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A SUSTAINABLE APPROACH TO CONCRETE PRODUCTION USING RECYCLED PAVEMENT MATERIALS

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Abstract
The growing deterioration of the environment, fueled by rapid urbanization and excessive resource consumption, has highlighted the urgent need for sustainable construction practices. One promising approach is the incorporation of recycled pavement waste aggregate as a partial replacement for natural aggregate in concrete production. This study investigates the environmental and structural viability of using recycled aggregate in concrete by replacing 5%, 10%, 15%, and 20% of conventional aggregate. The workability of fresh concrete was evaluated through slump cone and compaction factor tests, while compressive strength tests were conducted to assess the performance of hardened concrete. Experimental results reveal that concrete containing recycled aggregate demonstrated satisfactory performance compared to conventional concrete. The findings suggest that partial replacement of natural aggregate with recycled material can reduce construction costs, conserve natural resources, minimize energy usage, and offer an environmentally responsible alternative without significantly compromising strength and durability.

I. INTRODUCTION

Construction and Demolition Waste (CDW) is one of the largest sources of recycled materials worldwide due to the vast quantities of aggregates it generates [1]. The growing demand for natural aggregates in the construction sector has led to material scarcity and environmental degradation [2, 3]. As global population increases, so does the demand for new construction and the rehabilitation of existing infrastructure. Traditionally, materials from demolished structures are discarded, while new resources are extracted for fresh construction needs [4, 5]. This practice contributes significantly to environmental degradation, making the construction industry one of the highest carbon-emitting sectors [6]. In response, several countries have introduced restrictions on the excessive use of natural aggregates [7]. Among CDW, concrete constitutes a major portion accounting for approximately 70% to 75% of global construction and demolition waste [8], as demonstrated in Figure 1. This makes the concrete industry particularly unsustainable due to the sheer volume of material ending up in landfills.

Aggregates are a primary component in both concrete and asphalt pavement production, constituting 60%–80% of concrete and 90%–95% of asphalt pavement by volume [9, 10]. In the United States alone, approximately 480 million tons of asphalt pavement are used annually, with a typical service life of 15–25 years [11]. Upon reaching the end of their lifespan, roads are frequently demolished and only partially reconstructed, resulting in the generation of substantial quantities of waste material.

Disposing of this pavement waste in landfills is an inefficient and unsustainable solution. Recycling offers a more viable approach, as it mitigates landfill pressure, conserves natural resources, and reduces overall environmental impact. Reusing pavement concrete not only helps protect aggregate quarries but also reduces costs and construction time, making it a more environmentally responsible strategy [12]. Pavement concrete typically consists of an asphalt binder and mineral aggregate, while traditional concrete is a mix of Portland cement, fine aggregate, and coarse aggregate [13]. Coarse aggregates, which make up 60%–80% of the total aggregate volume, significantly influence the cost and performance of concrete. This study explores the potential of using recycled pavement aggregate as a partial replacement for natural coarse aggregates in concrete production, highlighting its environmental and technical benefits.

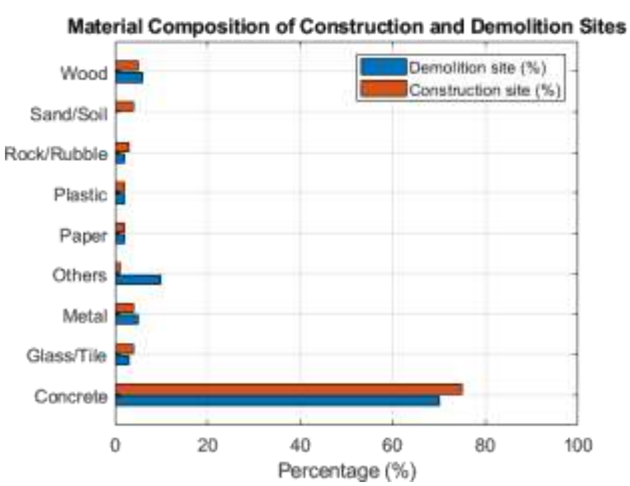

Figure 1 Material Composition of Construction and Demolition Sites

II. RESEARCH SIGNIFICANCE

The significance of this study lies in addressing the urgent need for sustainable construction practices by exploring the use of recycled pavement waste aggregate (RPWA) as a partial replacement for natural coarse aggregate in concrete. While extensive research has been conducted on incorporating various waste materials into concrete [14-23], the specific use of RPWA remains relatively underexplored, particularly in terms of its influence on both fresh and hardened concrete properties. With the depletion of natural resources and the mounting environmental burden of construction and demolition waste, this research contributes to circular economy principles by repurposing waste materials into valuable construction components. The study systematically evaluates the effect of RPWA on the compressive strength and workability of concrete, examining performance variations at substitution levels of 5%, 10%, 15%, and 20% (C5, C10, C15, and C20), with C0 serving as the control mix. By providing comparative data on both fresh and hardened concrete properties, the research deepens understanding of RPWA's structural feasibility and presents a practical approach to reducing environmental impact, conserving natural aggregates, and promoting cost-effective, eco-friendly concrete solutions suitable for wide-scale application.

III. MATERIALS AND METHODS

i. MATERIALS

The properties of the materials used in the concrete mix design are summarized in Table 1. All materials were sourced locally. Coarse aggregate consisted of Sargodha crushed gravel, while Lawrencepur sand was used as the fine aggregate. Ordinary Portland Cement (Type I), conforming to ASTM C150 [24], served as the binding material. Recycled pavement waste aggregate, collected from Raiwand Road in Lahore, Pakistan, was crushed to a maximum size of 20 mm and used to partially replace the natural coarse aggregate. Potable water was used in all concrete mixes to ensure consistency and suitability for hydration. The concrete mix was designed to achieve a target compressive strength of 20 MPa, with a fixed mix proportion ratio of 1:2:2.4 (cement: sand: coarse aggregate) to ensure the desired strength performance.

ii. TEST SPECIMENS

Concrete specimens were prepared using standard 150 mm cubic molds, in accordance with ASTM C109/C109M-20b [25] for mortar cubes and ASTM C192/C192M-23 [26] for making and curing concrete test specimens in the laboratory. For each replacement level of recycled pavement waste aggregate (RPWA), a total of nine specimens were cast. Compressive strength was evaluated at 7, 14, and 28 days, with three specimens tested at each age, following ASTM C39/C39M-24 [27] to ensure accuracy and repeatability.

The mixing process was conducted using a mechanical concrete mixer, following ASTM C192/C192M-23 [24]. Initially, the recycled pavement waste aggregate and natural coarse aggregates were dry mixed to ensure homogeneity. The inner surface of the mixer was pre-wetted before the gradual addition of cement (ASTM C150/C150M-23) [24], fine aggregate (ASTM C33/C33M-18) [28], coarse aggregate (ASTM C33/C33M-18) [28], and potable water (ASTM C1602/C1602M-18) [29]. After all the ingredients were added, mixing continued for at least two minutes to produce a uniform and workable mix.

During casting, the fresh concrete was placed into molds in three approximately equal layers, each compacted using 25 strokes of a standard tamping rod (ASTM C143/C143M-20) [30] to eliminate entrapped air. The top surface was leveled using a trowel for a smooth finish. Specimens were kept under ambient laboratory conditions ASTM C192 [26] for 24 hours before being demolded. After demolding, all specimens were submerged in a curing tank filled with lime-saturated water, maintained per ASTM C511-23 [31], until the designated testing age.

Table 1 Properties of Materials Used

Aggregate Type	Bulk Specific Gravity (ASTM C127-04)	Water Absorption (%) (ASTM C127)	Fineness Modulus (ASTM C117-05)	Unit Weight (kg/m³) (ASTM C29/C29M)	Moisture Content (%) (ASTM C566)
Fine Sand	—	—	2.39	—	—
Coarse Gravel	2.65	1.55	—	1530	0.72
Recycled Pavement Waste Aggregate	2.50	2.20	—	1125	0.12

IV. RESULTS AND DISCUSSIONS

Both the fresh and hardened properties of concrete were comprehensively evaluated to understand the effects of incorporating recycled pavement waste aggregate. In the fresh state, workability was assessed using the slump test and the compaction factor test, conducted in accordance with ASTM C143/C143M [30] and ASTM C1170/C1170M [32], respectively. These tests provided valuable information on the consistency and internal compatibility of the concrete mix. For the hardened state, the unit weight (density) of the concrete was determined as per ASTM C642-13 [33], which offers insights into the compactness and potential durability of the material. Additionally, the compressive strength of the concrete was measured at curing intervals of 7, 14, and 28 days, in accordance with ASTM C39/C39M [27], to evaluate the mechanical performance over time. This integrated testing approach facilitated a thorough assessment of both the workability and structural characteristics of the concrete incorporating recycled aggregates.

i. SLUMP TEST

The workability of the concrete mixtures was evaluated immediately after mixing using the slump test. As illustrated in Figure 2, a clear reduction in slump values was observed with increasing levels of recycled pavement waste aggregate. This trend indicates a decline in workability, likely due to the angular shape and higher absorption characteristics of the recycled aggregate, which reduce the free water available in the mix. Lower slump values correspond to a stiffer mix, suggesting that higher replacement levels may adversely affect the ease of placement and compaction.

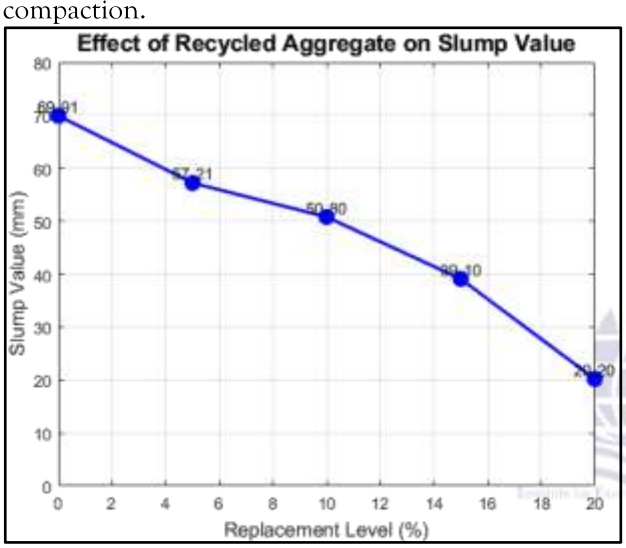

Figure 2 Slump Value vs Replacement

ii. COMPACTION FACTOR TEST

This test was conducted to further evaluate the workability characteristics of the concrete mixes. As illustrated in Figure 3, a progressive decline in compaction factor values was observed with increasing replacement levels of recycled pavement waste aggregate. This reduction indicates a consistent decrease in workability, likely due to the rough texture and irregular shape of the recycled aggregates, which increase internal friction within the mix. The lower compaction factor values suggest that higher replacement levels result in less cohesive and more difficult-to-place concrete, reinforcing the findings from the slump test.

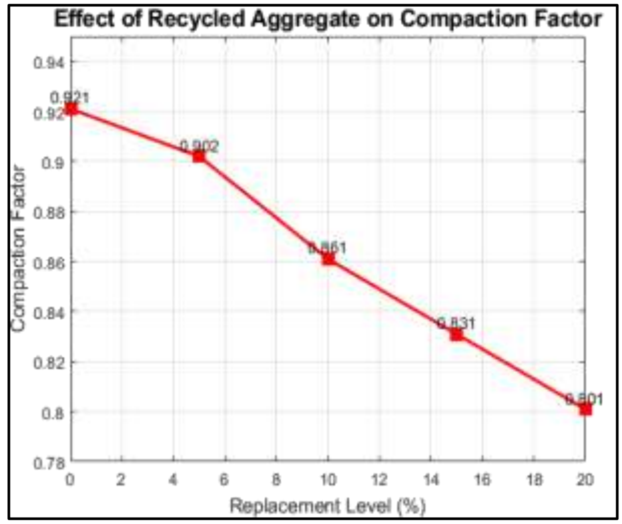

Figure 3 Compaction Factor vs Replacement

iii. UNIT WEIGHT

The unit weight of concrete is a critical parameter influenced by the specific gravity of its constituent materials. As recycled pavement waste aggregate was incorporated into the mix, a noticeable decline in unit weight was observed, primarily due to the lower specific gravity and higher porosity of the recycled material compared to natural aggregates. The control mix exhibited a unit weight of 2477 kg/m³, while mixes with 5%, 10%, 15%, and 20% replacement levels (C5 to C20) showed gradual reductions to 2471, 2431, 2417, and 2401 kg/m³, respectively. This trend is clearly depicted in Figure 4, highlighting the impact of increasing recycled content on the overall density of the hardened concrete. Additionally, the percentage reduction in unit weight relative to the control mix—0.2%, 1.8%, 2.4%, and 3% for C5, C10, C15, and C20, respectively—is illustrated in Figure 5, further emphasizing the inverse relationship between replacement level and concrete density. These reductions may have implications for structural applications where concrete mass and self-weight are critical design considerations.

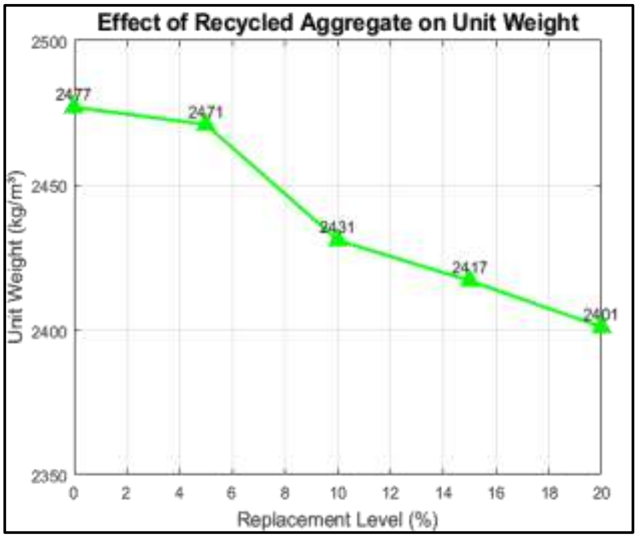

Figure 4 Unit weight vs Replacement

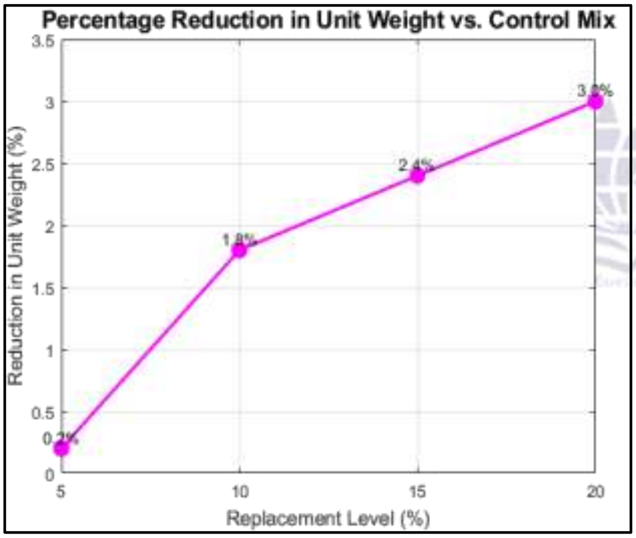

Figure 5 Reduction in unit weight vs Replacement

iv. CONCRETE COMPRESSIVE STRENGTH TESTING

The compressive strength of concrete mixes incorporating recycled pavement waste aggregate was evaluated at 7, 14, and 28 days to understand the influence of aggregate replacement over time. As depicted in Figure 6, compressive strength consistently declined with increasing levels of replacement across all curing ages. At 28 days, the control mix achieved a strength of 24.4 MPa, whereas the mixes with 5%, 10%, 15%, and 20% recycled aggregate (C5, C10, C15, and C20) exhibited strengths of 22.3, 21.4, 20.0, and 18.1 MPa, respectively. This downward trend is quantified in Figure 7, where the percentage reductions in strength at 28 days reached approximately 8%, 12%, 17%, and 26%, respectively, relative to the control. The reduction in strength can be attributed to the weaker mechanical properties and higher porosity of recycled aggregates compared to natural aggregates. These characteristics weaken the interfacial bond between the cement paste and aggregate particles. Moreover, the irregular morphology and rough surface of recycled aggregates may lead to poor compaction and lower density, contributing to reduced load-bearing capacity.

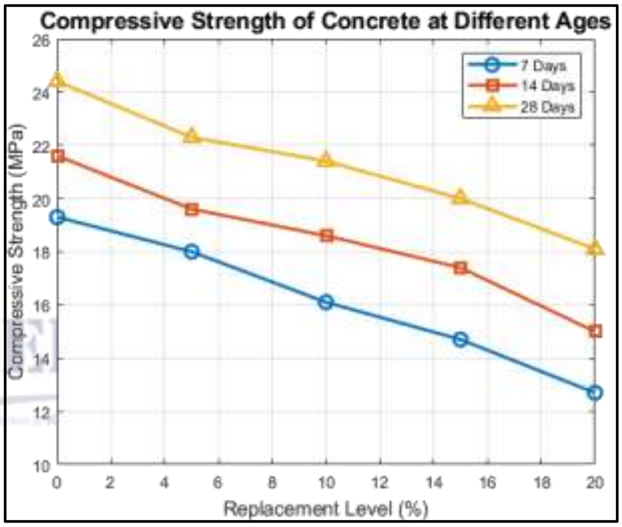

Figure 6 Actual Compressive Strength at Different Ages

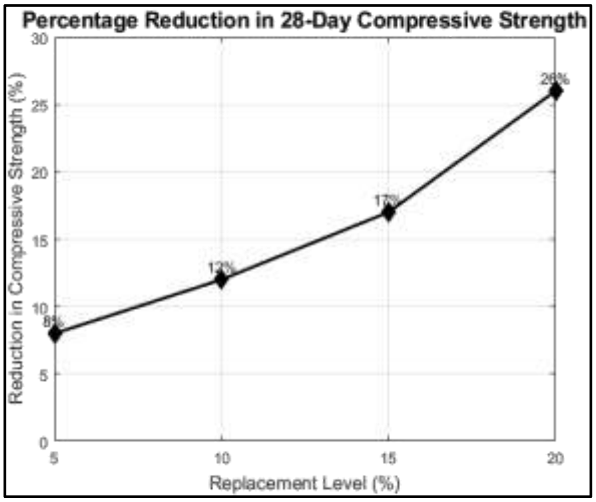

Figure 7 Loss in compressive strength vs Replacement

v. COMPARISON OF ACTUAL AND PREDICTED COMPRESSIVE STRENGTH OF CONCRETE USING MACHINE LEARNING APPROACH.

Figure 8 illustrates the comparison between predicted and actual compressive strength values of concrete using machine learning approach at different curing ages (7, 14, and 28 days) across various replacement levels of a recycled pavement waste aggregate, ranging from 0% to 20% using supervised regression. At all curing ages, both predicted and actual strength values exhibit a decreasing trend with increasing replacement levels, indicating a reduction in strength as the substitution increases. However, the 28-day strengths are consistently higher than those at 14 and 7 days, which is expected due to the ongoing hydration and strength gain over time [34, 35]. Overall, the predicted values closely follow the actual measurements at each age, with only minor deviations, suggesting that the predictive model developed in this study is accurate in forecasting the compressive strength of concrete at different stages and replacement levels.

Table 2 Error Metrics

7 Days	RMSE 0.1587	MAE 0.1333	R^2 0.9982
14 Days	RMSE 0.1946	MAE 0.1600	R^2 0.9969
28 Days	RMSE 0.1182	MAE 0.1000	R^2 0.9990

The model shows **very strong predictive accuracy** across all ages as shown in Table 2.

- Minimal errors (RMSE & MAE < 0.20 MPa) indicating high prediction precision.
- High reliability (R^2 > 0.996).
- The predicted curves closely follow the actual experimental data, further supporting the model's accuracy and trustworthiness.

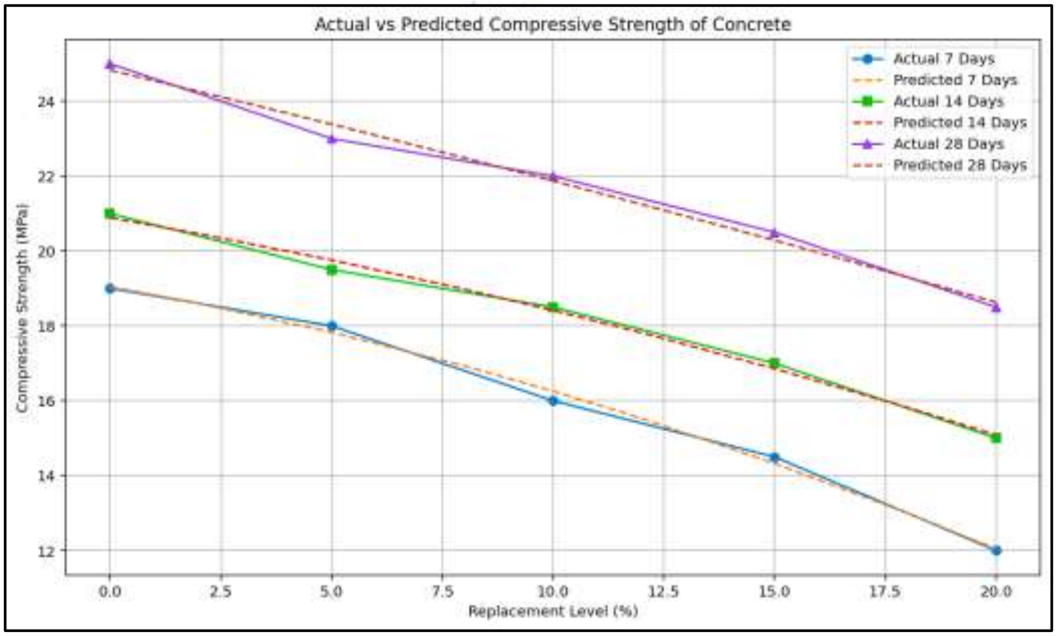

Figure 8 Predicted vs Actual Compressive Strength at Different Ages

Figure 9 illustrates the concept of relative strength, which represents the comparative performance of concrete containing recycled asphalt coarse aggregate against that of the conventional control mix. Essentially, relative strength is expressed as the ratio of the compressive strength of the recycled aggregate concrete to the compressive strength of the standard mix without any recycled content. This metric provides insight into the extent to which incorporating recycled aggregates affects the structural capacity of the concrete, enabling a clear assessment of the material's efficiency and suitability for practical applications.

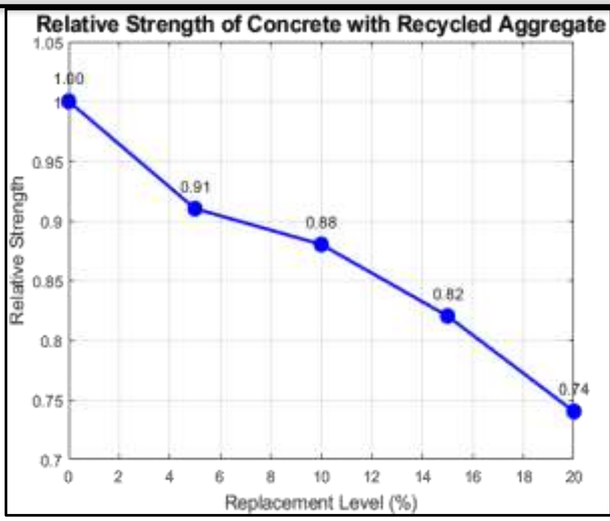

Figure 9 Relative Strength vs Replacement

V. CONCLUSIONS

The experimental results demonstrate a significant reduction in compressive strength with increasing percentages of recycled pavement waste aggregate (RPWA). This decline in strength is primarily attributed to the residual bitumen coating on the surface of the recycled aggregates, which adversely affects the interfacial transition zone (ITZ) between the aggregate and the cementitious matrix. Specifically, the residual bitumen content, measured at approximately 4.8%, hinders proper bonding within the concrete microstructure, leading to decreased mechanical performance. It was observed that a residual bitumen content approaching or slightly below 5% allows the mix to retain acceptable compressive strength levels, thereby achieving a balance between sustainability and structural integrity. Furthermore, incorporating RPWA at a replacement level of 15% proved to be an optimal threshold, beyond which the reduction in strength becomes pronounced and potentially detrimental. At this replacement level, a compressive strength reduction of approximately 26% was recorded in comparison to the control mix. While this represents a notable decrease, the performance remains within acceptable limits for certain non-structural or low-load applications. Overall, the findings suggest that controlled use of RPWA, particularly when residual bitumen is minimized, can enhance the sustainability and cost-effectiveness of concrete production without compromising essential strength parameters beyond permissible limits.

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