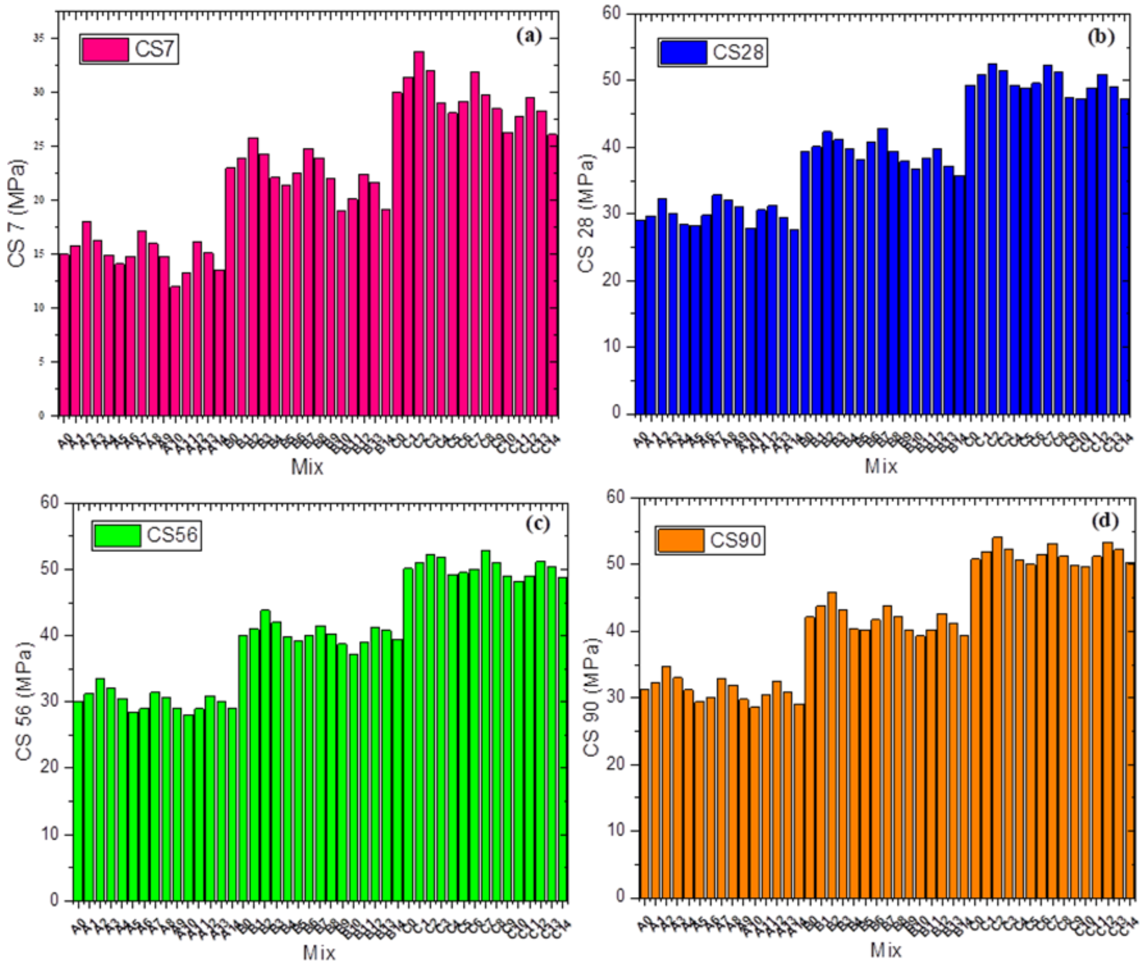


**Figure 1:** Compressive Strength (a) 7 days, (b) 28 days, (c) 56 days (d) 90 days

### 4.2 Validation of the RSM Model

The adequacy of the Response Surface Methodology (RSM) model was assessed using standard diagnostic plots, including normal probability plots, residual analysis, Cook's distance, Box–Cox transformation, DFFITS, and predicted-versus-actual plots (Fig. 2). The residuals followed an approximately normal distribution, and random scatter of studentized residuals confirmed homoscedasticity and independence of observations. Cook's distance and DFFITS values remained below the recommended limits, indicating the absence of influential observations. Furthermore, the Box–Cox analysis suggested that no transformation of the response variable was required. The close agreement between predicted and experimental values confirmed that the developed quadratic model accurately describes the compressive strength behaviour of glycerin-incorporated concrete and is suitable for subsequent optimization.

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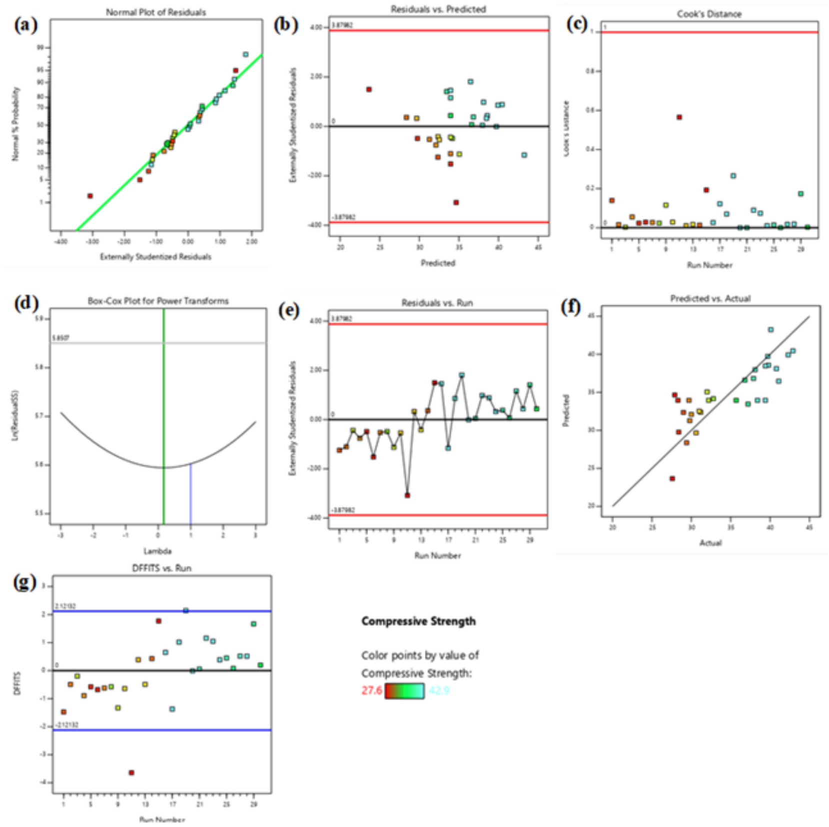


**Fig. 2** Diagnostic plots for the RSM model based on central composite design for Compressive Strength (a) Normal probability plot, (b) Externally studentized residuals vs. predicted values, (c) Box-Cox plot, (d) Cook's Distance vs run number, (e) Predicted vs. actual values, (f) Externally studentized residuals vs. run number, (g) DFFITS vs run number

### 4.3 Response Surface Analysis of Compressive Strength

Three-dimensional response surface plots (Fig. 3) illustrate the interaction between glycerin dosage, water-to-binder ratio, concrete grade, and workability on compressive strength. The results indicate that the water-to-binder ratio is the most influential parameter governing strength development. Lower water-to-binder ratios produced denser microstructures and consequently higher compressive strengths. Glycerin exhibited a nonlinear effect, with strength increasing up to an optimum dosage of **5–7.5%** before declining at higher concentrations. Higher concrete grades consistently achieved superior strength owing to increased cement content and improved matrix density. Although slump exhibited only a secondary influence, excessive workability associated with higher water contents resulted in slight reductions in compressive strength. Overall, the response surfaces identified an optimum region corresponding to **5–7.5% glycerin**, a **water-to-binder ratio of 0.40–0.45**, and **M40 concrete**, which provided the maximum compressive strength.

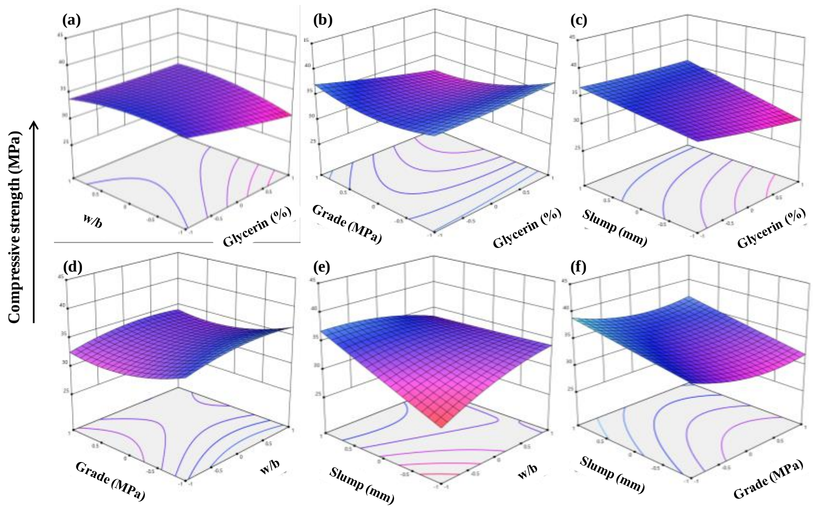

**Figure 3:** Three-dimensional response surface plots showing the interaction between glycerin dosage, water-to-binder ratio, and compressive strength.

### 4.4 Specific Heat Capacity

The incorporation of glycerin substantially enhanced the specific heat capacity of concrete, demonstrating its effectiveness as a bio-based phase change material. The RSM model developed for predicting specific heat capacity satisfied all statistical assumptions, including normality of residuals, constant variance, and absence of influential outliers. Excellent agreement between predicted and experimental values confirmed the reliability of the developed regression model for thermal performance evaluation.

### 4.5 Response Surface Analysis of Specific Heat Capacity

The three-dimensional response surfaces (Fig. 4) indicate that glycerin dosage is the dominant factor influencing the specific heat capacity of concrete. Specific heat capacity increased progressively with glycerin incorporation up to approximately 5–7.5%, beyond which the rate of improvement became marginal. Lower water-to-binder ratios and higher concrete grades provided slight additional improvements because of their denser microstructures and enhanced moisture retention. Slump exhibited only a minor influence compared with glycerin dosage. These results demonstrate that glycerin significantly improves the thermal energy storage capacity of concrete while maintaining satisfactory mechanical performance when incorporated at optimized levels.

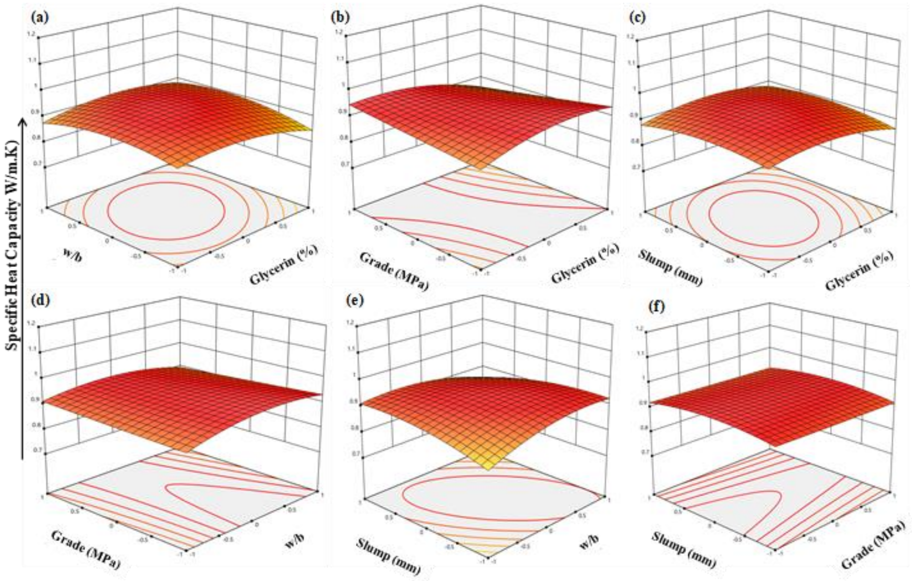


**Figure 4:** 3D surface plots for Specific heat capacity

## 5. CONCLUSIONS

This study investigated the mechanical and thermal performance of glycerin-incorporated concrete by evaluating the combined influence of glycerin dosage, water-to-binder (w/b) ratio, and concrete grade using an experimental approach integrated with Response Surface Methodology (RSM). The results demonstrate that glycerin can serve as an effective bio-based phase change material (PCM), enhancing the thermal energy storage capability of concrete while maintaining satisfactory mechanical performance when incorporated at an optimum dosage.

The experimental results revealed that glycerin significantly influenced both the fresh and hardened properties of concrete. Workability decreased progressively with increasing glycerin content, whereas compressive strength exhibited a dosage-dependent response. An optimum glycerin content of **5–7.5%** (by weight of mixing water) produced the highest compressive strength across all concrete grades. Beyond this range, strength decreased due to delayed cement hydration, increased microstructural porosity, and reduced interparticle bonding. Lower water-to-binder ratios (0.40–0.45) consistently produced superior mechanical performance because of reduced capillary porosity and improved matrix densification. Among the investigated mixtures, **M40 concrete** incorporating **5–7.5% glycerin** achieved the highest compressive strength, reaching approximately **55–57 MPa** after 90 days of curing.

Thermal characterization confirmed that glycerin effectively enhanced the thermal energy storage capability of concrete. The incorporation of glycerin increased the specific heat capacity while reducing thermal conductivity and thermal diffusivity, thereby improving the thermal insulation performance of the concrete. These improvements indicate that glycerin-modified concrete can effectively moderate temperature fluctuations and contribute to passive thermal regulation in buildings. However, thermal improvements approached a saturation level beyond approximately **7.5% glycerin**, suggesting that excessive glycerin provides limited additional thermal benefits.

The Response Surface Methodology based on Central Composite Design successfully captured the nonlinear relationships and interaction effects among glycerin dosage, water-to-binder ratio, concrete grade, and workability. Diagnostic analyses confirmed the statistical adequacy and predictive capability of the developed models, demonstrating their suitability for optimizing both mechanical and thermal performance. Multi-response optimization identified an optimum design region consisting of a **water-to-binder ratio of 0.40–0.45**, **glycerin dosage of 5–7.5%**, and **medium- to high-strength concrete (M30–M40)**, providing an effective balance between structural performance and thermal energy storage.

**Table 2** Details of experiments carried out

| S.No | Test | Age of concrete (days) | Specimen size (mm) | Apparatus/instrument |
|---|---|---|---|---|
| 1 | Slump | Fresh concrete | - | Standard slump cone |
| 2 | Compressive strength | 7, 28, 56, 90 | 150X150X150 (cube) | Compression testing machine / universal testing machine |
| 3 | Thermal Conductivity | 28 | 100 X 200 (Cylindrical) | KD2-Pro thermal conductivity analyzer |
| 4 | Specific Heat Capacity | 28 | 100 X 200 (Cylindrical) | Calorimeter |
| 5 | Thermal Diffusivity | 28 | Computed based on Thermal conductivity and Specific Heat Capacity | |

Overall, the findings demonstrate that glycerin is a promising sustainable additive for multifunctional concrete applications. By simultaneously improving thermal energy storage and maintaining adequate structural performance, glycerin-modified concrete offers significant potential for energy-efficient buildings, passive thermal regulation systems, and environmentally sustainable infrastructure. The integration of experimental investigation with statistical optimization provides a practical framework for designing next-generation concrete materials that satisfy both structural and energy-performance requirements.

## FUTURE SCOPE

Future research should investigate the long-term durability of glycerin-modified concrete under aggressive environmental conditions, including freeze–thaw cycles, chloride penetration, sulfate attack, and carbonation. Microstructural characterization using techniques such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Thermogravimetric Analysis (TGA) would provide further insight into the interaction between glycerin and cement hydration products. In addition, life-cycle assessment (LCA), techno-economic evaluation, and large-scale field validation are recommended to assess the practical feasibility of glycerin-modified concrete in commercial energy-efficient construction. Further studies may also explore hybrid PCM systems combining glycerin with supplementary cementitious materials or encapsulation techniques to improve long-term thermal stability and mechanical durability.

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