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A Blueprint for Carbon-Negative Construction: A Comparative Analysis of CCUS Integration in Concrete

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INTRODUCTION & AIM

The construction sector is responsible for approximately 37% of global CO_2 emissions, largely driven by the production of conventional Portland cement. To achieve net-zero goals and meet the Paris Agreement targets, concrete must transition from a carbon-intensive material to a climate-positive technology capable of permanently mineralizing CO_2. This work presents a strategic framework for engineering carbon-negative concrete by evaluating emerging technologies across three pathways: mineral sequestration, bio-based CO_2 utilization, and innovative engineered systems. These technologies are assessed based on CO_2 uptake capacity, mechanical performance, scalability, and industrial feasibility.

Aim: To identify and compare the most promising CO_2-sequestering concrete technologies and establish a roadmap for transforming concrete from a major source of emissions into a durable, scalable carbon sink.

METHOD

A structured comparative methodology was adopted to evaluate emerging carbon-negative concrete technologies. A comprehensive literature review was conducted using databases including Scopus, Web of Science, and PubMed, supported by patents, technical reports, and industrial documents. Technologies were selected based on relevance, novelty, applicability to concrete, and technological readiness. All identified technologies were organized into three core categories:

- Mineral pathways – direct CO_2 mineralization into stable carbonates
- Bio-based pathways – CO_2 sequestration via microbial or biomass-derived mechanisms
- Engineered pathways – electrochemical or chemical innovations beyond conventional hydration chemistry

Each technology was systematically assessed using the following criteria:

- CO_2 sequestration efficiency (kg CO_2 per m^3 or per ton of binder)
- Resulting compressive strength and durability Technological readiness level (TRL)
- Scalability and industrial feasibility
- Resource availability and environmental co-benefits

RESULTS & DISCUSSION

The comparative evaluation of nine CO_2-sequestering concrete technologies revealed a clear trade-off between mechanical performance and carbon uptake (Figure 1). Electrochemical aggregate technology demonstrated the highest sequestration potential, approaching 300 kg CO_2 per ton of concrete, but exhibited low compressive strength, limiting its structural applicability. Conversely, olivine-based systems, seawater-derived concrete, bicarbonate mixes, and carbonated water technologies achieved high strength values (35–48 MPa) with moderate CO_2 uptake. The most promising pathways were washout-water-pretreated biochar and accelerated carbonation of Portland limestone cement (AC-PLC), both of which achieved substantial CO_2 uptake (150–200 kg/t) while maintaining compressive strengths above structural thresholds (>25 MPa). This indicates that hybrid mineral–bio-based strategies present the most viable route for delivering carbon-negative concrete at scale.

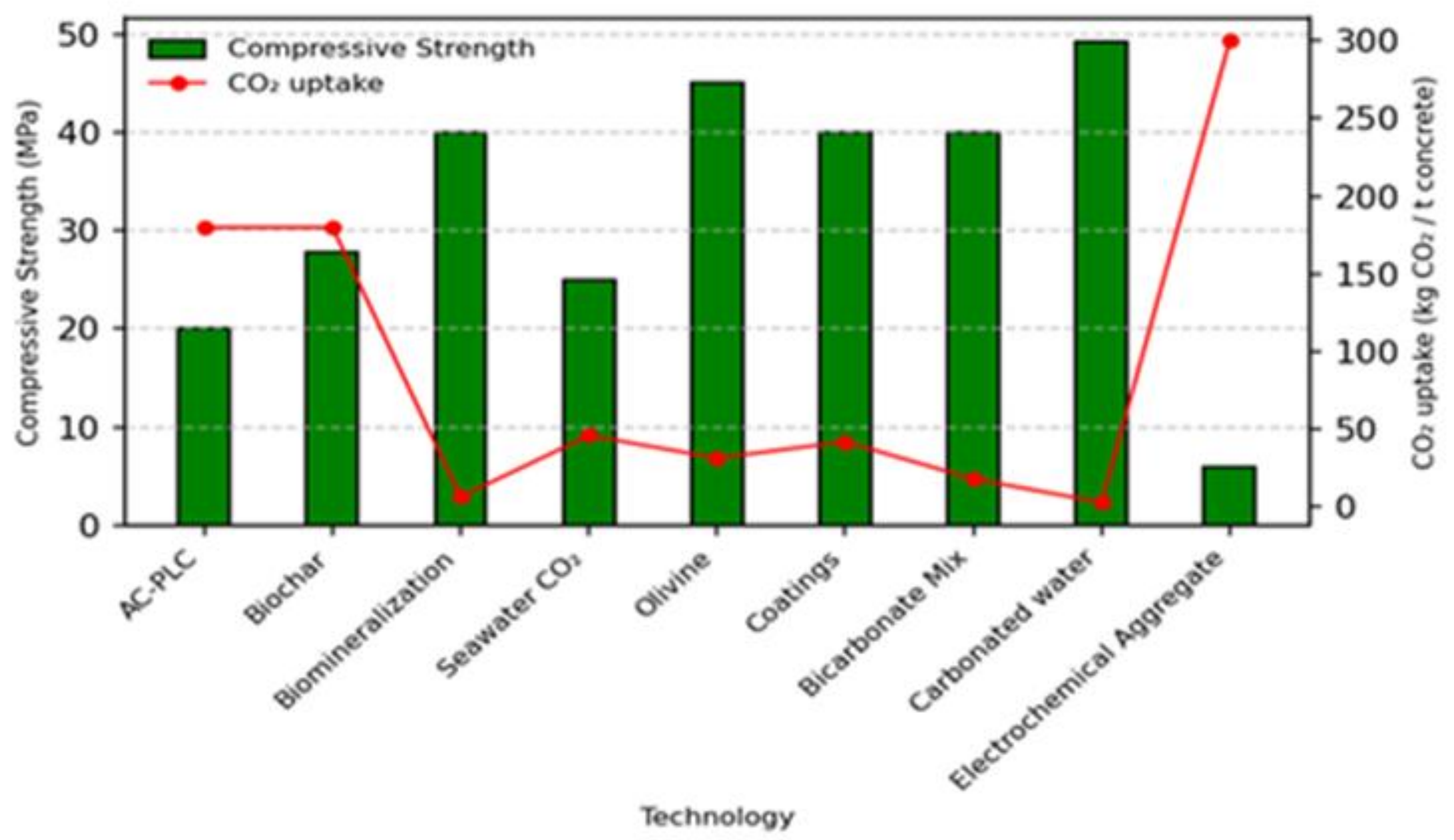

Figure 1. Comparative performance of carbon-negative concrete technologies.

CONCLUSION

Emerging technologies show that concrete can become carbon-negative. Biochar systems and accelerated carbonation offer the best balance of CO_2 uptake and strength. These pathways present the most promising route for scalable adoption.

FUTURE WORK / REFERENCES

Future research will focus on optimizing hybrid carbonation–biochar systems, validating their long-term durability under real environmental conditions, and conducting full life-cycle assessments to confirm net-negative emissions at an industrial scale.