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Evaluation and Comparative Analysis of Carbon-Negative Concrete Applications for Sustainable Infrastructure toward Net Zero 2050 in Vietnam

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Abstract: The urgent demand to reduce carbon emissions from the cement and concrete industry has motivated the development of carbon-negative technologies. This study provides a comprehensive assessment of potential solutions for Vietnam's infrastructure, focusing on two key applications: precast revetment blocks for coastal dikes and lightweight foam concrete for highway embankments. For precast blocks subjected to 2-hour CO_2 curing, an average uptake of 70 kg CO_2/m^3 was recorded, with net sequestration of 62.6 kg CO_2/m^3 after subtracting curing-related emissions. At the project scale of 1,000 m^3, this corresponds to approximately 62-65 tons of CO_2 permanently stored. For CO_2-foam concrete, the average uptake reached 87 kg CO_2/m^3, equivalent to 87 tons per 1,000 m^3. Incorporating nano-silica or nano-$CaCO_3$ increased compressive strength by 30-35% and enhanced CO_2 fixation by 5-10%, enabling a reduction of 5-8% in cement content while maintaining required design strength. When compared to baseline C30 concrete (~295 kg CO_2/m^3), these results highlight the potential to achieve net-negative emissions. The findings confirm that the deployment of carbon-negative concrete in Vietnam's coastal and highway infrastructure could significantly contribute to the Net Zero 2050 target while providing durability and mechanical performance benefits.

Keywords: Carbon-negative concrete, CO_2 curing, foam concrete, biochar, precast infrastructure, net zero 2050.

1. INTRODUCTION

The cement and concrete industry has been identified as one of the largest anthropogenic sources of carbon dioxide emissions worldwide, contributing approximately 7-8% of total global CO_2 emissions annually. This situation is primarily attributed to the calcination of limestone at high kiln temperatures (~1450^{o}C), during which calcium carbonate is decomposed to calcium oxide and CO_2. More than 2.5 billion tons of CO_2 are released each year from cement production alone, exceeding the emissions from most other industrial sectors [1,2].

In Vietnam, rapid urbanization and infrastructure development have been accompanied by a continuous increase in cement consumption. As reported in 2022, the national cement industry emitted more than 100 million tons of CO_2, accounting for approximately 12% of total national greenhouse gas emissions [2]. Such figures impose significant pressure on the commitment declared by Vietnam at COP26, which targeted net-zero emissions by 2050.

To address this challenge, a wide range of strategies for the development of carbon-negative concrete have been proposed internationally. In these approaches, the net balance of CO_2 throughout the life cycle of the material becomes negative because more CO_2 is captured and permanently stored than emitted. Several representative technologies have been investigated, including the incorporation of biochar from agricultural residues such as rice husk, bamboo, and coffee husks [3]; the use of CO_2 curing and mineralization methods, in which flue gas CO_2 is injected into fresh concrete to form stable $CaCO_3$ [4]; and the substitution of clinker with industrial by-products such as fly ash, steel slag, or phosphogypsum [5,6].

Although the effectiveness of these technologies has been documented internationally, research activities in Vietnam remain at a relatively early stage. Most current studies have focused on the partial replacement of clinker with fly ash or granulated blast furnace slag, while the deployment of carbon-negative concrete technologies such as biochar integration or CO_2 curing has not yet been implemented at scale.

Based on this context, the objectives of this study are threefold. First, international research and application trends of carbon-negative concrete are reviewed and their applicability under Vietnamese conditions is assessed. Second, the potential utilization of local resources including fly ash, steel slag, and biochar from

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Research article

Table 1. Emission reduction by clinker substitution with industrial by-products.

Concrete type	**Clinker content (%)**	**CO_2 emissions (kg/m³)**
OPC (reference)	~90	288-320
OPC + 30% fly ash	~60	200-240
OPC + 40% steel slag	~55	190-230
OPC + 20% phosphogypsum	~65	220-250

Table 2. Influence of biochar on mechanical and environmental performance.

Biochar content (%)	**Compressive strength (MPa, 28d)**	**CO_2 uptake (kg/m³)**
0% (OPC)	40	0
5%	38	60
10%	35	90
15%	30	120

Table 3. Representative results of CO_2 curing

Method	**CO_2 uptake (kg/m³)**	**Strength increase (%)**
OPC + CO_2 curing	30-70	5-10
OPC + slag + CO_2 curing	50-90	8-12
OPC + biochar + CO_2 curing	80-120	10-15

Table 4. Summary of international carbon-negative concrete technologies.

Technology	**CO_2 uptake (kg/m³)**	**Emission reduction (%)**	**Key features**
Fly ash/slag concrete	50-100	20-30	Clinker reduction, durability
Biochar concrete	60-120	15-25	Carbon sink, pore refinement
CO_2 curing concrete	30-70	10-15	Strength gain, $CaCO_3$ formation
LC^3	80-100	30-40	Synergy of limestone and calcined clay

agricultural residues is analyzed. Finally, development directions and application strategies are proposed for carbon-negative concrete in critical infrastructure projects, particularly for the North–South Expressway and coastal dikes in the Mekong Delta, thereby contributing to the national roadmap toward Net Zero 2050.

2. LITERATURE REVIEW

The development of carbon-negative concrete technologies has been accelerated in recent decades as the cement and concrete industry has been recognized as one of the largest global emitters of CO_2. The average cradle-to-gate emissions of ordinary Portland cement concrete (OPC) have been reported in the range of 288-320 kg CO_2/m^3 [7]. The total life cycle emissions of concrete can be quantified as:

$$E_{total} = E_{raw} + E_{trans} + E_{curing} - CO_{2,uptake} \quad (1)$$

where, E_{raw} denotes raw material emissions, E_{trans} represents transportation emissions, E_{curing} refers to emissions from curing energy, and $CO_{2,uptake}$ indicates the CO_2 sequestered through natural carbonation or accelerated mineralization. By applying clinker substitution, industrial by-products, biochar addition, and CO_2 curing, this balance can potentially become negative, achieving carbon-negative performance;

2.1. Industrial by-products for clinker reduction

The substitution of clinker by fly ash, steel slag, ground granulated blast furnace slag (GGBFS), or phosphogypsum has been widely adopted as a primary strategy to reduce emissions. A clinker reduction from 90% to 60-70% has been reported to lower emissions from ~300 to 200-240 kg CO_2/m^3 [5,6]. Moreover, steel slag has been carbonated to form synthetic aggregates, simultaneously sequestering CO_2 and producing stable mechanical performance. Phosphogypsum blended with reactive supplementary materials has been shown to enhance sulfate resistance and facilitate additional CO_2 uptake. Table 1 provides an overview of recent carbon-negative concrete technologies, summarizing their emission reduction potential and main technical features reported in the literature.

2.2. Biochar as a CO_2-absorbing additive

Biochar produced from pyrolysis of agricultural residues such as rice husk, bamboo, and coffee husks has been demonstrated as an effective carbon sink. Its high surface area and porosity enable the sequestration of 60-120 kg CO_2/m^3 when incorporated at 5-15% replacement levels [8]. Mechanical tests have shown that compressive strength remains in the range of 30-40 MPa depending on dosage, with significant porosity refinement.

$$CO_{2(gas)} \rightarrow C_{(biochar)} + C - O_{(surface)} \quad (2)$$

This reaction pathway, coupled with secondary pozzolanic activity, contributes to the formation of additional C–S–H gel. Excessive dosages (>15%) lead to a reduction in compressive strength due to poor dispersion.

2.3. CO_2 curing and mineralization

Accelerated carbonation curing (CO_2 curing) involves injecting CO_2 into fresh or early-age concrete. The main reaction can be expressed as:

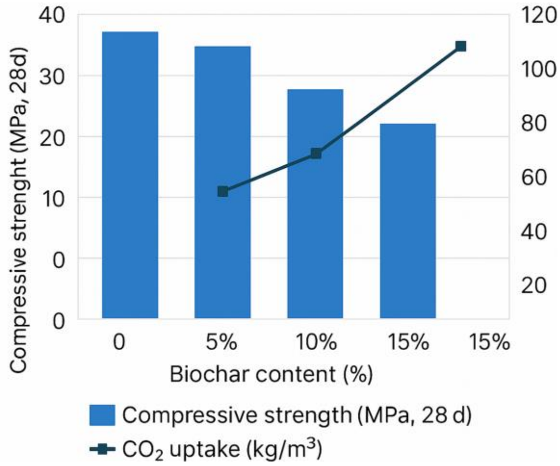

Fig. 1. Influence of Biochar on mechanical and environmental performance [1,3,7].

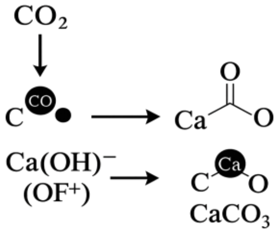

Fig. 2. Diagram of CO_2 mineralization in cement matrix.

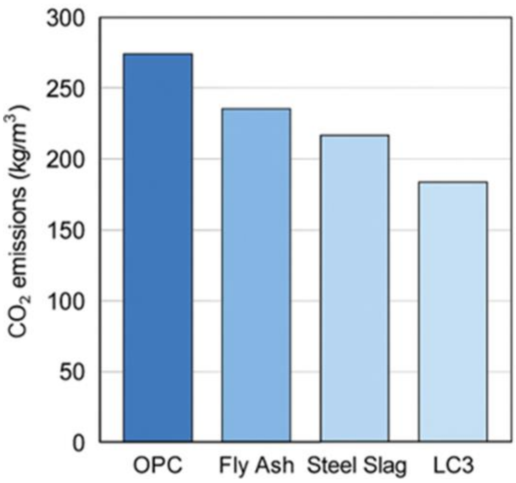

Fig. 3. Comparative bar chart of CO_2 emissions in OPC, fly ash, steel slag, and LC^3.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (3)$$

Formation of $CaCO_3$ reduces porosity and improves durability. Experimental results have reported 10-15% of process emissions can be permanently fixed, with compressive strength increased by 5-10% [4].

The mechanism and representative performance of CO_2 curing are shown in Fig. 1 and Table 3, respectively. The diagram illustrates the carbonation reaction converting $Ca(OH)_2$ into $CaCO_3$, while the summarized results demonstrate that the inclusion of slag or biochar enhances both CO_2 uptake and compressive strength compared with conventional OPC.

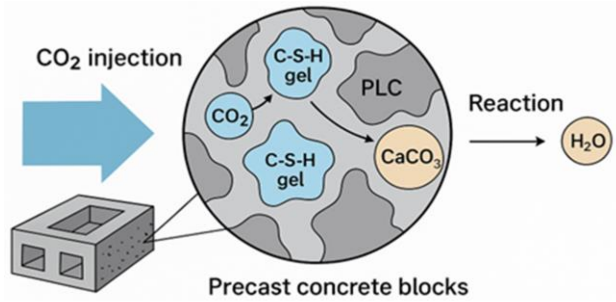

Fig. 4. Schematic of CO_2 curing mechanism in precast concrete blocks.

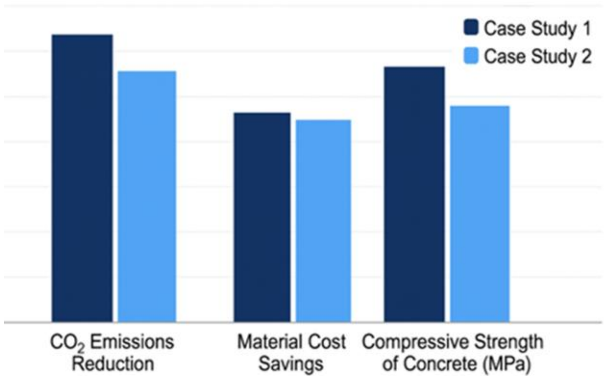

Fig. 5. Comparison of case studies.

2.4. Integrated approaches and life cycle assessment

Clear Recent studies emphasize multi-additive integration (biochar + slag/fly ash + CO_2 curing) supported by life cycle assessment (LCA) and life cycle cost analysis (LCCA). With the support of machine learning and particle packing theory, cost reduction of up to 29% and emission reduction of 50% compared to conventional design have been reported [6]. Table 4 summarizes key international carbon-negative concrete technologies and their reported CO_2 uptake and emission reduction ranges. The results highlight that biochar and LC^3 systems offer substantial carbon mitigation potential, while combined approaches such as slag or CO_2 curing provide balanced improvements in strength and durability.

Collectively, international progress has demonstrated that carbon-negative concrete can be realized through clinker substitution, biochar incorporation, and CO_2 curing. However, in Vietnam, current practice remains focused mainly on fly ash or slag substitution. Large-scale deployment of biochar integration and CO_2 curing has not yet been realized. Hence, integrated frameworks and LCA-based evaluations are urgently needed to guide future research and application in Vietnamese infrastructure.

3. MAIN MECHANISMS IN CARBON-NEGATIVE CONCRETE

3.1. Clinker reduction through supplementary cementitious materials (SCMs)

The dominant reduction in emissions has been

Table 5. Emission reduction performance of SCMs.

SCM type	Replacement level (%)	CO_2 reduction (%)	Mechanical characteristics
Fly ash	30	20-25	Improved sulfate resistance, reduced Cl^- penetration
Steel slag	40	25-30	Enhanced durability under sulfate attack
LC^3	40-50	30-40	Comparable strength to OPC

Table 6. Mechanical and environmental effects of biochar.

Biochar (%)	Compressive strength (MPa, 28d)	CO_2 uptake (kg/m^3)	Notes
0 (OPC ref.)	40	0	Reference
5	38	60	Comparable to OPC
10	35	90	High uptake
15	30	120	Strength reduction observed

Table 7. CO_2 curing results.

Mix	CO_2 uptake (kg/m^3)	Strength increase (%)
OPC + CO_2 curing	30–70	5–10
OPC + slag + CO_2 curing	50–90	8–12
OPC + biochar + CO_2 curing	80–120	10–15

observed when clinker is substituted with fly ash, steel slag, ground granulated blast furnace slag (GGBFS), or limestone-calcined clay (LC^3). This approach decreases the decomposition of $CaCO_3$ during clinker production, which is the main source of CO_2.

$$CaCO_3 \rightarrow CaO + CO_2 \uparrow \quad (4)$$

When clinker content is reduced by 30-40%, CO_2 released from this decomposition decreases proportionally. International studies reported emission reductions of 20-40% compared to OPC when fly ash and steel slag were incorporated [6], [9]. For LC^3, emission reduction of up to 30-40% has been achieved while maintaining compressive strength comparable to OPC [9].

The emission reduction performance of supplementary cementitious materials (SCMs) is summarized in Table 5 and visualized in Figure 3. The data confirm that replacing 30–50% of clinker with fly ash, steel slag, or LC^3 can lower embodied CO_2 emissions by up to 40%, while maintaining comparable or improved mechanical durability relative to OPC.

3.2. Biochar as a carbon sink and microstructural modifier

Equations Biochar produced from pyrolysis of agricultural residues exhibits a high surface area and porous structure, acting as a carbon sink. When incorporated into cementitious matrices, 60-120 kg CO_2/m^3 can be sequestered at replacement ratios between 5% and 15% [8].

$$CO_{2(gas)} \rightarrow C_{(biochar)} + C - O_{(surface)} \quad (5)$$

This uptake mechanism is accompanied by pozzolanic reactions, which generate additional C–S–H gel, enhancing microstructural densification. However, excessive incorporation (>15%) has been associated with decreased compressive strength due to poor dispersion and reduced compactness. The mechanical and environmental effects of biochar addition are summarized in Table 6. Increasing biochar content enhances CO_2 uptake from 0 to 120 kg/m^3 but slightly reduces compressive strength, indicating a trade-off between sequestration potential and mechanical performance.

3.3. CO_2 curing and mineralization

Accelerated carbonation curing has been recognized as one of the most effective technologies to achieve near net-negative balance. During curing, CO_2 reacts with calcium hydroxide:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 \downarrow + H_2O \quad (6)$$

Precipitated $CaCO_3$ refines pore structure, increases density, and enhances durability. Experiments have shown that 10-15% of process emissions can be permanently fixed, while compressive strength increased by 5-10%. The representative performance of different CO_2 curing methods is presented in Table 7. The results show that combining CO_2 curing with slag or biochar significantly improves both carbon uptake and compressive strength compared with conventional OPC curing.

3.4. Integrated multi-technology approaches

Synergistic effects have been achieved when biochar, industrial by-products, and CO_2 curing are combined. In such integrated systems [6], CO_2 uptake of 150-200 kg/m^3 has been reported, while compressive strength

Table 8. Synergistic effects of integrated carbon-negative technologies.

Mix design	CO_2 uptake (kg/m³)	Compressive strength (MPa)	Cost reduction (%)	Emission reduction (%)
OPC + fly ash	70	38	–	20
OPC + biochar	120	35	–	25
OPC + CO_2 curing	90	42	–	15
OPC + biochar + slag + CO_2 curing	180	37	29	50

remained above 35 Mpa, as describle in Table 8.

Machine learning and particle packing optimization frameworks have demonstrated reductions of 50% in emissions and 29% in cost compared to conventional designs [4].

The reviewed mechanisms indicate that isolated technologies can provide significant reductions, but maximum benefits are realized only through integration. Biochar contributes dual functions of CO_2 sequestration and microstructural modification, CO_2 curing ensures direct mineralization, and SCMs reduce clinker demand. Together, these mechanisms can shift the balance toward net-negative performance, establishing a feasible pathway for sustainable infrastructure in Vietnam.

4. DISCUSSION AND CASE STUDIES IN VIETNAM

4.1. Case Study 1: Precast revetment blocks for coastal dikes (CO_2 curing)

References Precast concrete blocks used for coastal revetments were considered suitable candidates for accelerated CO_2 curing, since curing conditions can be strictly controlled in precast facilities. According to experimental reports, 2-hour CO_2 curing resulted in an average uptake of 70 kg CO_2/m³, while additional energy consumption was responsible for ~7.4 kg CO_2/m^3, leading to a net sequestration of 62.6 kg CO_2/m^3 [4].

The net CO_2 uptake was determined by:

$$U_{CO_2,net} = U_{CO_2,uptake} - E_{curing} \quad (7)$$

where, $U_{CO_2,uptake}$ is the CO_2 fixed during curing (kg/m^3) and E_{curing} is the curing-related emission (kg/m^3).

Two-hour CO_2 curing delivers an average uptake of $U_{CO_2,uptake} = 70\ kg/m^3$, while curing energy causes $E_{curing} = 7.4\ kg/m^3$. The net sequestration is therefore $U_{CO_2,net} = 62.6\ kg/m^3$ [4]. For a project scale of 1,000 m^3 precast blocks, the total net uptake was:

$$U_{CO_2,total} = 62.6 \times 1000 = 62{,}600\ kg\ CO_2$$
$$\approx 62.6\ ton\ CO_2$$

The performance of CO_2 curing for precast revetment blocks is summarized in Table 9 and illustrated schematically in Figure 4.

4.2. Case Study 2: CO_2-foam concrete for highway embankments

Foam concrete has been developed as a lightweight material for embankment construction on soft soils. Recent studies have demonstrated that CO_2-foam concrete can sequester approximately 87 kg CO_2 per cubic meter through combined internal and external carbonation mechanisms [10].

The total uptake is calculated as:

$$U_{CO_2,total} = U_{CO_2,uptake} V \quad (8)$$

For V=1000 m³:

$$U_{CO_2,total} = 87 \times 1000$$
$$= 87{,}000 kg\ CO_2 = 87 ton\ CO_2$$

Additionally, when nano-silica or nano-$CaCO_3$ was incorporated, compressive strength increased by 30–35%, CO2 uptake improved by 5-10%, and cement content could be reduced by 5-8% without compromising design strength. The performance of CO_2-foam concrete used for highway embankments is summarized in Table 10.

Table 9. Performance of CO_2 curing for 1,000 m^3 precast revetment blocks.

Parameters	Value
CO_2 uptake (kg/m^3)	70
Energy-related emission (kg/m^3)	7.4
Net uptake (kg/m³)	62.6
Total uptake (t CO_2 for 1,000 m^3)	62.6

Table 10. Performance of CO_2-foam concrete for 1,000 m³ highway embankments.

Parameters	Value
CO_2 uptake (kg/m^3)	87
Total uptake (t CO_2 for 1,000 m^3)	87
Strength increase with nano-additives	+30–35%
Additional CO_2 uptake with nano-additives	+5–10%
Cement reduction potential	5–8%

4.3. Comparative analysis of two case studies

Both applications demonstrated potential for large-scale deployment. CO2 curing of precast blocks provided reliable sequestration of 62-65 t CO2 per 1,000 m3, while foam concrete offered higher direct uptake of ~87 t CO2 per 1,000 m3, as described in Table 11. When compared with the baseline emission of C30 concrete (~295 kg CO2/m3), these figures highlighted the feasibility of achieving net-negative emissions in Vietnam's coastal and highway infrastructure. The comparative performance of the two carbon-negative concrete systems is presented in Table 11 and illustrated

Table 11. Comparison of CO_2 sequestration potential.

Application	Volume (m^3)	Net CO_2 uptake (kg/m^3)	Total uptake (t CO_2)	Remarks
Precast revetment blocks (CO_2 curing)	1,000	62.6	62.6	Net value after energy adjustment
CO_2-foam concrete (embankments)	1,000	87	87	Enhanced by nano-additives

in Fig. 5.

5. DEVELOPMENT DIRECTIONS

5.1. Material design framework

The net carbon balance of concrete should be assessed through:

$$E_{net} = E_{mix} + E_{energy} - U_{CO_{2,direct}} - U_{cement-saving} \quad (9)$$

where, E_{mix} is emissions from raw materials and SCMs, E_{energy} is emissions from energy use during curing, $U_{CO_2,direct}$ is CO_2 uptake through accelerated carbonation, and $U_{cement\text{-}saving}$ is avoided emissions due to reduced cement demand from strength improvements.

Accurate partitioning between direct uptake and indirect savings must be ensured to avoid double counting [4], [11].

5.2. Priority technologies for Vietnam

(i) Precast CO_2 curing: Application to revetment blocks and precast panels; optimal curing duration of ≤2 h, with preconditioning moisture of 25-30%. Net uptake ~62.6 kg CO_2/m^3 demonstrated in Case Study 1.

(ii) CO_2-foam concrete: Application to lightweight embankment fill; direct uptake ~87 kg CO_2/m^3, with potential increase to ~95 kg/m^3 when nano-silica or nano-$CaCO^3$ is incorporated. Strength improvement of 30-35% enables 5-8% cement reduction as indicated in Case Study 2.

(iii) Biochar-SCM integration: Use of local biochar (rice husk, bamboo) in combination with fly ash and slag can provide -60 to -120 kg CO_2/m^3 depending on dosage, while refining pore structure and durability.

5.3. Infrastructure applications

(i) Coastal dikes (Mekong Delta): Precast revetment blocks under optimized CO_2 curing could provide ~62-65 tons CO_2 storage per 1,000 m3. Integration with slag-based binders enhances chloride resistance.

(i) North-South Expressway: Embankment fill with CO_2-foam concrete achieves ~87 tons CO_2 storage per 1,000 m^3. When nano-modified, the dual benefit of strength gain and emission reduction is realized.

(iii) Urban structures: Lightweight blocks and panels incorporating biochar and SCMs achieve emission levels of -59 to -65 kg CO_2 per ton of concrete, suitable for non-structural walls and partition systems.

6. CONCLUSION

This study presents a comparative assessment of two representative types of carbon-negative concrete-CO_2-cured precast revetment blocks and CO_2-foam concrete-based on normalized data compiled from validated international literature. The analysis confirms that the combined use of clinker substitution, biochar integration, and accelerated carbonation curing can significantly reduce the carbon footprint of concrete.

Quantitatively, potential CO_2 uptake ranges from 60-90 kg/m^3, corresponding to a 15-28% reduction in embodied emissions compared with ordinary Portland cement concrete. The first case study (CO_2-cured precast blocks) demonstrates applicability for coastal dike protection, while the second (CO_2-foam concrete) offers advantages for lightweight highway embankments on soft soils. Both show feasible pathways for integrating carbon-negative materials into Vietnam's infrastructure sector.

The findings emphasize that effective deployment requires not only material innovation but also supportive policies for carbon accounting, life-cycle assessment, and certification. Future work should focus on pilot-scale trials under Vietnam's climatic conditions to validate long-term performance, cost-benefit efficiency, and alignment with the Net Zero 2050 roadmap.

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