Evaluation of Crack Sealing Performance in Concrete with Various Agents.

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ABSTRACT

The paper investigates the crack-sealing performance of concrete modified with different chemical and supplementary agents such as epoxy resin, encapsulated epoxy, gypsum, fly ash, and coconut coir. Cracking in concrete structures remains a critical problem, reducing durability and increasing maintenance costs, particularly in resource-limited settings. This research attempts to address such challenges by exploring self-healing concrete systems that can enhance service life while remaining cost-effective. Laboratory-scale cube and cylinder specimens were prepared and tested for compressive and split tensile strength at 7 and 28 days, with controlled crack induction to assess healing potential. Results showed that epoxy resin provided the highest early-age strength gain and effective crack sealing, while gypsum demonstrated moderate sealing but a reduction in strength. Fly ash combined with coir offered comparable strength to control mixes and highlighted potential for sustainable applications, although untreated coir fibers partially degraded within the cement matrix. Encapsulated epoxy samples revealed delayed but visible crack healing, validating the potential of encapsulation systems for long-term applications. The study highlights both the opportunities and limitations of different agents, emphasizing the need for durability assessment under environmental exposure, performance in reinforced specimens, and the treatment of natural additives to improve compatibility. The findings suggest that chemical agents like epoxy deliver immediate performance benefits, while supplementary additives like fly ash and coir open avenues for sustainable, affordable self-healing concrete solutions.

Keywords: Self-healing concrete, crack-sealing agents, epoxy resin, gypsum, fly ash, coir, compressive strength, sustainability

1. INTRODUCTION

Concrete is one of the most widely used construction material globally due to its high compressive strength, versatility, and affordability. However, one of its major limitations lies in its susceptibility to cracking under mechanical and environmental stresses during service life. These cracks, although sometimes micro in scale, serve as vulnerable pathways for the ingress of water, oxygen, and harmful ions, which accelerate steel reinforcement corrosion and significantly reduce the lifespan of the structure (Edvardsen, 1999). This issue becomes more pronounced in developing countries like Nepal, where maintenance and repair practices are often limited due to financial or technical constraints.

To mitigate this problem, the concept of **self-healing concrete (SHC)** has emerged as a sustainable innovation in the field of civil engineering materials. The idea is to develop a concrete that can autonomously repair its own cracks, much like biological systems heal wounds. Initially proposed in the early 1990s and formally researched in the 2000s, SHC has since gained attention for its potential to enhance durability, reduce maintenance costs, and extend the service life of concrete structures (Jonkers et al., 2010).

Multiple self-healing mechanisms have been explored globally, including **autogenous healing**, **microbial-induced healing**, **chemical healing through expansive or crystalline agents**, and **encapsulation techniques** using polymers. Researchers like Hearn (1998) and Van Tittelboom et al. 2011) have demonstrated that self-healing can occur naturally through continued hydration of unreacted cement or precipitation of calcium carbonate. However, these mechanisms often work effectively only under specific environmental conditions and are limited in healing crack widths larger than 0.2–0.3 mm.

Despite significant international progress in SHC research, practical implementation is still in its infancy—especially in regions like Nepal, where low-cost, locally available materials are preferred. Moreover, many studies have focused either on complex microbial systems that require controlled environments or on expensive polymer-based capsules. This creates a critical research gap for testing simpler, cost-effective healing agents that can perform under standard field conditions.

This study focuses on bridging this gap by evaluating and comparing the performance of **four self-healing agents**: **epoxy resin**, **epoxy resin encapsulated using gelatin and gum arabic**, **gypsum**, and a combination of **fly ash and coconut coir fibers**. The agents were selected based on a thorough literature review of their healing mechanisms, compatibility with cementitious materials, and practical feasibility in the context of Nepalese infrastructure.

Unlike other studies that rely solely on cubes or theoretical healing evaluations, this study includes both cube and cylinder specimens where necessary (e.g., for tensile evaluation with fly ash + coir). Healing was assessed using sealing observations. OPC (43 Grade) was used throughout to ensure early-age strength and reduce variability, and steel reinforcement was intentionally avoided to eliminate corrosion-related confounding effects during healing evaluation.

By exploring these agents within a controlled experimental setup, our aim is not only to understand their individual healing capacities but also to determine their practical application potential for real-world structural repairs and new builds—especially in rural and low-budget environments. This work builds upon previous research while introducing novel combinations (e.g., fly ash with coir) that are yet to be extensively studied. Ultimately, this study contributes to the broader effort of developing sustainable, self-repairing materials that align with the needs of emerging economies.

2. OBJECTIVE OF THE STUDY

2.1 Main Objective

The main objective of this study is to evaluate the feasibility and effectiveness of using different self-healing agents such as epoxy resin, epoxy encapsulated in gelatin-gum arabic, gypsum, and a combination of fly ash with coconut coir, in Ordinary Portland Cement (OPC)-based concrete. The study aims to assess their crack-sealing capability, practicality for application in Nepalese infrastructure.

2.2 Specific Objectives

To compare the early age compressive strength of concrete samples incorporated with various self-healing agents against control specimens, in accordance with IS 516 (Bureau of Indian Standards, 1959).

To observe visual crack sealing and self-healing phenomena by inducing artificial cracks and monitoring over time.

To investigate the water-cement ratio, workability (slump), and healing efficiency of each agent through experimental testing.

To examine the practical feasibility of using low-cost, locally available materials such as fly ash and coconut coir as self-healing components in Nepal's construction context.

To contribute to existing literature by presenting experimental data on less-studied healing agents like gypsum and natural fibers, and assess their sustainability and cost-effectiveness in concrete applications.

3. METHODOLOGY

Two research methods were primarily adopted in this study to ensure scientific accuracy and practical feasibility. They are:

- **Experimental Method**
- **Literature Review and Material Source Mapping**

3.1 Experimental Method

This research involves a comparative experimental analysis of various self-healing agents: **epoxy resin**, **epoxy encapsulated in gelatin-gum arabic**, **gypsum**, and a hybrid of **fly ash with coconut coir fibers**. A control mix was also prepared for reference.

3.1.1 Materials Used

- ➢ **Cement:** OPC 43 grade (Huaxin), with a specific gravity of 3.15, was used throughout.
- ➢ **Fine Aggregates**: Locally available river sand, sieved through 4.75 mm IS sieve.
- ➢ **Coarse Aggregates**: Angular crushed stone, <20 mm size.
- ➢ **Water**: Clean tap water suitable for concrete mixing and curing.
- ➢ **Self-Healing Agents**:
- ✓ Epoxy Resin: 555g used with w/c = 0.55.
- ✓ Encapsulated Epoxy: 180g epoxy + 45g hardener encapsulated in 100g gelatin and 100 ml gum arabic solution.
- ✓ Gypsum: Added at 17% of cement weight.
- ✓ Fly Ash + Coir: Fly ash partially replaced cement; coir fibers pretreated and added as reinforcement.

3.1.2 Specimen Details

- **Cube Size**: 150 mm × 150 mm × 150 mm for compressive testing.
- **Cube Size**: 70 mm × 70 mm × 70 mm for healing assessment. (epoxy resin and epoxy encapsulation).
- **Cylinder Size**: 150 mm diameter × 300 mm height used for compressive strength and split tensile testing (gypsum and fly ash–coir specimens).

3.2 Testing Methods

3.2.1 Workability (Slump Test)

Workability was assessed as per **IS 1199:1959**, using the slump cone method. Variations in slump among mixes were observed due to differing agent compositions.

3.2.2 Compressive Strength Test

As per **IS 516:1959**, cube compressive strength was determined at 7 and 28 days. The load was applied using a compression testing machine, and results were recorded in MPa.

3.2.3 Induction and Observation of Healing

Cracks were manually induced using compressive strength testing machine at 16th day of curing.

Crack sealing was observed at 28th day.

3.2.4 Cylinder Tensile Testing

Cylinders were used to assess split tensile strength particularly of fly ash–coir mixes where matrix bonding and fiber bridging could be observed.

3.2.5 Cylinder Compressive Testing

Cylinders were used to assess compressive strength particularly of gypsum mix where effect of high percentage of gypsum could be observed.

3.3 Literature Review and Material Source Mapping

A comprehensive review of national and international standards (e.g., IS 456, IS 10262, ACI 224R), academic journals (e.g., Edvardsen, 1999; Jonkers et al., 2010; Van Tittelboom et al., 2011), and previous studies on self-healing agents guided the experimental approach.

Materials such as fly ash and gypsum were selected not only for their healing potential but also for their availability in the Nepalese context, with field visits conducted to United Cement, Naubise, Kathmandu for sample collection.

4. RESULTS

This section outlines the findings of strength recovery and healing efficiency of various self-healing agents used in concrete, through compressive strength tests conducted at specified intervals, slump tests for workability, and visual assessments after crack induction.

4.1 Compressive Strength Test

A total of five different concrete mixes were tested for compressive strength at both 7-day and 28-day intervals: **Control Mix**, **Epoxy Resin**, **Epoxy Encapsulated**, **Gypsum**, and **Fly Ash + Coconut Coir**. The compressive strength was measured on standard cubes of size 150 mm × 150 mm × 150 mm in accordance with **IS 516 (1959)**.

7-Day Compressive Strength (MPa)

Table 1: 7th day compressive strength

Mix Type	Sample 1	Sample 2	Sample 3	Average
Control	11.08	12.98	14.10	14.50
Epoxy Resin	13.74	16.58	15.05	15.12
Epoxy Encapsulation	15.00	12.99	13.00	13.66
Gypsum	11.26	13.00	11.26	11.84
Fly Ash + Coir	13.97	14.69	14.46	14.37

Table 1 presents the 7-day compressive strength results of concrete specimens with different crack-sealing agents. The control mix achieved an average strength of **14.50 MPa**, which served as the reference. Among the modified mixes, epoxy resin exhibited the highest strength (**15.12 MPa**), showing a notable improvement over the control. Epoxy encapsulation also reached a comparable strength (**13.66 MPa**), though slightly lower than epoxy resin. The gypsum-modified mix showed the lowest strength (**11.84 MPa**), indicating that its addition reduced the early-age strength of concrete. Interestingly, the fly ash with coir mix achieved **14.37 MPa**, very close to the control. Overall, epoxy resin demonstrated the most significant enhancement in 7-day compressive strength, while gypsum had an adverse effect.

28-Day Compressive Strength (MPa)

Table 2: 28th day compressive strength

Mix Type	Sample 1	Sample 2	Sample 3	Average
Control	22.62	18.48	17.21	19.19

Epoxy Resin	15.55	20.28	15.32	17.04
Epoxy Encapsulation	13.92	16.31	11.71	13.98
Gypsum	15.05	17.12	16.99	16.37
Fly Ash + Coir	14.37	16.76	18.93	16.68

Table 2 presents the 28-day compressive strength results of concrete specimens with different crack-sealing agents. The control mix achieved an average strength of **19.19 MPa**, which served as the reference. Among the modified mixes, **fly ash with coir exhibited the highest strength (16.69 MPa)**, showing a relatively better long-term performance compared to other agents. The **gypsum-modified mix also performed well (16.39 MPa)**, achieving strength values close to fly ash with coir. The **epoxy resin mix reached an average of 17.05 MPa**, slightly below the control but still maintaining considerable strength. However, the **epoxy encapsulation mix showed the lowest strength (13.98 MPa)**, indicating reduced efficiency in improving long-term compressive capacity. Overall, while none of the additives surpassed the control in strength, **fly ash with coir and gypsum demonstrated promising potential** by achieving strengths close to the control.

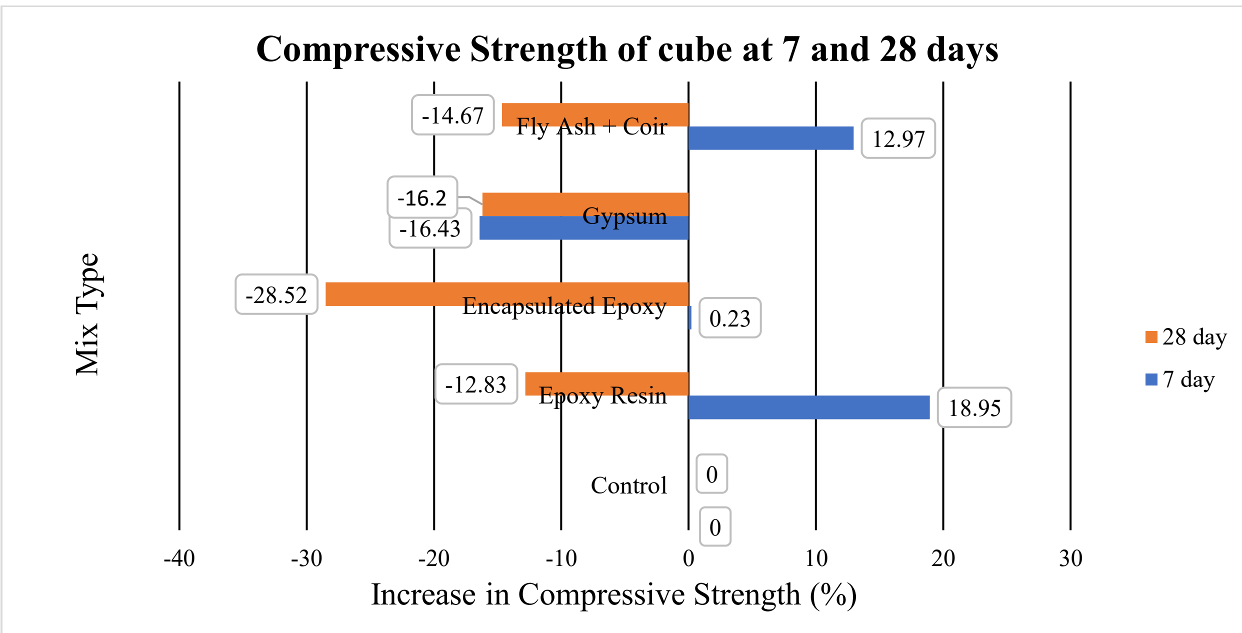

Figure 1: Increase in compressive strength

Fig. 1 presents the percentage deviation in compressive strength of modified concrete mixes compared to the control at 7 and 28 days. At 7 days, epoxy resin achieved the highest improvement of **18.95%**, followed by fly ash + coir at **12.97%**, both exceeding the control mix. In contrast, gypsum (−16.43%) and epoxy encapsulation (0.23%) exhibited reduced or negligible strength gains at early ages.

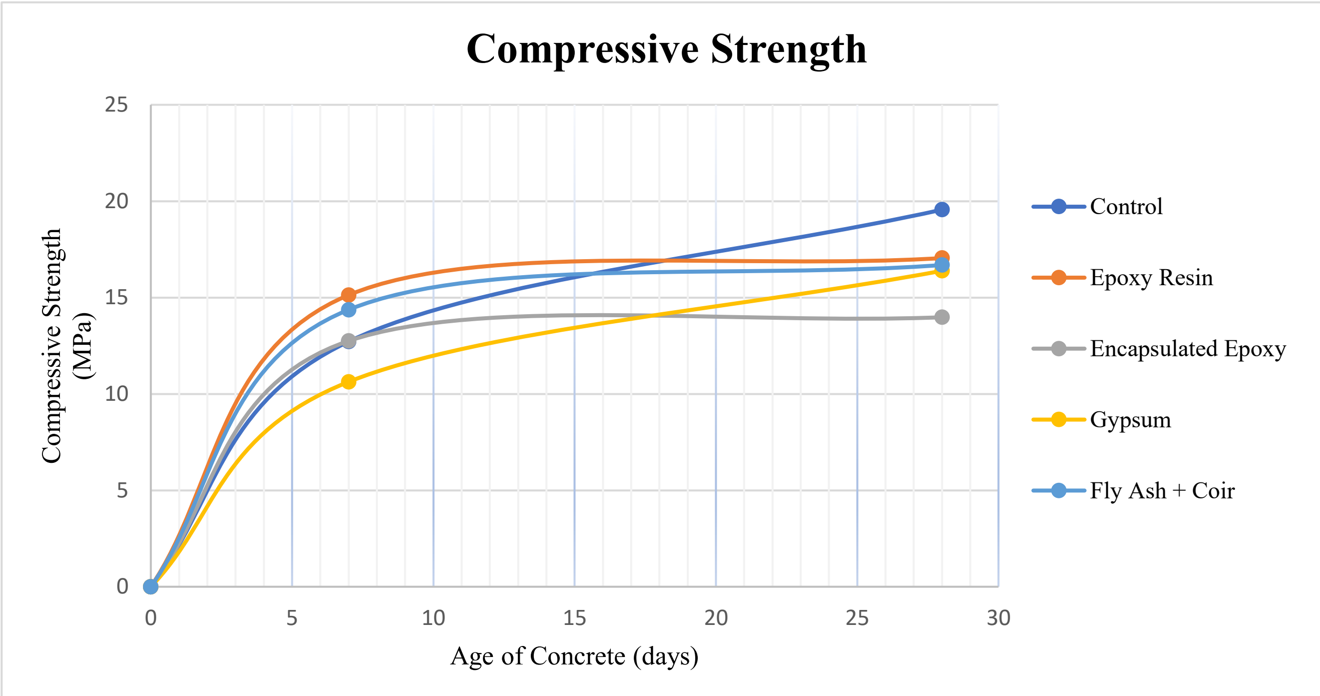

Figure 2: Compressive strength of different mixes

At 28 days, the trend shifted, with **all modified mixes showing lower strength than the control**. Encapsulated epoxy maintained farthest parity with the control **(-28.52%)**, while epoxy resin (−12.83%), gypsum (−16.20%), and fly ash + coir (−14.67%) recorded significant reductions. Notably, encapsulated epoxy demonstrated consistent strength retention at later ages, whereas other mixes showed early gains but subsequent decline in performance.

Fig 2 shows the strength curve for all the mixes including control mix. In the case of epoxy resin mix, an increase in early age strength is found more than 28 days. It is also observed that control mix had the highest 28th day strength.

4.3 Cylinder Split Tensile Strength

Table 3: Split tensile strength

Mix Type	Load(kN)	Flexural strength (Mpa)
Fly ash + coir	197.66	2.80
	205.77	2.91
	145.94	2.06
Average	-	2.59

Table 3 presents the split tensile strength results of concrete cylinders modified with fly ash and coir. The specimens recorded flexural strengths ranging from 2.06 MPa to 2.91 MPa, with an average strength of 2.59 MPa. This indicates that the addition of fly ash and coir provided a moderate tensile capacity.

4.2 Compressive Strength of Core

Table 4: Compressive strength of gypsum core

Mix type	Compressive strength (Mpa)
Gypsum	24.64
	15.22
	13.38

Table 4 presents the compressive strength results of core specimens prepared with gypsum. The measured values ranged from 13.38 MPa to 24.64 MPa, showing significant variation among the samples. The highest strength (24.64 MPa) indicates that gypsum incorporation can locally enhance compressive performance, while the lower results suggest variability in its effectiveness.

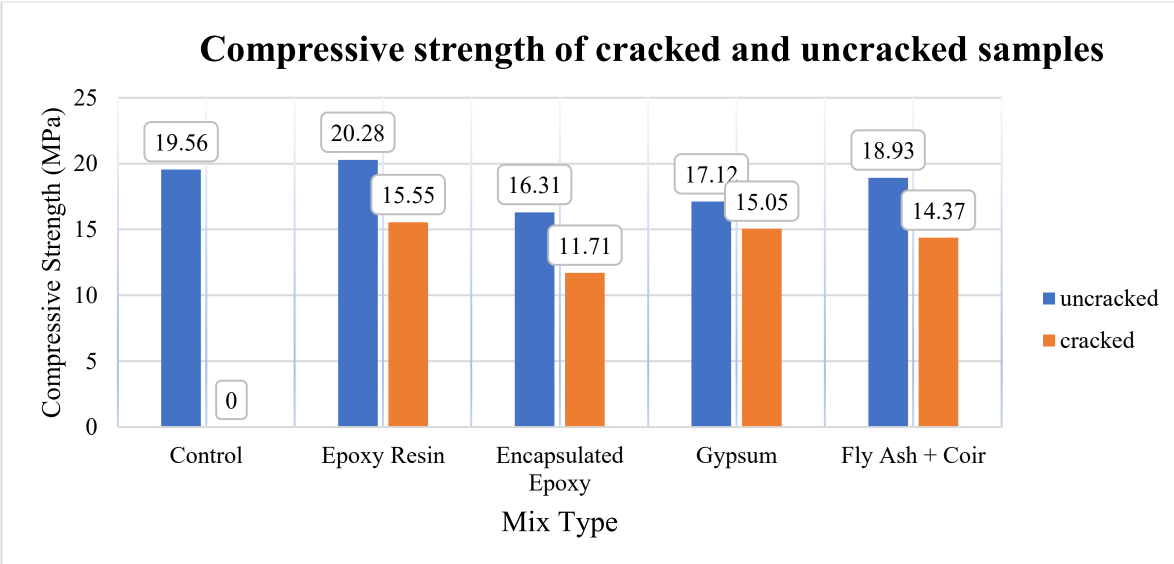

Figure 3: Compressive strength of cracked v/s uncracked samples

Figure 3 shows the compressive strength at 28 days, of uncracked specimens showed that epoxy resin (20.28 MPa) achieved the highest strength, slightly surpassing the control (19.56 MPa). Fly ash with coconut coir (18.93 MPa) also performed comparably close to the control, while gypsum (17.12 MPa) and encapsulated epoxy (16.31 MPa) exhibited relatively lower strengths, highlighting issues of brittleness and weaker bonding. For cracked specimens, epoxy resin (15.55 MPa) and gypsum (15.05 MPa) demonstrated higher residual strength compared to encapsulated epoxy (11.71 MPa) and fly ash + coir (14.37 MPa).

4.3 Strength Recovery

$$Recovery\ (\%) = \frac{28d\ Compressive\ strength, cracked}{28d\ Compressive\ strength, uncracked} \times 100$$

- Epoxy resin:

$$\frac{15.55}{20.28} x\ 100\ =\ 76.68\%$$

- Gypsum:

$$\frac{15.05}{17.12} x\ 100\ =\ 87.91\%$$

- Fly ash + Coir:

$$\frac{14.37}{18.93} x\ 100\ =\ 75.91\%$$

- Epoxy encapsulated:

$$\frac{11.71}{16.31} x\ 100\ =\ 71.80\%$$

Among the cracked specimens, gypsum demonstrated notable self-healing potential. Epoxy resin and gypsum regaining compressive strengths of 15.55 MPa and 15.05 MPa, respectively. This corresponds to approximately 77% strength recovery for epoxy resin and 88% recovery for gypsum when compared with their uncracked counterparts. The fly ash + coir combination exhibited moderate healing performance with a strength of 14.37 MPa (~76%), while encapsulated epoxy showed the least recovery at 11.71 MPa (~72%), which can be attributed to incomplete release of the epoxy and weak interfacial bonding.

4.4 Workability (Slump Test)

The workability of fresh concrete mixes was tested using the slump cone method per **IS 1199 (1959)**. The values observed reflect the effect of healing agents on the flowability and internal cohesion of concrete:

Table 5: Slump test

Mix Type	Slump (mm)
Control	28
Epoxy Resin	88
Epoxy Encapsulation	55
Gypsum	30
Fly ash + coir	28

The epoxy resin mix exhibited the highest slump due to its liquid nature, while gypsum maintained near-control behavior. Encapsulation increased slump but still remained workable.

4.5 Visual Crack Healing Observation

Crack induction was performed on samples, i.e., 16th day post-casting. Healing was observed after 28^{th} days under moist conditions:

- **Epoxy Resin**: No sign of cracks sealing observed at 28^{th} day.
- **Epoxy Encapsulated**: Partial healing observed—likely limited capsule rupture due to lack of localized cracking.
- **Gypsum:** Almost complete healing of cracks observed at 28^{th} day.
- **Fly Ash Coir**: No any crack sealing observed until 28^{th} day.

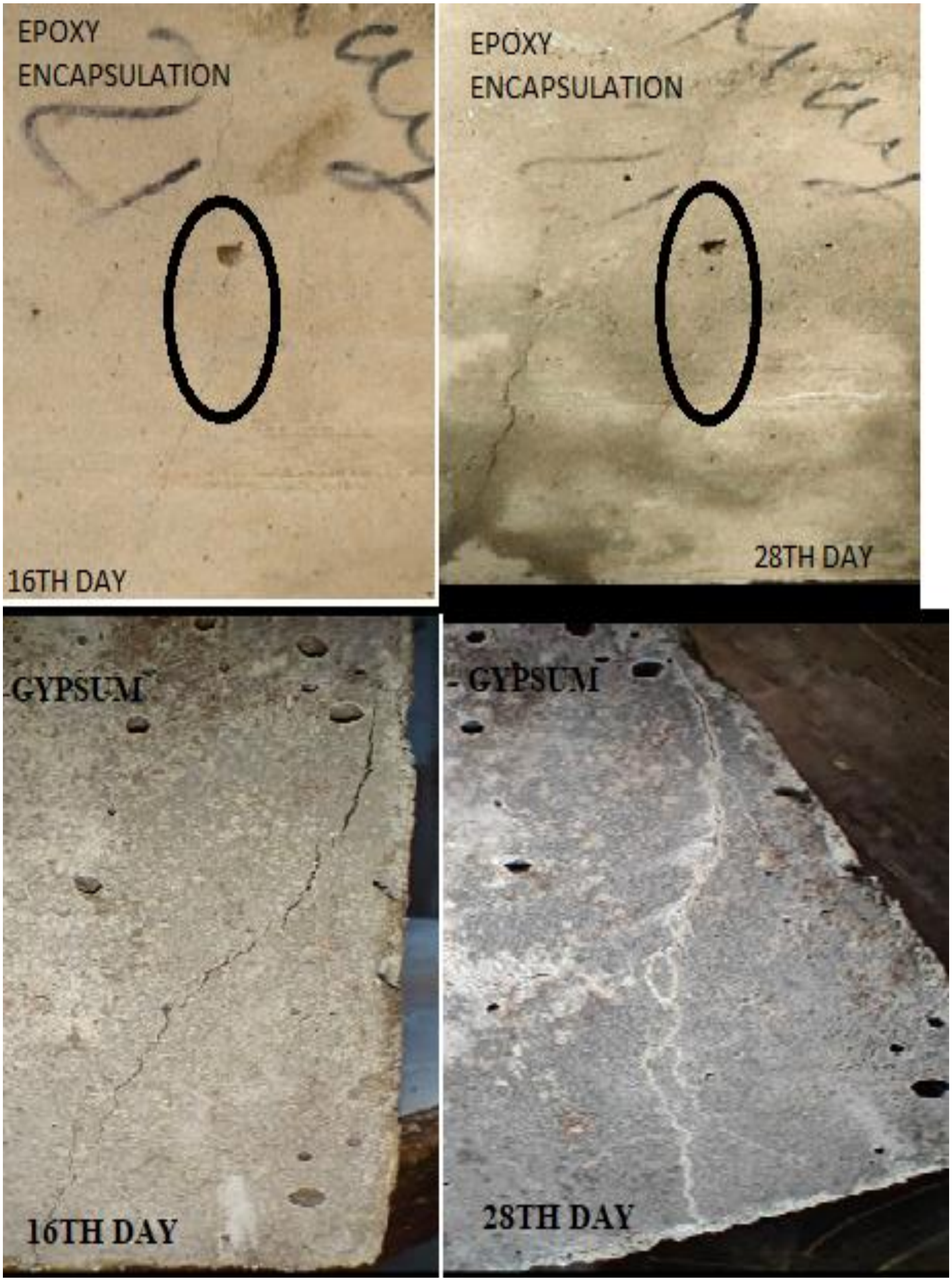
EPOXY ENCAPSULATION
16TH DAY
EPOXY ENCAPSULATION
28TH DAY
GYPSUM
16TH DAY
GYPSUM
28TH DAY

Figure 4: Visual observations of crack sealing of different mixes

5. DISCUSSION

The experimental investigation was conducted to evaluate the self-healing efficiency of different agents incorporated into concrete, specifically: epoxy resin, epoxy encapsulation, gypsum, and a combination of fly ash and coconut coir. The findings from compressive strength tests at 7 and 28 days, slump tests, and visual crack-sealing observations were analyzed to compare the healing performance of each material relative to the control mix.

5.1 Control Mix Performance

The control concrete, with a 1:1.5:3 nominal mix and a slump value of 28 mm, exhibited expected mechanical properties. Its 7-day average compressive strength was approximately 14.5 MPa, and 28-day results ranged from 16.88 MPa to 22.22 MPa. These results serve as the benchmark for evaluating the effect of self-healing agents.

5.2 Epoxy Resin Mix

The epoxy resin mix showed a significantly higher slump of 88 mm, indicating increased workability due to the resin's lubricating nature. Although its early compressive strength at 7 days (13.74 to 16.58 MPa) was comparable to the control, the epoxy mix's crack bridging ability was not visually evident.

5.3 Epoxy Encapsulation Mix

Epoxy encapsulation with gelatin and gum arabic shells exhibited a moderate slump of 55 mm and a 7-day compressive strength in the range of 12.99–15 MPa, which was slightly lower than the control mix. This reduction can be linked to the incomplete release or uneven distribution of epoxy during the early curing phase. Encapsulated systems, however, are designed for delayed healing, activated once cracks form. Visual inspection after crack induction (on day 16) revealed partial sealing of hairline cracks.

5.4 Gypsum Mix

Gypsum was used at 17% of the cement weight. The mix showed a slump of 30 mm and a 7-day compressive strength lower than the control, around 13 MPa. This was anticipated due to gypsum's slower setting and reduced early-age strength. However, visual crack sealing was notable, especially in surface cracks. Gypsum is known for forming crystalline products that can fill voids and improve durability over time. The use of both cubes and cylinders for gypsum allowed assessment of both compressive properties, acknowledging gypsum's lower bond strength in tension.

5.5 Fly Ash + Coconut Coir Mix

The combination of fly ash, a pozzolanic material, and coconut coir fibers, a natural reinforcement, aimed to enhance long-term durability and toughness. The mix displayed evidently high early-age strength but showed **no** crack sealing. The addition of fly ash did not to contribute to later strength. Coconut coir's high lignin content was expected to offer resistance to degradation, and pre-treatment helped in improving bonding with the matrix, but coirs were dissolved in concrete matrix.

5.6 Comparative Performance

Among all agents tested, epoxy resin showed the highest workability, while gypsum and epoxy encapsulation mixes demonstrated the best visible healing of surface cracks. In contrast, gypsum may not offer high mechanical strength but compensates by sealing micro-cracks.

6. CONCLUSION

This study focused on evaluating and comparing the crack-sealing efficiency of selected agents—**epoxy resin**, **epoxy encapsulation**, **gypsum**, and **fly ash combined with coconut coir**—as alternative healing solutions in concrete. The main objective was to assess their feasibility in improving crack-sealing behavior and mechanical performance under controlled conditions, with special emphasis on low-cost and locally available materials for application in Nepal's infrastructure.

The experimental results revealed that each healing agent brought distinct advantages and limitations:

- **Epoxy resin** showed excellent workability and potential for high-strength crack sealing but was limited by cost and lack of further hydration potential.
- **Epoxy encapsulation** offered a delayed healing mechanism through triggered release upon cracking. While its early-age strength was slightly lower than the control, it showed promise for long-term durability once activated.
- **Gypsum**, although weaker in early strength, effectively sealed micro-cracks. When linked to crack-healing observations, the compressive strength of gypsum cores helps explain the high strength recovery (~88%) observed in cracked cube specimens. The ability of gypsum to maintain structural integrity while expanding into cracks contributes to effective self-healing, allowing it to seal cracks and restore load-bearing capacity even if absolute strength is lower than epoxy resin. This confirms gypsum's potential as a cost-effective and efficient healing agent in concrete.

- **Fly ash and coconut coir** emerged as a promising combination that balances workability, crack bridging, and long-term strength gain using low-cost, locally available materials.

Ultimately, this research contributes to the growing field of **sustainable and cost-effective self-healing concrete technologies**, especially relevant for developing countries like Nepal. The results provide a comparative foundation for further work on optimizing dosage, agent distribution, and field-scale validation. With proper refinement, these techniques could help reduce repair costs, extend structure service life, and support Nepal's transition toward more resilient and durable infrastructure systems.

REFERENCE

- Alghamri, R., Kanellopoulos, A., & Al-Tabbaa, A. (2016). Gypsum in self-healing concrete: Mechanisms and performance. *Cement and Concrete Research*, 89, 110–118. https://doi.org/10.1016/j.cemconres.2016.08.007

- Ali, M. (2012). Effect of alkali treatment on coconut fiber. *Construction and Building Materials*, 34, 369–375. https://doi.org/10.1016/j.conbuildmat.2012.02.052

- Edvardsen, C. (1999). Water permeability and autogenous healing of cracks in concrete. *ACI Materials Journal*, 96(4), 448–454.

- Gupta, P., & Sharma, R. (2018). Natural fibers and their composites: A review on mechanical behavior. *Journal of Reinforced Plastics and Composites*, 37(11), 739–755. https://doi.org/10.1177/0731684418756862

- Hearn, N. (1998). Self-sealing, autogenous healing and continued hydration: What is the difference? *Materials and Structures*, 31(8), 563–567. https://doi.org/10.1007/BF02480593

- IS 456. (2000). *Plain and Reinforced Concrete – Code of Practice*. Bureau of Indian Standards.

- Jiang, C., Fan, K., Wu, F., & Chen, D. (2017). Experimental study on the mechanical properties and microstructure of a sustainable cementitious composite incorporating recycled aggregate and polyvinyl alcohol fiber. *Construction and Building Materials*, 144, 516–523. https://doi.org/10.1016/j.conbuildmat.2017.03.229

- Jonkers, H. M., Thijssen, A., Muyzer, G., Copuroglu, O., & Schlangen, E. (2010). Application of bacteria as self-healing agent for the development of sustainable concrete. *Ecological Engineering*, 36(2), 230–235. https://doi.org/10.1016/j.ecoleng.2008.12.036

- McIntyre, J. E. (2004). *Synthetic fibres: Nylon, polyester, acrylic, polyolefin*. Woodhead Publishing.

- Montgomery, D. C. (2019). *Design and analysis of experiments* (10th ed.). Wiley.

- Sharma, P., & Goyal, A. (2020). Encapsulation techniques in polymer chemistry: A review. *International Journal of Scientific Research in Science and Technology*, 7(5), 111–117. https://doi.org/10.32628/IJSRST207521

- Sisomphon, K., Copuroglu, O., & Koenders, E. A. B. (2012). Self-healing of surface cracks in mortars with expansive additive and crystalline additive. *Cement and Concrete Composites*, 34(4), 566–574. https://doi.org/10.1016/j.cemconcomp.2012.01.005

- Van Tittelboom, K., De Belie, N., Van Loo, D., & Jacobs, P. (2011). Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent. *Cement and Concrete Composites*, 33(4), 497–505. https://doi.org/10.1016/j.cemconcomp.2011.01.004