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DURABILITY AND RELATED PROPERTIES OF CEMENT-BASED COMPOSITES CONTAINING CERAMIC WASTE TILE POWDER

Summary: The increasing environmental impact of cement production has driven the search for sustainable supplementary cementitious materials (SCMs). The incorporation of ceramic waste tile powder (CWTP) as a partial cement replacement in concrete and mortar has proven to be significant for durability and related properties improvement, enhancing the microstructure of cementitious composites, reducing porosity and capillary absorption, while simultaneously promoting the formation of additional C–S–H gel through pozzolanic reactions. It has been observed that the optimal level of cement replacement with CWTP depends on the investigated durability property, with overall performance improvements achieved within a range of approximately 5% to 40%. Lower replacement levels (around 5–20%) show more favorable results in terms of acid and sulfate resistance, while higher levels (30–40%) significantly contribute to the reduction of capillary absorption and chloride ion penetration, confirming that the effectiveness of CWTP varies depending on the dominant degradation mechanism.

Keywords: ceramic waste tile powder, cement replacement, durability, capillary absorption

TRAJNOST I POVEZANA SVOJSTVA CEMENTNIH KOMPOZITA KOJI SADRŽE PRAH KERAMIČKOG OTPADA OD PLOČICA

Rezime: Sve veći uticaj proizvodnje cementa na životnu sredinu podstakao je potragu za održivim dodatnim cementnim materijalima (SCM). Ugradnja praha od otpadnih keramičkih pločica (CWTP) kao delimične zamene cementa u betonu i malteru pokazala se značajnom za poboljšanje trajnosti i srodnih svojstava, unapređujući mikrostrukturu cementnih kompozita, smanjujući poroznost i kapilarno upijanje, uz istovremeno podsticanje formiranja dodatnog C–S–H gela putem pucolanskih reakcija. Uočeno je da optimalni nivo zamene cementa CWTP-om zavisi od ispitivanog svojstva trajnosti, pri čemu su ukupna poboljšanja performansi ostvarena u opsegu zamene od približno 5% do 40%. Niži nivoi zamene (oko 5–20%) pokazuju povoljnije rezultate u pogledu otpornosti na dejstvo kiselina i sulfata, dok viši nivoi zamene (30–40%) značajno doprinose smanjenju kapilarnog upijanja i prodora hloridnih jona. Ovi rezultati potvrđuju da efikasnost CWTP-a varira u zavisnosti od dominantnog mehanizma degradacije.

Ključne reči: prah keramičkog otpada od pločica, zamena za cement, trajnost, kapilarno upijanje

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1. INTRODUCTION

On a global scale, the construction sector is one of the largest consumers of natural resources, utilizing approximately 50% of all extracted raw materials and contributing more than one-third of greenhouse gas emissions associated with the built environment [1–4].

According to European Union legislation [5], construction and demolition waste (C&DW) includes materials generated during the construction, renovation, reconstruction, demolition, or dismantling of buildings and infrastructure. In most cases, this type of waste is disposed of in landfills [6].

Such waste generated by the construction sector accounts for around 30% of the total waste produced globally [7], while it is estimated that more than 35% of the total generated C&DW is landfilled each year [8].

As part of C&DW, ceramic tile waste (CWT), which is mainly generated during the production, construction, renovation, and demolition of buildings, includes broken tiles, rejected production batches, and unused cutting residues [9,10]. On a global scale, more than 10 million square meters of ceramic tiles are produced annually [11]. Detailed studies have shown that 15–30% of materials are converted into waste during ceramic manufacturing processes [12,13].

This study deals with CWT as finely ground powder obtained from ceramic tile waste generated during manufacturing and polishing processes, i.e. ceramic waste tile powder (CWTP).

Solid waste generated during ceramic tile production can be classified into waste produced before and after glazing and firing. The first group mainly consists of clay mixture residues or broken ceramic pieces that can be reused in tile production. The second group consists of waste that is usually discarded, as it contains too many impurities to be reintroduced into the production process [14]. During the polishing process, waste is generated that retains the same characteristics as the original product and therefore has potential for reuse in the construction industry. This process is carried out at the end of the production line to ensure uniform tile dimensions. Excess material from the edges is removed using diamond grinding wheels in the presence of water [15].

Experimental studies indicate that partial replacement of ordinary Portland cement (OPC) with finely ground ceramic waste enables the production of more sustainable binders with reduced environmental impact. Although numerous studies [16–23] have investigated the rheological and mechanical properties of cementitious composites incorporating ceramic powder, including CWTP, as a supplementary cementitious material (SCM), data on the durability of these systems remain limited.

As shown in Figure 1, CWT exists in two color variations, white and red [13].

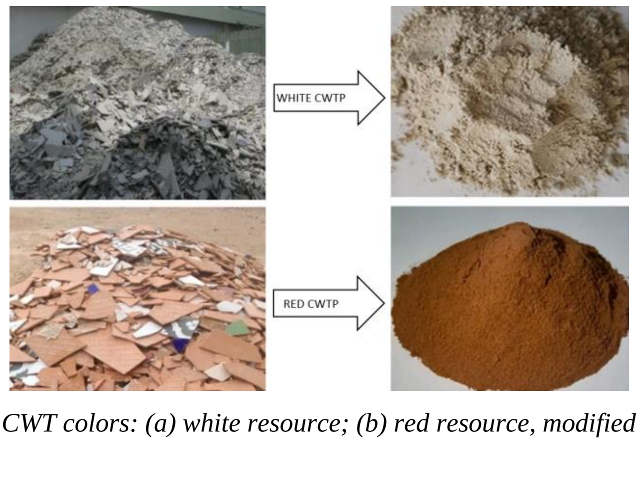

Figure 1: CWT colors: (a) white resource; (b) red resource, modified from [13]

During the grinding process, a significant increase in the specific surface area of the material occurs, as coarser particles are broken down into a larger number of finer particles.

Previous studies [17], [24–25] have shown that CWTP contains more than 70% of silicon dioxide, aluminum oxide, and iron oxide, thereby meeting the requirements of ASTM C618 [26] for pozzolanic materials. The presence of silicon dioxide and aluminum oxide promotes pozzolanic reactions and contributes to the improvement of concrete compressive strength.

CWTP, which has a high content of silica and alumina, can potentially improve the compressive strength of cement-based composites when used as a partial cement replacement up to a certain level. Previous studies have shown that the use of CWTP as SCM can positively influence the compressive strength of mortar and concrete. The best results are generally achieved at replacement levels up to 10%, where either an increase or a negligible change in strength is observed compared to reference mixtures [27]. At higher replacement levels (above 15–20%), a reduction in strength occurs due to the decreased cement content and reduced formation of hydration products.

In addition, mortar mixtures containing CWTP have shown further strength development at later curing ages, which is attributed to pozzolanic activity and the filler effect, both of which contribute to the formation of a denser microstructure [28–31]. Overall, the results indicate that CWTP can be effectively used as SCM at optimized replacement levels, most commonly in the range of 5–15% when mechanical performance is the primary requirement.

In general, most available research focuses predominantly on permeability and chloride ion ingress resistance, while other key durability parameters of cement-based composites incorporating ceramic waste powder remain insufficiently investigated. The improved durability of cementitious composites is mainly attributed to microstructural enhancement of the matrix, particularly the refinement of pore size and reduction of pore connectivity. Furthermore, increased resistance to chemical attack is linked to the reduced content of portlandite ($Ca(OH)_2$), which is consumed during pozzolanic reactions, resulting in a denser and more stable internal structure of the composite.

This paper presents a concise review of available studies addressing the durability and related properties of cement composites in which cement is partially replaced with CWTP. The analyzed research covers capillary absorption, drying shrinkage, sulfate and acid resistance, as well as chloride ion penetration, with the aim of assessing the influence of CWTP on microstructural changes and the long-term durability of concrete and mortar.

2. WATER ABSORPTION DUE TO CAPILLARY ACTION

Sorptivity represents the ability of porous materials to absorb and transport water or other liquids through interconnected capillary pore networks [13]. This parameter is closely related to the microstructure of the material, particularly pore size distribution and pore connectivity, and plays a crucial role in durability-related properties such as permeability, resistance to environmental exposure, and the long-term performance of cement-based composites.

The observed improvement is mainly attributed to the fine particle size of CWTP, which produces a strong micro-filler effect and enhances pore refinement, together with the activation of pozzolanic reactions that promote the formation of a denser and more homogeneous cementitious matrix. Consequently, total porosity is reduced and the internal structure of the cementitious materix is significantly refined, leading to lower water penetration and improved durability.

Li et al. [32] reported that the use of CWTP as a partial cement replacement at levels up to 40% results in a reduction in capillary sorptivity.

Furthermore, the increased formation of C–S–H gel at optimal CWTP levels contributes to reduced porosity and the development of a more compact and structurally dense internal microstructure of concrete.

3. DRYING SHRINKAGE

Studies show that drying shrinkage of concrete can lead to crack formation, reduced tensile strength, loss of prestress, and structural deformations [33]. The inclusion of CWTP as a cement replacement significantly mitigates this shrinkage [17]. This effect is particularly pronounced when the replacement exceeds 20%, with shrinkage reductions ranging from 29% to 60% compared to control mixes. For 50 MPa concrete, the reduction was 28–53%, while for 75 MPa concrete it was 25–27%, when CWTP was used at replacement levels of up to 40% [17].

In high-performance concrete, a significant reduction in shrinkage was observed, ranging from approximately 12% to 27% [34]. In mortars, it was observed that average drying shrinkage decreases in mixtures containing CWTP compared to standard OPC mortar after 90 days of curing [35].

Based on the available results related to drying shrinkage, a cement replacement level of 20–40% with CWTP can be recommended, as the most pronounced reductions in shrinkage were observed at replacement levels exceeding 20%. However, the final optimal replacement level should be determined by considering not only shrinkage behavior but also the mechanical properties and durability of concrete.

This improvement is attributed to a reduced free water content and a denser microstructure, resulting from the pozzolanic activity of CWTP [17].

4. RESISTANCE TO SULPHATE ATTACK

Sulfates present in soil or seawater can chemically attack OPC concrete when exposed to such environments. Upon contact with sulfate solutions, sulfate ions react with calcium hydroxide and tricalcium aluminate phases in the cement paste, leading to the formation of gypsum and expansive ettringite. These reactions may cause microcracking, strength loss, and long-term deterioration of the concrete structure.

The severity of sulfate attack depends on several factors, including sulfate concentration, concrete composition, and the incorporation of SCMs such as waste ceramic powder. These additions can modify the chemical processes within the cementitious matrix, improving resistance to sulfate attack and reducing material degradation [36–37].

Li et al. [32] reported that incorporating CWTP at replacement levels of 5% and 10% in mortar mixtures significantly enhanced resistance to surface deterioration. These mixtures exhibited reduced spalling and fewer surface cracks compared to control specimens. At a 20% replacement level, the improvement was even more pronounced, with no observable spalling and crack-free surfaces. This behavior is attributed to the pozzolanic activity of CWTP, which improves microstructure development, densifies the cement matrix, and reduces weak zones susceptible to cracking and degradation.

In addition, Mohammadhosseini et al. [38] reported that OPC mortar experienced a mass loss of 0.7% after three months of immersion, whereas mortar containing CWTP showed a mass gain of 1.7% under the same conditions in a Na_2SO_4 solution.

The incorporation of CWTP, which consumes weak calcium hydroxide and promotes the formation of additional C–S–H gel, results in a denser internal concrete structure with improved resistance to sulfate attack [13].

In terms of sulphate resistance, a CWTP replacement level of 10–20% is recommended, with 20% showing the best performance in preventing cracking and improving durability.

Overall, the study highlights the positive role of CWTP in increasing the structural integrity and long-term durability of cementitious materials.

5. RESISTANCE TO CHLORIDE INGRESS

Chlorides are a primary factor in accelerating the corrosion of steel reinforcement in concrete. El-Dieb and Kanaan [17] evaluated chloride ion penetration in concrete incorporating CWTP at replacement levels of 10–40%. The results at 28 days showed a clear reduction in chloride permeability with increasing CWTP content, with measured values decreasing from 3899 to 590 coulombs. This improvement was mainly attributed to the pozzolanic activity of CWTP, which enhances matrix densification and refines the pore network, thereby limiting chloride transport through the concrete.

Figure 2 shows that as the SCM content in concrete increases, chloride ion penetration decreases, meaning that the concrete becomes less permeable to chlorides [17].

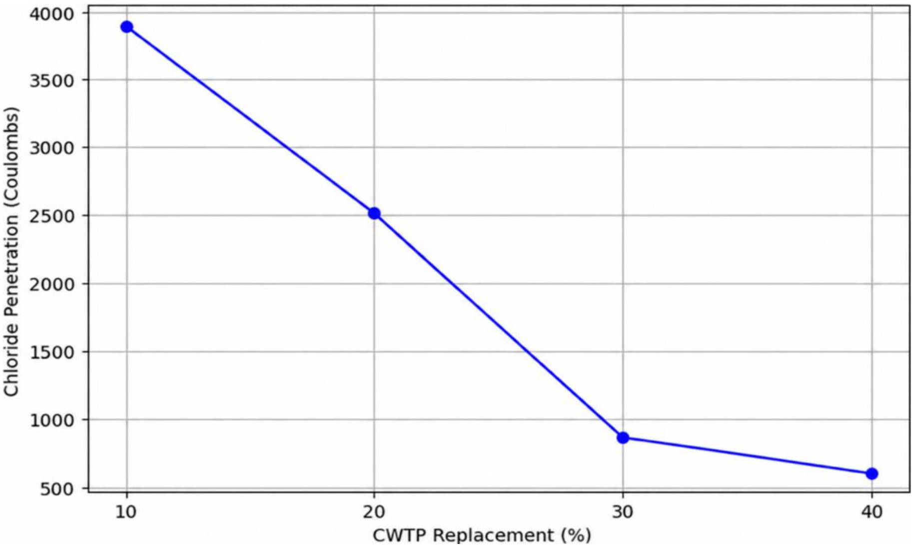

Figure 2: Chloride ion penetration in concrete with 10–40% CWTP at 28 days, modified from [17]

The reduced chloride ingress in concrete containing CWTP is attributed to the lower volume of permeable pores within the cement matrix, which restricts ion transport through the material. In addition, the pozzolanic activity of CWTP promotes the formation of additional C–S–H gel, leading to a denser concrete microstructure and further reduction in pore connectivity.

As a result, CWTP-modified concrete exhibits enhanced resistance to chloride-induced chemical attack, thereby improving the long-term durability of concrete structures, particularly in aggressive environments such as seawater or contaminated soil.

Mohammadhosseini et al. [39] investigated the effect of CWTP as a cement replacement in mortars. After 18 months of exposure, the mass of specimens increased by 3.8% in OPC mortar and by 2% in mortar containing CWTP. The CWTP mortar also exhibited an average penetration depth of 5 mm, whereas the reference mortar showed a penetration depth of 15 mm [39].

According to Kannan et al. [40], the reduced penetration of chloride ions in concrete containing CWTP can be attributed to its less permeable pore structure compared to concrete without ceramic waste.

Chloride ion penetration into the concrete matrix is one of the most detrimental processes directly affecting the long-term durability and safety of concrete structures [41-43]. Chloride ions can penetrate through pores and microcracks in the concrete, reach the surface of the reinforcement, and initiate an electrochemical corrosion reaction. This process leads to the expansion of corroded particles, the development of internal stress, formation of cracks, and, over time, a reduction in the load-bearing capacity and stability of the structure.

Due to the severity of this issue, reducing pore connectivity and limiting chloride ingress are key strategies for improving concrete durability, and the use of additives such as CWTP has shown significant potential in achieving these objectives.

Based on the presented results, CWTP replacement levels between 10% and 40% can be recommended for improving resistance to chloride ingress, with the most significant reduction in permeability and chloride penetration observed at higher replacement levels within this range.

6. ACID RESISTANCE

Resistance to acid attack represents a key durability requirement for concrete structures since acidic environments are particularly harmful due to their direct contribution to reinforcement corrosion. Statistical data indicate that more than 40% of structural damage and failures are associated with steel reinforcement corrosion [22].

Mohit et al. [44] examined the potential of using CWTP as a partial cement replacement in mortars exposed to hydrochloric acid. After 56 days of exposure, the reference specimen showed a mass loss of 8.64%, while mixes containing 5–25% CWTP exhibited slightly lower or comparable mass losses, ranging between 7.11% and 9%.

The corresponding results regarding mass loss and compressive strength reduction for different CWTP contents after 56 days of hydrochloric acid exposure are presented in Figure 3.

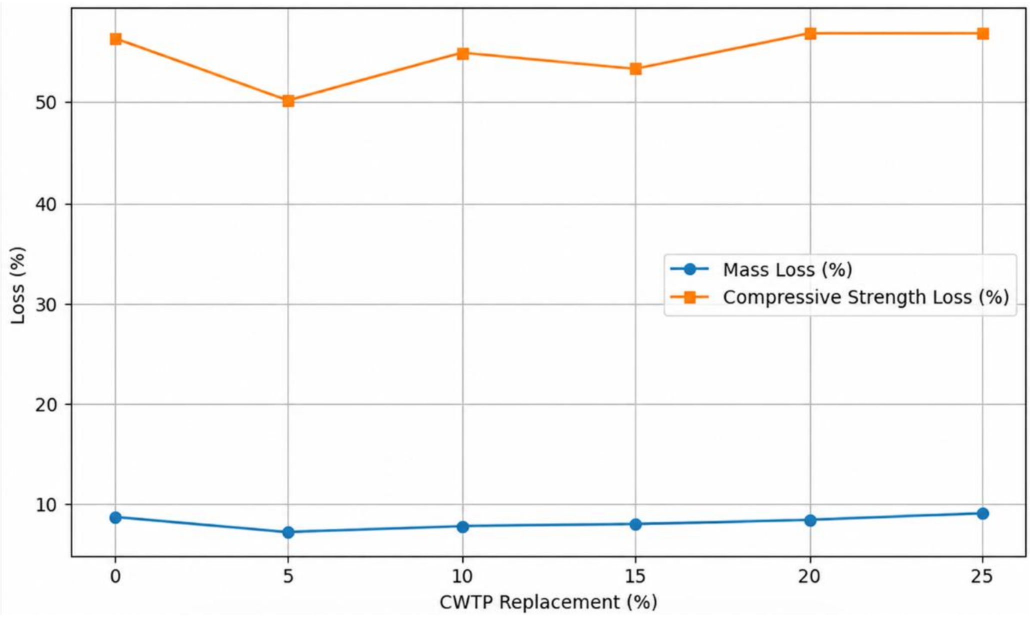

Figure 3: Effect of CWTP replacement on mass loss and compressive strength of mortar after 56 days of hydrochloric acid exposure, modified from [44]

Similarly, all specimens experienced a reduction in compressive strength. The mixtures with 5% CWTP demonstrated the lowest strength reduction (approximately 50%), while higher replacement levels resulted in more pronounced losses, reaching about 57%. Compared with the control concrete, which lost around 56% of its initial strength, the results indicate that incorporating a small proportion of CWTP can mitigate the adverse effects of acid attack, whereas higher CWTP contents do not provide additional improvement in resistance.

Results reported in study [22] show a pronounced decrease in compressive strength of concrete with increasing exposure to acidic environments (HCl and H_2SO_4). The compressive strength tests of ceramic powder-modified concrete were performed after 28 days of standard curing followed by immersion in a 2% sulfuric acid solution for 90 days to evaluate acid resistance. In the control zone (Z0), the compressive strength was approximately 42 MPa, while in zone Z6 it decreased to about 19 MPa, corresponding to an overall strength loss of around 50%. A similar degradation trend was observed for both acids, indicating progressive deterioration of the microstructure and a reduction in mechanical properties due to prolonged acid attack.

Based on the presented results, an optimal CWTP replacement level of approximately 5% can be recommended for improving resistance to acid attack, as higher replacement levels do not provide additional benefits and may even increase compressive strength loss compared to the control mix.

7. CONCLUSIONS

Based on the presented data and analyses, the use of CWTP as a partial cement replacement in concrete and mortars demonstrates a significant positive impact on the durability of cementitious composites. Specifically:

• Capillary absorption: CWTP is recommended as a partial cement replacement at levels of up to 40%, as this proportion effectively reduces capillary sorptivity through pore structure refinement and the development of a denser cementitious matrix, leading to improved concrete durability.

• Drying shrinkage: Based on the available results on drying shrinkage, a CWTP replacement level of 20–40% can be recommended, as the greatest reductions in shrinkage were observed above 20%. However, the final optimal content should also consider mechanical properties and overall durability of concrete.

• Sulfate resistance: Based on the presented results, a CWTP replacement level of 10–20% can be recommended for improving resistance to sulfate attack, with 20% showing the most favorable performance in terms of crack prevention and surface durability.

• Chloride ingress: CWTP replacement in the range of 30–40% is recommended, as it provides the greatest reduction in chloride ion penetration through pore refinement and matrix densification, thereby significantly enhancing the durability of reinforced concrete in aggressive environments.

• Acid resistance: A low CWTP content of around 5% is recommended, since this level results in the highest resistance to acid attack, minimizing mass loss and compressive strength reduction after prolonged exposure to acidic conditions.

Based on the review of available studies, the optimal CWTP replacement level depends on the investigated durability property, with overall improvements observed within a range of approximately 5% to 40%. Lower replacement levels (around 5–20%) are most effective for acid and sulfate resistance, while higher levels (30–40%) significantly enhance resistance to capillary absorption and chloride ingress, indicating that CWTP can be an effective SCM on the required durability performance of concrete.

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