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Eco-Friendly Concrete Produced from Ceramic Waste

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الخرسانة الصديقة للبيئة المصنوعة من مخلفات السيراميك

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Abstract:
The construction sector is increasingly shifting towards sustainable practices, driven by the urgent need to curb the depletion of natural resources and reduce the carbon footprint. This paper aims to review the feasibility of utilizing ceramic waste generated from the tile and sanitary ware industry, as well as construction and demolition debris as a sustainable alternative to traditional materials in concrete production. The research examines the mechanical properties (compressive strength, tensile strength, and flexural strength) and durability characteristics (chloride penetration resistance, sulfate resistance, freeze-thaw resistance, and permeability) of concrete incorporating ceramic waste, supported by the latest scientific literature. The findings indicate that the optimal replacement of ceramic waste whether used as aggregate or as a supplementary cementitious material can significantly enhance mechanical performance and durability, while delivering tangible environmental and economic benefits. This makes the technique a promising avenue towards achieving sustainable development goals in the construction industry.

Keywords: Eco-Friendly Concrete; Ceramic Waste; Mechanical Properties; Durability; Compressive Strength; Supplementary Cementitious Materials; Recycled Aggregate; Pozzolanic Activity; Sustainability; Chloride Penetration Resistance.

الملخص
يشهد قطاع البناء والتشييد تحولاً متزايداً نحو الممارسات المستدامة، مدفوعاً بالحاجة الملحة للحد من استنزاف الموارد الطبيعية وخفض البصمة الكربونية. تهدف هذه الورقة إلى استعراض إمكانية استخدام مخلفات السيراميك - الناتجة عن صناعة البلاط والأدوات الصحية ومخلفات الهدم والبناء - كبديل مستدام عن المواد التقليدية في إنتاج الخرسانة. يستعرض البحث الخصائص الميكانيكية (مقاومة الضغط، مقاومة الشد، ومقاومة الانثناء) وخصائص المتانة (مقاومة اختراق الكلوريد، مقاومة الكبريتات، مقاومة التجميد والذوبان، والنفاذية) للخرسانة المحتوية على مخلفات السيراميك، بدعم من أحدث المراجع العلمية. تشير النتائج إلى أن الاستبدال الأمثل لمخلفات السيراميك - سواء كركام أو كمادة أسمنتية تكميلية - يمكن أن يعزز الأداء الميكانيكي والمتانة بشكل ملحوظ، مع تحقيق فوائد بيئية واقتصادية ملموسة، مما يجعل هذه التقنية خياراً واعداً في طريق تحقيق أهداف التنمية المستدامة في صناعة البناء.

الكلمات المفتاحية: الخرسانة الصديقة للبيئة؛ مخلفات السيراميك؛ الخصائص الميكانيكية؛ المتانة؛ مقاومة الضغط؛ المواد الأسمنتية التكميلية؛ الركام المعاد تدويره؛ النشاط البوزولاني؛ الاستدامة؛ مقاومة اختراق الكلوريد

1 .Introduction

The construction industry is one of the largest consumers of natural resources, with concrete production alone consuming approximately 10–20 billion tons of aggregate annually worldwide (Zheng et al., 2023, as cited in Al-Harthy et al., 2025). In contrast, the ceramic industry and construction and demolition waste generate massive quantities of waste that pose a significant environmental burden. In China alone, ceramic waste production reaches about 18 million tons annually, where 30% of ceramic products are discarded due to manufacturing defects, and ceramic waste represents about 30% of total construction and demolition waste (Lin, 2023, as cited in Zhang et al., 2025).

The dual challenge of natural resource scarcity on one hand and increasing industrial waste on the other necessitates the search for innovative solutions to recycle these wastes into concrete production. Ceramic waste has gained increasing attention in recent years, as it can be utilized in three main ways: as a replacement for coarse aggregate, as a replacement for fine aggregate, and as supplementary cementitious materials (SCMs) after grinding into a fine powder (Ahmad et al., 2025). Ceramic materials possess physical and chemical properties that make them a promising candidate for this role, including their high hardness, abrasion resistance, and pozzolanic activity, which enables them to react with calcium hydroxide produced during cement hydration to form compounds that contribute to improving the microstructure of concrete (Meddah et al., 2025).

2 .Characteristics and Classification of Ceramic Waste

Ceramic waste originates from multiple sources, including waste from tile and sanitary ware factories, waste generated from demolition and renovation of buildings, and waste resulting from cutting and polishing operations in factories (AlArab & Hamad, 2025). The chemical composition of ceramic waste varies depending on its source and type; however, it is generally characterized by a high content of silica (SiO_2) and alumina (Al_2O_3), which are the primary elements responsible for pozzolanic activity. X-ray fluorescence (XRF) analyses have shown that the silica content in ceramic waste powder can reach approximately 71.4%, with significant proportions of alumina and sodium oxides (Ahmed et al., 2026).

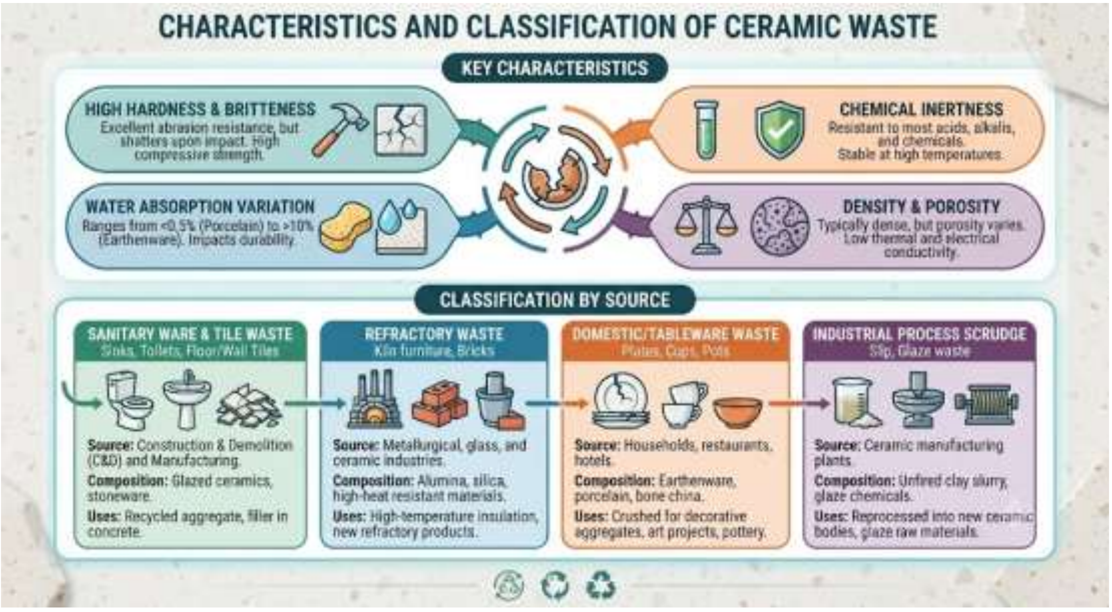

Figure 1: Characteristics and classification of ceramic waste

The performance of ceramic waste in concrete is highly dependent on particle size and fineness. The smaller the particle size, the greater the specific surface area, and consequently the greater the effectiveness in pozzolanic reactions. Studies have indicated that when the particle size is less than 20 mm, the optimal replacement ratio ranges between 20–30% by weight for both ceramic powder and glass powder (Zhang et al., 2025). This classification presented in Table 1 helps identify the source and the typical quality of the waste stream.

Table 1: classification of wastes

<table>
<tr><th>Classification</th><th>Source</th><th>Description</th></tr>
<tr><td>Production Waste (Pre-Consumer)</td><td>Ceramic Manufacturing Plants</td><td>Waste generated during the manufacturing process. It is the most consistent and high-quality source.</td></tr>
<tr><td>Firing Waste</td><td>Kiln reject, broken tiles, sanitary ware.</td><td>These materials are fully fired and are most similar to natural aggregate. This is the primary source for aggregate replacement.</td></tr>
<tr><td>Green Waste</td><td>Unfired, dried products.</td><td>These are still in a clay-like state. They can be easily re-pulped and recycled back into the production process.</td></tr>
<tr><td>waste types</td><td rowspan="2">Building Sites and Demolition</td><td>Waste from new construction (off-cuts) and demolition of old buildings.</td></tr>
<tr><td>waste types</td><td>This stream is highly heterogeneous. It is mixed with other materials (mortar, plaster, wood, bricks) and requires significant processing (crushing, separation, cleaning) before it can be reused as aggregate.</td></tr>
</table>

3 .Mechanical Properties

3.1 Compressive Strength

Compressive strength is one of the most important mechanical properties of concrete, and numerous studies have demonstrated a marked improvement in this property when using ceramic waste at optimal ratios. A study by Rehman et al. (2025) found that replacing 20% of coarse aggregate with ceramic waste increased compressive strength by 22% at 28 days, rising from 27.27 MPa to 33.27 MPa. Another study showed that replacing 20% of coarse aggregate and 50% of fine aggregate with ceramic waste achieved compressive strength values of 32.98 MPa and 35.83 MPa, respectively (Khan et al., 2025). Additionally, the waste types are tabulated in Table

Table 2: Waste Types

Waste Type	Replacement Ratio	Increase in Compressive Strength	Reference
Recycled fine ceramic aggregate	20%	40.7%	(Al-Harthy et al., 2025)
Coarse ceramic aggregate	20%	22.0%	(Rehman et al., 2025)
Ceramic powder (as replacement for fine aggregate)	30%	10.5%	(Ahmed et al., 2026)
Ceramic powder + natural pozzolan	10% + 15%	8.12 – 11.49%	(AlArab & Hamad, 2025)

When using ceramic waste powder as a partial replacement for cement, results showed that replacement ratios between 5–10% achieve the highest improvement in compressive strength, as the pozzolanic powder consumes calcium hydroxide and forms calcium silicate hydrate (C-S-H) gel, which contributes to increased concrete density and improved strength (Meddah et al., 2025). A study by AlArab and Hamad (2025) demonstrated that the concrete mix containing 10% ceramic powder and 15% natural pozzolan achieved an increase in compressive strength ranging between 8.12–11.49% compared to reference specimens.

Remarkably, some studies have achieved higher replacement ratios with impressive results. Patel et al. (2025) reported that replacing 60% of natural aggregate with ceramic tile waste having zero water absorption led to a 31.5% increase in compressive strength. However, researchers agree that exceeding the optimal ratios (generally ranging between 10–20% as cement replacement, and 20–60% as aggregate replacement) leads to deterioration in mechanical performance due to increased porosity and weak bonding between the cement paste and aggregate particles (Ahmad et al., 2025; AlArab & Hamad, 2025).

3.2 Tensile Strength

Split tensile strength and flexural tensile strength are important properties that reflect the concrete's ability to resist cracking under loads. A study by Rehman et al. (2025) showed that the split tensile strength reached its maximum value (4.20 MPa) when using 20% ceramic waste as a replacement for coarse aggregate. Another study showed that replacing 20% of fine aggregate with ceramic waste achieved a 47.6% improvement in tensile strength (Al-Harthy et al., 2025).

In the context of using ceramic powder as a cement replacement, AlArab and Hamad (2025) indicated that the optimal mix (Kh15C10) achieved an increase in tensile strength ranging between 3.60–6.33%. Ahmed et al. (2026) also showed that replacing 20% of fine aggregate with ceramic powder led to an optimal improvement in tensile strength of 4.68%. This improvement is attributed to the enhanced microstructure of the concrete resulting from pozzolanic reactions, which contribute to stronger bonding between concrete components.

3.3 Flexural Strength

Flexural strength is an important measure of concrete performance in structural elements subjected to bending moments. Studies have shown a notable improvement in this property when using ceramic waste, where the optimal mix (Kh15C10) achieved an increase in flexural strength ranging between 2.99–12.45% (AlArab & Hamad, 2025). Patel et al. (2025) reported that replacing 60% of aggregate with ceramic tile waste led to a 10.8% increase in flexural strength, while Ahmed et al. (2026) showed that replacing 30% of fine aggregate with ceramic powder achieved a 5.92% improvement in flexural strength.

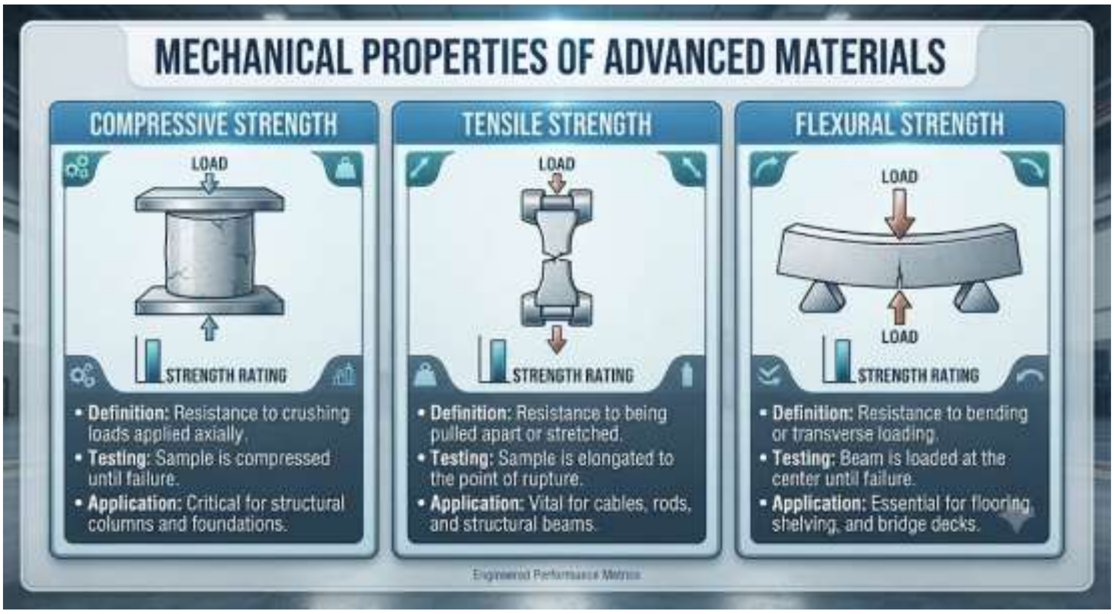

Figure 2: Flexural Strength

4 .Durability Properties

4.1 Chloride Penetration Resistance

Chloride ion penetration resistance is one of the most important indicators of concrete durability, especially in structures exposed to marine environments or de-icing salts. A comprehensive review by Ahmad et al. (2025) indicated that the use of ceramic waste improves chloride penetration resistance at optimal replacement ratios (typically 10–20%). AlArab and Hamad (2025) confirmed that combining ceramic powder with natural pozzolan led to a significant reduction in permeability, reaching a 99.82% reduction compared to reference specimens.

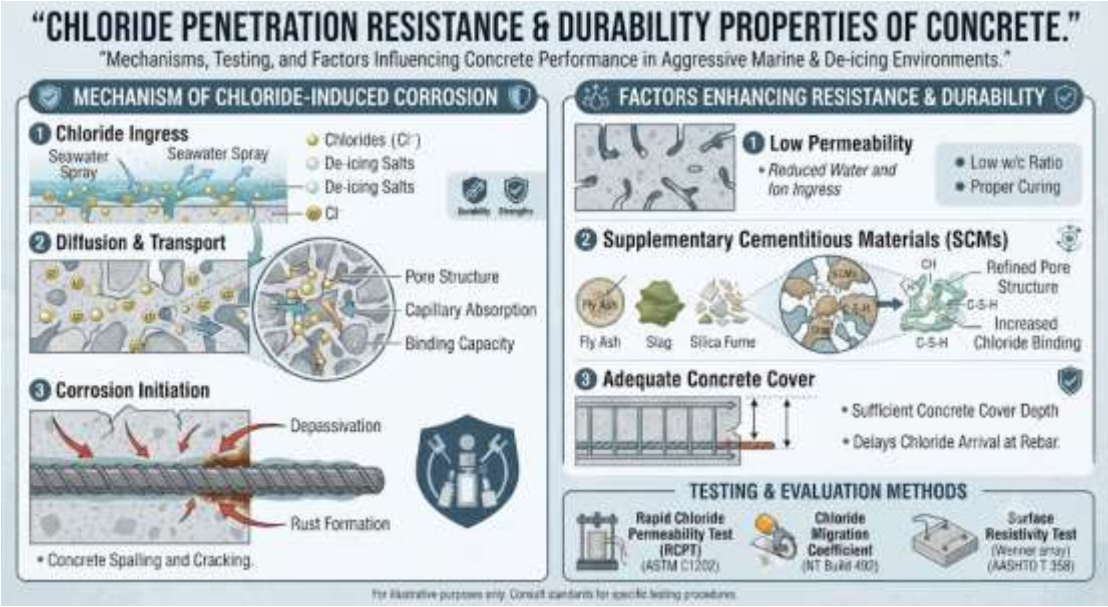

Figure 3: Chloride Penetration Resistance

Patel et al. (2025) also demonstrated that using ceramic tile waste with zero water absorption contributes significantly to improving durability by reducing chloride permeability and enhancing the Interfacial Transition Zone (ITZ). It should be noted that some studies have cautioned that concrete containing ceramic aggregate may show insufficient resistance to chloride penetration in some cases due to increased porosity resulting from aggregate water absorption (Chen et al., 2025), emphasizing the importance of selecting appropriate ratios and the quality of the waste used.

4.2 Sulfate Resistance

Sulfate attack resistance is a vital property for concrete exposed to soil or water containing sulfate salts. A recent study showed that adding ceramic waste powder and sugarcane bagasse ash led to a noticeable improvement in sulfate resistance compared to reference concrete (Hassan et al., 2025). Another study indicated that replacing 60% of ordinary Portland cement with ceramic tile powder along with the addition of 4–6% silica nanoparticles extracted from waste glass led to a significant enhancement in concrete resistance to both sulfuric acid and sulfate attack (Al-Masri et al., 2025).

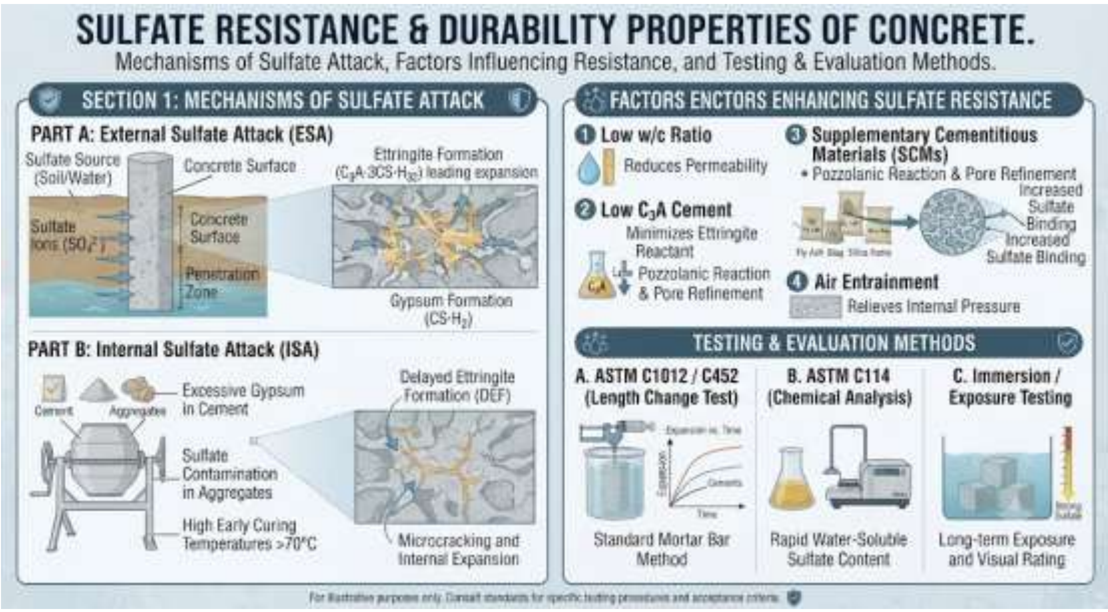

Figure 4: Sulfate Resistance

4.3 Freeze-Thaw Resistance

Concrete resistance to repeated freeze-thaw cycles is an important indicator of its durability in cold climates. A study by Zhang et al. (2025) showed that specimens containing 20% ceramic particles as replacement exhibited the best freeze-thaw resistance, failing only after 398 freeze-thaw cycles, whereas exceeding 20% led to a significant decrease in this resistance. A review by Ahmad et al. (2025) indicated that concrete containing ceramic waste improves freeze-thaw cycle resistance at appropriate dosages.

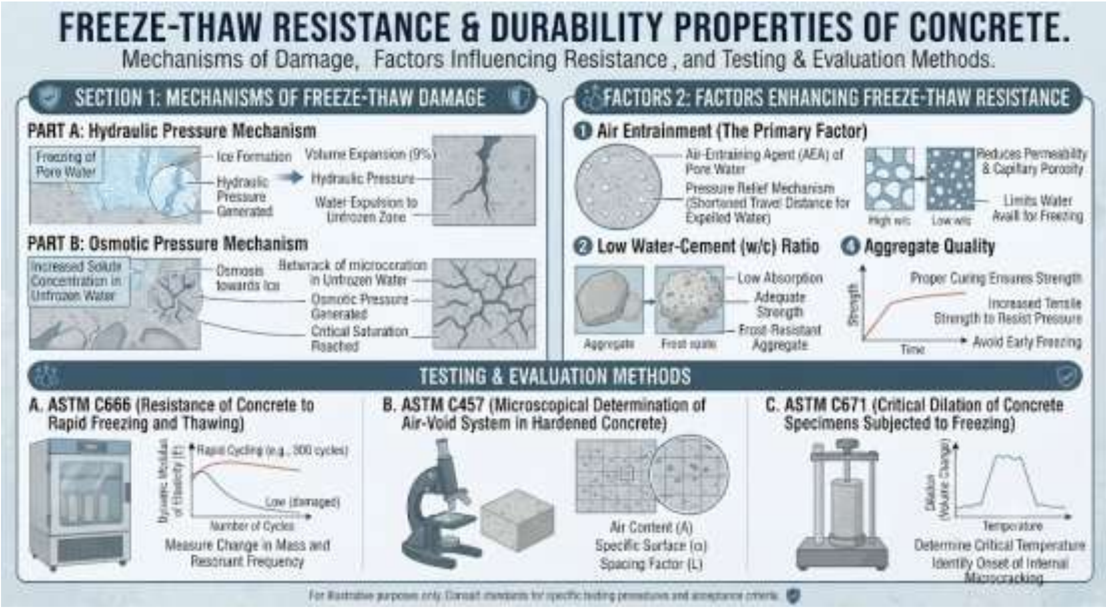

Figure 5: Freeze-Thaw Resistance

4.4 Absorption and Permeability

Low water absorption and permeability are fundamental indicators of durable concrete. AlArab and Hamad (2025) found that the optimal mix achieved a reduction in water absorption ranging between 35.74–77.33% compared to reference specimens. Patel et al. (2025) also indicated that using ceramic waste with zero water absorption contributes to improving the microstructure of concrete and reducing porosity. This improvement is attributed to the microfilling effect of fine ceramic particles that fill voids between aggregate particles, and to pozzolanic reactions that produce additional C-S-H gel that seals pores.

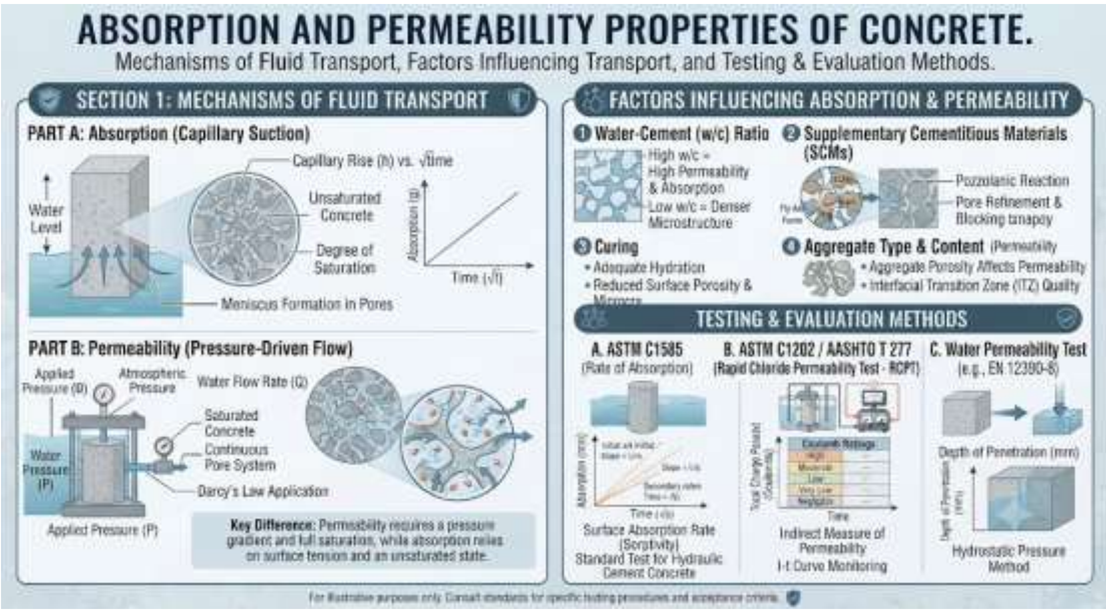

Figure 6: Absorption and Permeability

4.5 Microstructure and Interfacial Transition Zone

The Interfacial Transition Zone (ITZ) between the cement paste and aggregate is one of the weakest zones in conventional concrete. Microscopic studies have shown that using ceramic waste as aggregate leads to the formation of a denser and more stable ITZ compared to natural aggregate (Medina et al., 2012). Patel et al. (2025) confirmed that ceramic waste with zero water absorption works to improve the ITZ and enhance microstructural integrity. This improvement in microstructure positively reflects on both the mechanical properties and durability of the concrete.

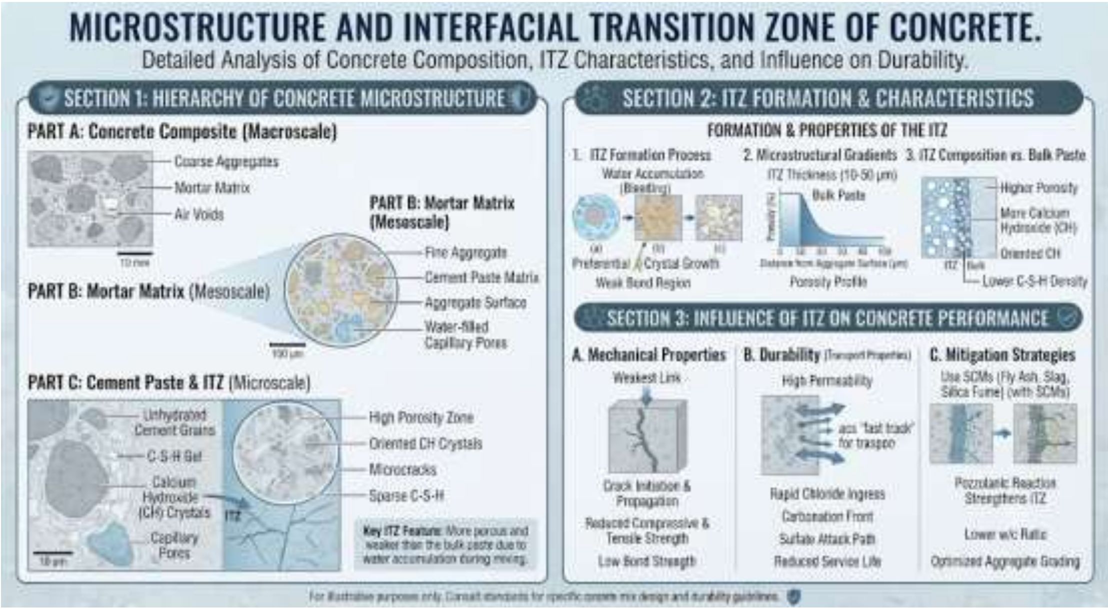

Figure 7: Microstructure and Interfacial Transition Zone

5 .Sustainability and Environmental Impact

Beyond technical performance improvement, using ceramic waste in concrete carries significant environmental and economic benefits. On one hand, it contributes to reducing the amount of waste sent to landfills, alleviating land pressure and reducing environmental pollution (Zhang et al., 2025). On the other hand, it reduces the extraction of natural resources (aggregate and raw materials for cement), contributing to the conservation of natural resources and limiting environmental degradation associated with quarrying and mining operations (Ahmad et al., 2025).

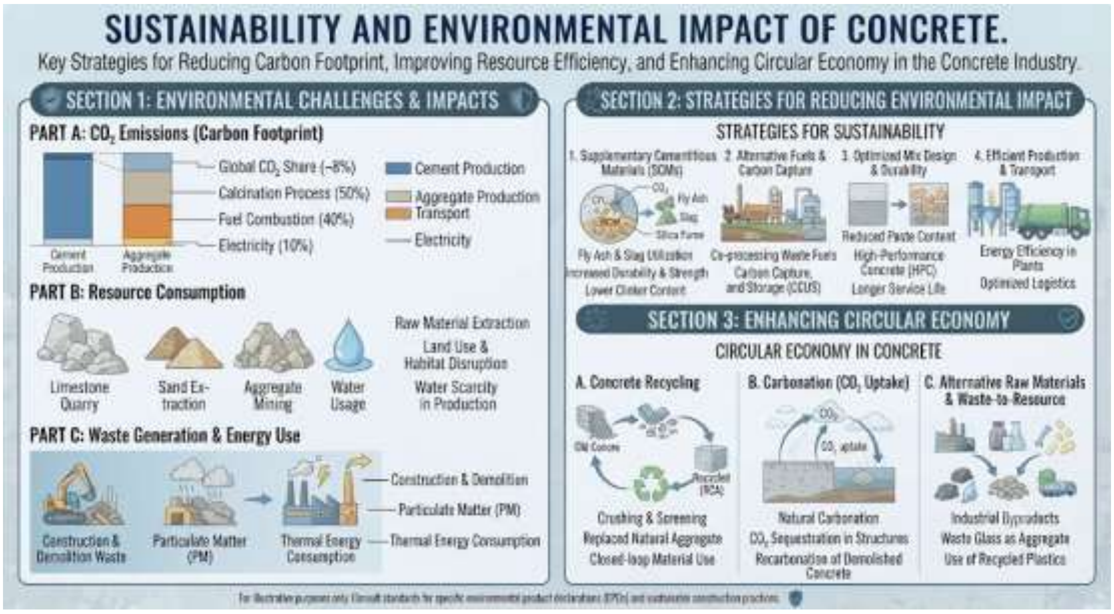

Figure 8: Sustainability and Environmental Impact

In terms of carbon footprint, a study by Khan et al. (2025) showed that replacing aggregate with ceramic waste can reduce carbon dioxide emissions during concrete production by an amount ranging between 6–250 kg CO_2e/ton, depending on the application. AlArab and Hamad (2025) indicated that partially replacing cement with ceramic powder and natural pozzolan contributes to reducing cement demand and thus lowering CO_2 emissions and promoting circular economy principles. A study by Abdel-Halim et al. (2025) estimated that replacing 10% of cement with ceramic powder can reduce embodied CO_2 emissions by 7–10%.

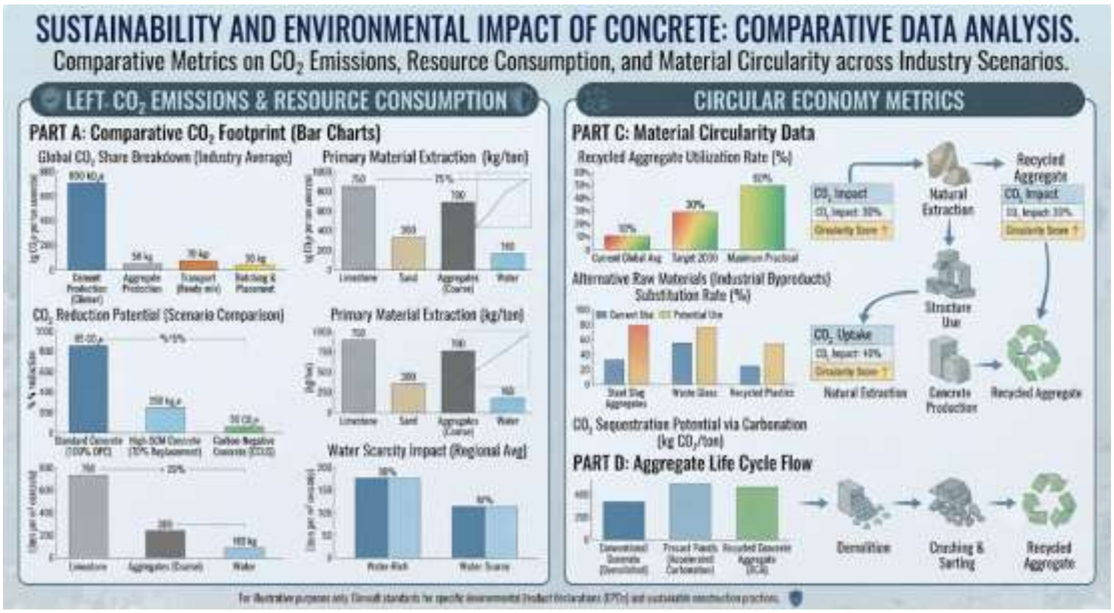

Figure 9: Comparison of data analysis

These benefits align with the United Nations Sustainable Development Goals (SDGs), particularly Goal 11 (Sustainable Cities and Communities), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action) (Al-Masri et al., 2024). Furthermore, Life Cycle Assessment (LCA) of concrete containing ceramic powder has demonstrated its economic and environmental feasibility, as replacing 30% of fine aggregate with ceramic powder can reduce manufacturing costs by approximately 2.3% (Ahmed et al., 2026).

6 .Challenges and Limitations

Despite the numerous benefits, the application of ceramic waste in concrete faces several challenges. The most prominent include:

1. Composition Variability: The chemical and mineralogical composition of ceramic waste varies depending on its source and type, leading to performance variability and difficulty in establishing unified standards (Ahmad et al., 2025).
2. Low Early Strength: The use of ceramic powder as a cement replacement may lead to low early strength due to the reduced reactivity of the powder at early ages (AlArab & Hamad, 2025).
3. Reduced Workability: The addition of ceramic powder or ceramic aggregate increases water demand and reduces workability due to the irregular particle shape and high water absorption (Ahmed et al., 2026).
4. Lack of Standards: There are currently no unified standards or clear guidelines for the large-scale application of ceramic waste in concrete (Zhang et al., 2025).
5. High Replacement Ratios: Exceeding the optimal replacement ratios (more than 20–30% for cement, and more than 60% for aggregate) leads to a notable deterioration in mechanical properties and durability (Meddah et al., 2025).

7 .Conclusion and Recommendations

Accumulated scientific evidence confirms that ceramic waste represents a promising and sustainable alternative to traditional materials in concrete production. When used at optimal ratios (10–20% as cement replacement, and 20–60% as aggregate replacement), ceramic waste contributes to improving mechanical properties (compressive strength, tensile strength, flexural strength) and durability characteristics (chloride resistance, sulfate resistance, freeze-thaw resistance, and low permeability). This improvement is attributed to the pozzolanic activity of ceramic powder and the microfilling effect, as well as the improvement of the ITZ when using ceramic aggregate.

On the other hand, this technology achieves tangible environmental benefits through reducing waste sent to landfills, conserving natural resources, and lowering carbon dioxide emissions, making it compatible with circular economy principles and sustainable development goals.

Recommendations:

1. Conduct further field studies and large-scale practical applications to evaluate the performance of concrete containing ceramic waste under real-world conditions.
2. Develop unified standards and technical specifications for the application of ceramic waste in concrete, including optimal replacement ratios based on the type of application and operating conditions.
3. Study the feasibility of using additional treatments (such as carbon dioxide curing, or the addition of reinforcing fibers) to improve concrete performance at high replacement ratios.
4. Conduct comprehensive Life Cycle Assessment (LCA) studies to evaluate the complete environmental and economic impact of concrete containing ceramic waste under various conditions and applications.

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