



Minimizing environmental impact: A comparative analysis of cement and recycled clay brick concrete in building construction

Damini Righteous Gilbert¹, Timothy Omotoyosi Awanu²

¹Department of Civil Engineering Federal University Otuoke, Bayelsa State, Nigeria

²School of Engineering, Institute of Entrepreneurship and Vocational Training, Nigeria

Correspondence Author: Damini Righteous Gilbert

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Abstract

The environmental challenges associated with cement production and the increasing accumulation of construction and demolition waste have intensified the search for sustainable alternatives in concrete production. This study investigated the suitability of waste clay brick powder (WCBP) obtained from demolition wastes in Bayelsa State, Nigeria, as a partial replacement for Portland Cement (PC) in concrete. The objective was to evaluate the effects of WCBP on the workability and compressive strength of concrete while promoting waste utilization and reducing dependence on cement. Concrete specimens were produced by replacing PC with WCBP at replacement levels of 5%, 10%, 15%, and 20% by weight. Standard laboratory tests were conducted to determine the workability and compressive strength characteristics of the concrete mixes, and the results were compared with those of conventional concrete made with 100% PC. The findings showed that all WCBP-modified mixes exhibited satisfactory workability. The optimum performance was achieved at a 10% replacement level, where the 28-day compressive strength increased by approximately 14–15% compared with the control mix. Although higher replacement levels resulted in a gradual reduction in strength, the concrete remained suitable for selected non-structural applications. A one-way Analysis of Variance (ANOVA) was conducted to assess the statistical significance of the differences in compressive strength among the mixes. The analysis yielded an F-value of 1.526 and a p-value of 0.233. Since the p-value exceeded the 0.05 significance level, the differences among the mean compressive strengths were not statistically significant at the 95% confidence level. Nevertheless, the practical improvement observed at the 10% replacement level highlights the positive contribution of WCBP to concrete performance. The study concludes that replacing 10% of PC with WCBP provides the best balance between mechanical performance and environmental sustainability. The adoption of WCBP in concrete production can reduce cement consumption, lower carbon emissions, and provide an effective means of managing demolition waste. It is recommended that WCBP be considered as a supplementary cementitious material in sustainable construction, while further studies should investigate its long-term durability and field performance.

Keywords: Environment, concrete, ANOVA compressive strength, recycled waste clay-brick

Introduction

The construction industry is a critical driver of economic growth and infrastructure development worldwide. Concrete remains the most widely used construction material due to its versatility, durability, and relatively low cost. However, the extensive use of Portland cement as the primary binding material in concrete has raised significant environmental concerns. Cement production is an energy-intensive process that requires the calcination of limestone at high temperatures, resulting in substantial carbon dioxide (CO₂) emissions. It is estimated that the cement industry contributes approximately 8% of global anthropogenic CO₂ emissions, making it one of the major industrial contributors to climate change (Abbas, 2025) ^[1]. In addition, the extraction of raw materials such as limestone and clay for cement manufacturing contributes to natural resource depletion, habitat destruction, and ecosystem degradation (Kusuma *et al.*, 2022) ^[34].

Growing awareness of environmental sustainability and the need to reduce the carbon footprint of construction activities have prompted researchers to explore alternative materials capable of partially replacing conventional cement in concrete production. One promising approach involves the utilization of construction and demolition waste materials, particularly recycled clay brick waste. The increasing

volume of demolished clay brick structures has generated large quantities of waste that are often disposed of in landfills, creating environmental and waste management challenges, especially in developing countries where recycling practices remain limited. Recycling these materials for concrete production offers an effective strategy for reducing landfill burdens, conserving natural resources, and supporting circular economy principles (Liu *et al.*, 2024) ^[36].

Recycled clay brick materials, especially when processed into fine powder, contain appreciable amounts of silica and alumina that may exhibit pozzolanic properties. Consequently, waste clay brick powder has the potential to function as a supplementary cementitious material capable of reducing cement consumption while maintaining acceptable engineering performance. Previous studies have reported that concrete incorporating recycled clay brick materials can achieve satisfactory mechanical properties, particularly in non-structural and low-load applications (Baikerikar *et al.*, 2023). Furthermore, the use of recycled clay brick waste contributes to environmental sustainability by reducing the demand for virgin construction materials and minimizing greenhouse gas emissions associated with cement production.

Despite these potential benefits, several concerns remain regarding the performance of recycled clay brick concrete. The porous nature of clay brick particles may increase water absorption and concrete porosity, potentially affecting strength and durability characteristics. While some studies have reported favorable performance at moderate replacement levels, others have observed reductions in compressive strength and long-term durability when excessive amounts of recycled clay brick materials are incorporated into concrete mixtures (Wu et al., 2024) ^[49]. These inconsistencies indicate the need for further investigation to determine optimum replacement levels that can balance environmental benefits with engineering requirements.

The environmental impact of conventional cement-based concrete therefore remains a significant challenge due to its high carbon footprint, intensive energy consumption, and reliance on non-renewable resources. At the same time, although recycled clay brick concrete presents a sustainable alternative capable of reducing construction waste and promoting resource efficiency, uncertainties regarding its mechanical performance, durability, and economic viability continue to limit its widespread adoption. A comprehensive evaluation comparing conventional cement concrete and recycled clay brick-modified concrete is therefore necessary to establish their relative advantages and limitations.

Accordingly, this study investigates the suitability of waste clay brick powder as a partial replacement for Portland cement in concrete production. The study evaluates the effects of varying replacement levels on the workability and compressive strength of concrete while assessing the potential environmental benefits associated with reduced cement consumption. The findings are expected to contribute to the development of sustainable construction materials and provide valuable information for engineers, researchers, policymakers, and industry practitioners seeking environmentally responsible alternatives for concrete production.

Literature Review

The increasing emphasis on sustainable development has intensified the search for environmentally friendly construction materials capable of reducing the ecological impacts associated with conventional concrete production. Concrete remains the most widely used construction material globally due to its versatility, strength, and economic advantages. However, the environmental burden associated with cement production has become a major concern because of its substantial energy requirements and greenhouse gas emissions. Consequently, researchers have focused on developing sustainable alternatives that can maintain acceptable engineering performance while minimizing environmental degradation. One promising approach involves the incorporation of recycled clay brick waste into concrete as a partial replacement for conventional cementitious materials or natural aggregates.

1. Environmental Impact of Cement-Based Concrete

Cement production is a major contributor to greenhouse gas emissions and environmental degradation. The manufacturing process involves the calcination of limestone and the combustion of fossil fuels, which together release large amounts of CO₂ into the atmosphere (Wu et al., 2024). Additionally, the extraction of raw materials for cement

production leads to the depletion of natural resources and significant ecological disturbances. Numerous studies have highlighted the environmental drawbacks of traditional cement-based concrete. Gou et al. (2020) investigated the life cycle assessment of cement and found that its carbon footprint is significantly higher than that of alternative construction materials. Similarly, Bélaïd (2022) ^[55] reported that cement production is responsible for approximately 2.8 billion metric tons of CO₂ emissions annually, making it a key driver of climate change. Despite efforts to incorporate supplementary cementitious materials such as fly ash and slag, the dependence on Portland cement remains a major challenge in reducing the construction sector's environmental impact.

To mitigate these effects, various researchers have explored alternative materials. Scrivener et al. (2018) ^[6] examined the potential of limestone calcined clay cement (LC3) and found that it reduces clinker content, thereby lowering emissions. However, scalability remains an issue, as LC3 production requires modifications in existing cement plants. These findings indicate the need for further research into alternative materials such as recycled clay brick aggregates, which offer the potential for sustainability while minimizing the environmental drawbacks of traditional cement.

2. Recycled Clay Brick Concrete: A Sustainable Alternative

Recycled clay bricks are derived from demolition waste and construction debris, offering a sustainable solution for reducing landfill waste and conserving natural resources (Hamdullah et al., 2020) ^[24]. The recycling of clay bricks into concrete mixes not only diverts waste from landfills but also reduces the demand for virgin aggregates such as crushed stone and sand.

Several studies have explored the feasibility of incorporating recycled clay bricks into concrete. Zhang et al. (2020) ^[58] conducted a comparative analysis of concrete mixes containing varying percentages of recycled brick aggregates and found that while compressive strength slightly decreased, the overall environmental benefits were substantial. Kou et al. (2018) similarly reported that up to 30% replacement of natural aggregates with crushed bricks resulted in an acceptable reduction in strength while significantly lowering the embodied energy of the concrete. However, some challenges have been identified regarding the use of recycled clay bricks in concrete. Ebrahimi et al. (2023) ^[19] noted that clay brick aggregates have a higher water absorption rate than conventional aggregates, which can affect the workability and durability of the concrete. This finding was supported by Taher et al. (2024) ^[49], who observed that water absorption in recycled brick aggregates leads to increased shrinkage and porosity, potentially affecting the long-term performance of the material. Despite these concerns, the benefits of reducing construction waste and promoting a circular economy make recycled clay brick concrete an attractive alternative for sustainable building practices.

3. Mechanical Properties and Structural Performance

The mechanical performance of concrete is a crucial factor in determining its suitability for construction applications. While traditional cement-based concrete is known for its high compressive strength and durability, the introduction of recycled clay brick aggregates presents both advantages and challenges.

Alnour *et al.*, (2021) conducted an experimental study on the mechanical properties of recycled clay brick concrete and found that its compressive strength was lower than that of conventional concrete but still met the requirements for non-structural applications. This finding was corroborated by Xiao *et al.* (2020) [58], who reported that a 20–30% replacement of natural aggregates with crushed brick resulted in minor reductions in compressive strength while maintaining adequate performance for certain structural elements.

The tensile strength and flexural properties of recycled clay brick concrete have also been examined in various studies. Ibrahim (2021) [29] found that bond strength between recycled brick aggregates and cement paste was weaker than that of natural aggregates, which could impact the overall durability of the material. Additionally, Muhedin and Ibrahim, (2023) investigated the flexural behavior of recycled clay brick concrete and reported that while it exhibited slightly lower load-bearing capacity, the material could still be effectively used in low-rise construction and non-load-bearing applications.

One of the key challenges associated with recycled clay brick concrete is its high porosity, which affects its resistance to freeze-thaw cycles and long-term durability (Xie *et al.*, 2019). Researchers have explored various treatment methods to enhance the mechanical properties of recycled brick aggregates, including chemical coatings and supplementary cementitious materials. Gonzalez & Navarro (2020) [24] proposed the use of silica fume and fly ash to improve the bonding properties of recycled brick aggregates, leading to enhanced strength and durability. However, further studies are needed to optimize these treatment methods for large-scale applications.

4. Economic Viability and Cost Considerations

The economic feasibility of using recycled clay brick concrete is another important aspect of sustainable construction. While the material offers environmental benefits, its cost-effectiveness must be evaluated to ensure its practical adoption in the construction industry.

Mansoor *et al.*, (2024) [37] conducted a life cycle cost analysis comparing conventional cement-based concrete with recycled clay brick concrete and found that while the initial production costs of the latter were slightly higher due to additional processing requirements, long-term savings were achieved through reduced landfill fees and waste management costs. Similarly, Dey *et al.* (2021) noted that the incorporation of recycled aggregates could lower the overall material costs in regions where construction and demolition waste is abundant. Despite these potential cost savings, challenges remain in terms of standardization and market acceptance. Many construction companies are hesitant to adopt recycled clay brick concrete due to concerns about quality control and regulatory compliance (Silva *et al.*, 2019) [43]. Additionally, transportation and processing costs for recycled materials can vary significantly based on regional factors, affecting the overall economic viability of the material.

5. Durability and Long-Term Performance

The long-term performance of recycled clay brick concrete is a crucial factor in determining its suitability for widespread construction applications. Several studies have examined its resistance to environmental factors such as

moisture exposure, freeze-thaw cycles, and chemical attacks (Kusuma *et al.*, 2022) [34]. Mansoor *et al.* (2024) [37] investigated the durability of recycled clay brick concrete in marine environments and found that while it exhibited higher porosity than conventional concrete, the addition of pozzolanic materials such as fly ash and silica fume improved its resistance to chloride penetration. Similarly, Hamdullah *et al.*, (2020) [24] analyzed the freeze-thaw resistance of recycled clay brick concrete and concluded that proper mix design adjustments, including the use of air-entraining agents, could enhance its durability in cold climates.

Materials and Methods

1. Materials

1.1 Portland Cement

Type me /II Portland cement was utilized in this study. Its chemical composition complies with ASTM specifications, as presented in Table 1. This type of cement is suitable for general construction purposes, particularly where moderate sulfate resistance and moderate heat of hydration are required.

Table 1: Chemical Properties of Cement (Ori and Dulu, 2015)

Oxide	Composition (%)
CaO	59.60
Fe ₂ O ₃	3.22
SiO ₂	20.62
Al ₂ O ₃	6.01
MgO	3.65
SO ₃	2.46
K ₂ O	0.71

1.2 Water

Clean, portable water was employed for all mixing and curing processes. The water used conformed to the requirements of BS EN 1008:2002, ensuring it was free from deleterious substances that could adversely affect the properties of the concrete.

1.3 Fine and Coarse Aggregates

The fine and coarse aggregates were sourced from the Wilberforce Islands in Bayelsa State. The coarse aggregate had a maximum nominal size of 20 mm. Both aggregate types met the quality and grading requirements outlined in BS EN 12620:2013, making them suitable for use in structural concrete applications.

1.4 Pulverized Waste Clay Brick

Waste clay bricks were obtained from local dumpsites in Bayelsa State. These bricks were crushed and pulverized into fine powder, as illustrated in Figure 1.



Fig 1: Waste Clay Bricks

The chemical composition of the resulting material is provided in Table 2. The processed clay brick powder satisfied the ASTM C618 (2015) [28] requirements for a pozzolanic material, with the combined content of SiO₂, Al₂O₃, and Fe₂O₃ exceeding 70%, indicating its suitability as a supplementary cementitious material in concrete.

2. Experimental Method

Concrete specimens were produced using a nominal mix ratio of 1:2:4 (cement: sand aggregate) by volume through the volume batching method. Ordinary Portland Cement (OPC) was used as the primary binding material in all concrete mixtures. The control mix consisted of 100% cement, while experimental mixes were prepared by partially replacing cement with waste clay brick powder at replacement levels ranging from 0% to 20% by weight of cement. A constant water-to-cement ratio of 0.50 was maintained throughout the study to ensure uniformity in hydration and workability characteristics.

The constituent materials were measured according to the specified mix proportions and thoroughly mixed to obtain a homogeneous concrete mixture. Immediately after mixing, slump tests were conducted on each batch to determine the workability of the fresh concrete and assess the influence of brick powder incorporation on consistency.

Fresh concrete was subsequently placed into standard steel cube moulds measuring 150 mm × 150 mm × 150 mm. The moulds were filled in layers, and each layer was compacted using a tamping rod to eliminate entrapped air and ensure

proper consolidation. The exposed surfaces of the specimens were carefully finished with a trowel to achieve a smooth and level surface.

After casting, the concrete cubes were left undisturbed at room temperature for 24 hours to permit initial setting and hardening. The specimens were then demoulded and immersed in a curing tank containing clean water until the respective testing ages of 3, 7, 14, 21, and 28 days. This curing process ensured adequate moisture availability for continued cement hydration and strength development.

A total of 80 concrete cube specimens were produced for the experimental investigation. The quantities of cement, brick powder, fine aggregate, coarse aggregate, and water required for the production of one cubic metre of concrete at a water-to-cement ratio of 0.50 were determined and are presented in Table 3. The prepared specimens were subsequently subjected to compressive strength testing at the specified curing ages to evaluate the effects of brick powder replacement on concrete performance.

Furthermore, statistical analysis was conducted to evaluate the influence of waste clay brick powder (WCBP) replacement levels on the compressive strength of concrete. The compressive strength data obtained from concrete specimens containing 0%, 5%, 10%, 15%, and 20% WCBP were analyzed using a one-way Analysis of Variance (ANOVA). The analysis was performed to determine whether the differences in compressive strength among the various replacement levels were statistically significant.

Table 3: Mix Quantities of Samples

Sample ID	Cement (kg)	Brick powder (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
CONTROL	300	0	690	1250
GWCB (5% Cement replacement)	285	15	690	1250
GWCB (10% Cement replacement)	270	30	690	1250
GWCB (15% Cement replacement)	255	45	690	1250
GWCB (20% Cement replacement)	240	60	690	1250

Results and Discussion

1. Workability Results

Table 4 slump test results for the different types of concrete created demonstrate that as more cement is substituted with brick blocks, a greater slump is attained. This suggests that the uniformity and workability of the concrete produced increased as the volume of fines from the brick blocks.

Table 4: Slump test results

Percentage Replacement	Slump (in mm)
0%	52
5%	53
10%	55
15%	62
20%	76

The slump test results, as shown in the Table 4, reveal a trend of increasing workability with higher percentages of recycled clay brick (RCB) replacement. At 0% RCB replacement, the slump value is 52 mm, indicating a relatively low workability. As the percentage of RCB increases, the slump values also rise, reaching 76 mm at 20% replacement. This suggests that the addition of recycled clay brick enhances the workability of the mixture, likely due to its fine particle size and moisture retention properties. The increase in slump from 52 mm to 76 mm

across the range of 0% to 20% replacement indicates a more fluid mix, which could potentially improve ease of handling and application in construction projects.

2. Compressive Test Results

The growing emphasis on sustainable construction materials has spurred significant interest in utilizing waste clay bricks as partial cement replacements in concrete mixtures. Table 4 presents the compressive strength development of cementitious composites incorporating varying percentages of waste clay brick powder (0% to 20%) across key curing periods (3, 7, 14, 21, and 28 days). The data reveal distinct trends in strength progression, highlighting the influence of clay content on both early-age and long-term.

Table 4: Compressive Strength of Waste Clay Bricks

% Clay Addition	Compressive strength (Mpa)				
	3 Days	7 Days	14 Days	21 Days	28 Days
0%	13.2	16.03	19.2	20.3	20.5
5%	16.4	17.0	20.0	19.3	19.1
10%	18.7	21.3	21.3	22.2	23.3
15%	14.5	19.0	19.5	21.1	22.2
20%	12.7	16.2	17.9	20.5	21.5

2.1 A Comparative Analysis of Cement and Recycled Clay Brick

The results presented in Figure 2 clearly demonstrate the relationship between clay content in the mixture and compressive strength over time, showing both positive and negative trends. For control samples (0% clay), compressive strength steadily increases from 13.2 MPa at 3 days to 20.5 MPa at 28 days, reflecting typical cement hydration (Zhang *et al.*, 2020) [22]. When 5% clay is added, strength initially rises to 16.4 MPa at 3 days but then declines after 14 days, reaching only 19.1 MPa at 28 days. This suggests that while small amounts of clay may enhance early strength, long-term hydration is hindered, potentially due to interference with cement hydration (Zhao *et al.*, 2021) [59]. With 10% clay, compressive strength reaches the highest value of 23.3 MPa at 28 days, indicating an optimal balance between clay and cement components (Wang & Zhang, 2022) [55]. This moderate addition appears to enhance the material's microstructure and inter particle bonding (Liu *et al.*, 2023) [35]. However, at 15% and 20% clay, strength decreases; at 15%, strength drops to 14.5 MPa at 3 days, recovering to 22.2 MPa at 28 days, while at 20%, it starts at 12.7 MPa at 3 days and reaches 21.5 MPa at 28 days. The decrease from 10% to 15% is 4.7%, and from 10% to 20%, it is 8%, highlighting diminishing returns from higher clay content (Chen *et al.*, 2025) [15]. Overall, these findings suggest that moderate clay addition (around 10%) improves compressive strength, but further increases lead to a reduction, likely due to an imbalance in the material's microstructure or reduced hydration efficiency (Zhao *et al.*, 2021) [59].

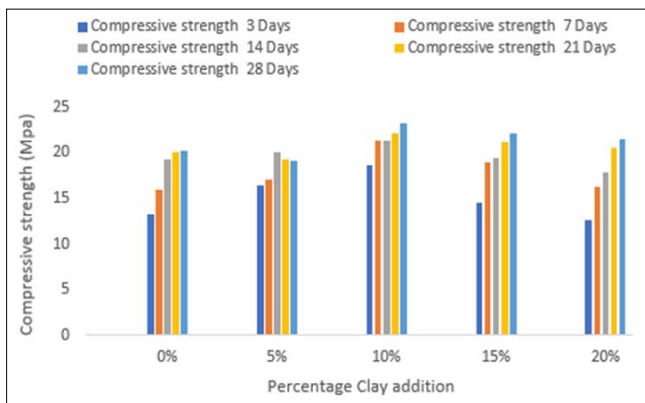


Fig 2: Compressive Strength Development of Cement replacement with Clay Brick

Similarly, A 10% replacement of cement with waste clay brick powder resulted in a significant improvement in compressive strength, showing an average increase of approximately 14% over the control mix. This indicates a favorable pozzolanic reaction at this substitution level. However, at higher substitution levels, strength gains diminish, suggesting a dilution effect of the cementitious material. Notably, at 20% replacement, compressive strength remains comparable to that of the control concrete, with no significant performance loss. These findings align with Bediako (2018) [6], who observed that both mortar and concrete containing 10% and 20% ground waste clay bricks (GWCB) showed statistically similar compressive strength to control samples at 3, 7, and 28 days. Bediako (2018) [6], identified 10% GWCB as the optimal replacement level, attributing the 14% strength increase to the pozzolanic activity of GWCB, which enhances strength by converting

calcium hydroxide into additional calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) compounds. The current study's results reinforce Bediako's conclusion, confirming that locally sourced waste clay bricks can activate pozzolanic reactions and positively influence strength development, especially at the 10% replacement level, which strikes an optimal balance between cementitious content and pozzolanic reactivity.

2.2 Statistical Analysis of Compressive Strength Data

Table 5 shows that a one-way ANOVA can be performed to determine whether the different percentages of waste clay brick powder (0%, 5%, 10%, 15%, and 20%) produced statistically significant differences in compressive strength.

Table 5: ANOVA Results

Source of Variation	SS	df	MS	F	p-value
Between Groups	44.409	4	11.102	1.526	0.233
Within Groups	145.510	20	7.276		
Total	189.919	24			

A one-way Analysis of Variance (ANOVA) was conducted to assess the effect of waste clay brick powder (WCBP) content on the compressive strength of concrete. The analysis produced an F-value of 1.526 and a p-value of 0.233. Since the p-value exceeded the 0.05 level of significance, the null hypothesis was accepted, indicating that the differences in mean compressive strength among concrete mixes containing 0%, 5%, 10%, 15%, and 20% WCBP were not statistically significant at the 95% confidence level.

Despite the lack of statistical significance, the results revealed notable practical differences in performance. The concrete mix containing 10% WCBP exhibited the highest compressive strength at all curing ages, attaining a 28-day strength of 23.3 MPa compared to 20.5 MPa for the control mix. This represents an increase of approximately 13.7%, suggesting that moderate incorporation of WCBP can enhance concrete strength. The improvement may be attributed to the pozzolanic activity of the brick powder and its ability to improve particle packing and microstructural densification.

However, replacement levels above 10% resulted in a gradual reduction in compressive strength, likely due to dilution of the cementitious matrix and reduced hydration efficiency. Overall, the findings indicate that a 10% replacement level provides the optimum balance between mechanical performance, waste utilization, and environmental sustainability.

Conclusion

This study demonstrated that waste clay brick powder can be effectively utilized as a partial replacement for Portland cement in concrete production. The results showed that the incorporation of waste clay brick powder improved the workability and compressive strength of concrete at appropriate replacement levels. Among the mixes investigated, the 10% replacement level produced the optimum performance, achieving a compressive strength increase of approximately 14–15% compared to the control mix. The findings further confirmed that waste clay brick powder possesses beneficial pozzolanic properties that contribute to strength development and overall concrete performance.

A one-way Analysis of Variance (ANOVA) was conducted to assess the significance of the observed differences in compressive strength. The analysis produced an F-value of 1.526 and a p-value of 0.233. Since the p-value exceeded the 0.05 significance level, there was no statistically significant difference among the mean compressive strengths of the concrete mixes at the 95% confidence level. However, the practical strength improvement observed at the 10% replacement level suggests that moderate incorporation of WCBP can positively influence concrete performance.

Beyond its engineering benefits, the use of waste clay brick powder offers significant environmental advantages by reducing construction and demolition waste disposal, decreasing reliance on Portland cement, and lowering the carbon footprint associated with concrete production. Therefore, the study concludes that waste clay brick powder is a viable and sustainable supplementary cementitious material for concrete production, particularly at a replacement level of 10%, where both mechanical performance and environmental sustainability are optimized.

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