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Durability, Mechanical, and Corrosion Characteristics of Recycled Aggregate Concrete Utilizing Locally Sourced Waste and Ultrafine Cerium Oxide

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ABSTRACT

This study seeks to identify an environmentally sustainable method for utilizing the synergetic effects of window glass (WG), ceramic powder (CP), and ultrafine cerium oxide (UFC) in developing concrete containing 25% coarse ceramic aggregate. Four different mixtures were formulated. The first represents control, consisting of 100% ordinary Portland cement (OPC), two other mixtures were composed of 10% WG, 10% CP and 80% OPC, and the fourth mixture consisted of four compositions of 79.5% OPC, 10% WG, 10% CP, and 0.5% UFC. The effect of these additives on recycled ceramic concrete (RA) properties, including workability and setting time, compressive strength, total water absorption, permeable pore ratio, electrical resistivity, and corrosion resistance, was studied. The results showed that when 10% WG and 0.5% UFC were combined, the components' synergistic effect was more noticeable. It had a compressive strength of 44.53, 48.83, and 56.17MPa after 28, 90, and 180 days, which is higher than the ternary mixtures of Portland cement, ultrafine cerium oxide, and ceramic powder, as well as the quaternary mixtures of Portland cement, WG powder, CP, and UFC. Moreover, it recorded a lower corrosion rate than the reference mix (RA-C), ternary mix (RA-CP10UFC0.5), and quaternary mixes (RA-CP10WG10UFC0.5) mixes. Meanwhile, the quaternary mix (RA-CP10WG10UFC0.5) showed 40% and 45% lower porosity and water absorption than the control mixture and 54% higher electrical resistivity values compared to the control mixture and ternary mixtures (RA-WG10UFC0.5 and RA-CP10UFC0.5) at 180 days.

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1. Introduction

Concrete, a prevalent construction material, requires large quantities of natural aggregates (NAS) and ordinary Portland cement (OPC) in its manufacturing [1, 2]. Over the past century, rapid population growth, along with the accelerated industrialization and urbanization of developing nations, has drastically intensified the pressure on natural resources [3]. Green concrete construction, which includes the effective utilization of construction, demolition, or industrial waste by utilizing them in manufacturing concrete, has garnered considerable research attention in this area. As a result, numerous studies have produced green, sustainable, and environmentally friendly concrete by substituting recycled glass and ceramic waste for cement or aggregates [4]. Aggregate plays a significant role in concrete's compressive strength and overall characteristics because it constitutes roughly 80% to 85% of the total mixture [5]. It has been suggested that using recycled aggregates made from ceramic wastes is a low-carbon and sustainable substitute for natural aggregate [6]. Several researchers have examined the impact of substituting varying amounts of ceramic waste for natural coarse aggregates on the resulting concrete's mechanical strength, electrical conductivity, and durability. They discovered a notable difference in strength results primarily attributed to the inconsistency of the ceramic material utilized as a source, which includes electrical insulators, kitchenware, sanitary ware, bricks, and tiles frequently used in concrete [7-10]. For example, Mohamed and Ahmed [11] explored the effects of replacing natural coarse aggregate with waste floor tiles coarse aggregate (WCA) on concrete mechanical performances at 0, 10, 20, 30, 50, and 100% substitutions. The data proved a significant improvement in the mechanical performance of concrete, involving compressive, tensile, and flexural strength, as the replacement of NCA by WCA increased, with the most significant improvement observed up to a 20% substitution level. Mousavi *et al*. [12] explored the impacts of replacing natural coarse aggregate with recycled ceramic aggregates derived from sanitary ceramics and tiles in high-strength concrete (HSC) at 10%, 20%, and 30% substitutions. The results indicated that up to 30% ceramic aggregate could be used while achieving a compressive strength greater than 60.7 MPa. Higher superplasticizer dosages were required for equivalent shrinkage, and the recycled aggregates exhibited increased absorption (2.54% for tiles and 1.54% for ceramics) compared to natural aggregates (0.39%). The chloride penetration depth was also greater in mixtures with recycled aggregates due to their higher porosity. Meanwhile, Paul *et al.* [13] found that the concrete strength decreased with increasing waste ceramic tile aggregate, although a 10% replacement was acceptable due to minimal strength reduction. Also, Giridhar *et al.* [14] observed a decline in strength with the increasing proportion of recycled ceramic utilized. Recycling ceramic aggregates (RA) is limited in construction because of their high-water absorption capacity. The disparity in water absorption between ceramic and natural aggregates complicate their incorporation into concrete; thus, leading to reduction in strength, workability, and durability [15, 16]. RAC's strength and durability have been increased using various pre-treatment procedures, such as microbial carbonate precipitation [17], accelerated carbonation method [18], and nanomaterial modification [14]. Pre-treatment procedures are inappropriate for the construction industry due to their complicated treatment processes and increased expenses. A more practical procedure for improving recycled aggregate concrete (RA) is the direct incorporation of supplemental cementitious materials (SCMS), which avoids the need for complicated modifications to raw materials [19-22]. It has been found that waste glass powder and ceramic materials, considered prospective SCMs, display good pozzolanic reactions [19, 20]. This mixture considerably improves concrete's mechanical characteristics and durability, particularly at late sages [23, 24]. Reactive SiO_2 and Al_2O_3 cause the material's pozzolanic reactivity. In some ceramics powder reactive silica can constitute up to 25% while, in glass it can reach as high as 50% [24-27]. Additional reaction products formed between amorphous silica in ceramic powder and glass and [$Ca(OH)_2$] from ordinary Portland cement hydration products allow for improved pore size and microstructure [28-30].

Cerium oxide is a rare-earth oxide compound that mimics cubic fluorite [31]. Its crystalline forms and valence states have been studied for numerous applications, including electronic, catalytic, electrical, mechanical, adsorption, optical, batteries, and electrochemical [32]. Numerous studies have explored the benefits of using cerium oxide in anticorrosive coatings [33-37]. Many studies investigated the separate effects of glass [38-42] and ceramic powder [43-46] on the properties of cementitious materials. Still, very few studies have investigated cerium oxide's effect on cementitious materials' properties [47, 48]. The combined impact of glass, ceramic powder, and ultrafine cerium oxide on the characteristics of recycled aggregate concrete has not been examined in any previous research. Therefore, this research aims to use ceramic powder (CP) prepared from wall ceramic waste, glass powder prepared from window glass waste, and ultrafine cerium dioxide powder prepared by fine grinding of micronized cerium dioxide to partially substitute ordinary Portland cement for improving the mechanical strength and durability features of recycled aggregate concrete comprising 25% coarse ceramic aggregate. The efficiency of the concrete produced containing WG, CP, and UFC and the reference (RA concrete) without additives was evaluated by conducting several tests, including the slump test, setting time, compressive strength, percentage of permeable pores, water absorption, electrical resistivity, and corrosion resistance.

2. Materials and Methods

2.1. Materials

MAS, a cement type often used in Iraq, was employed; based on ASTM C150, it is Ordinary Portland Cement (OPC) Type 1 [49]. **Table 1** displays its chemical makeup. Crushed gravel with a maximum size of 19 mm was utilized as the natural coarse aggregate (NC), and natural sand with a maximum size of 4.75 mm as the natural fine aggregate (NF). The NF and NC conformed to Iraqi standards No. 45 [50]. The coarse ceramic aggregate prepared from crushed ceramic wall waste was used with a maximum size of 19 mm. Ultra-fine cerium dioxide powder (UFC), window glass powder (WG), ceramic wall powder (CP), and ordinary Portland cement were utilized; their average particle sizes were 9.549 µm, 9.941 µm, 350 µm, and 10.96 µm, accordingly. A laser particle analyzer (Malvern MS3000) was employed to confirm the particle size. **Table 1** lists the chemical content of ordinary Portland cement, WG, CP, and UFC, all verified by XRF analysis. Their size distribution, as well as the gradation of (NC) and (NF), are shown in **Fig. 1**. The plasticizer commercially called hyperplastic PC200, according to ASTM C494, is categorized as type F [51], and was used. All the samples were mixed using regular tap water. Also, 10 mm iron bars with a length of 150 mm were used, as depicted in **Fig. 2.**

Table 1: The chemical composition of UFC, WG, OPC, and CP.

Component	CeO_2	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	TiO_2
OPC		21.84	4.72	61.14	3.60	2.97	0.65	0.29	2.26	1.69
WG	-	56.98	0.10	32.14	7.58	0.496	0.786	1.63	0.003	0.13
CP	-	33.27	5.45	33.72	18.67	0.791	3.090	1.398	0.178	3.12
UFC	94.65	0.4	0.005	0.321	0.620	0.190	-	-	-	0.187

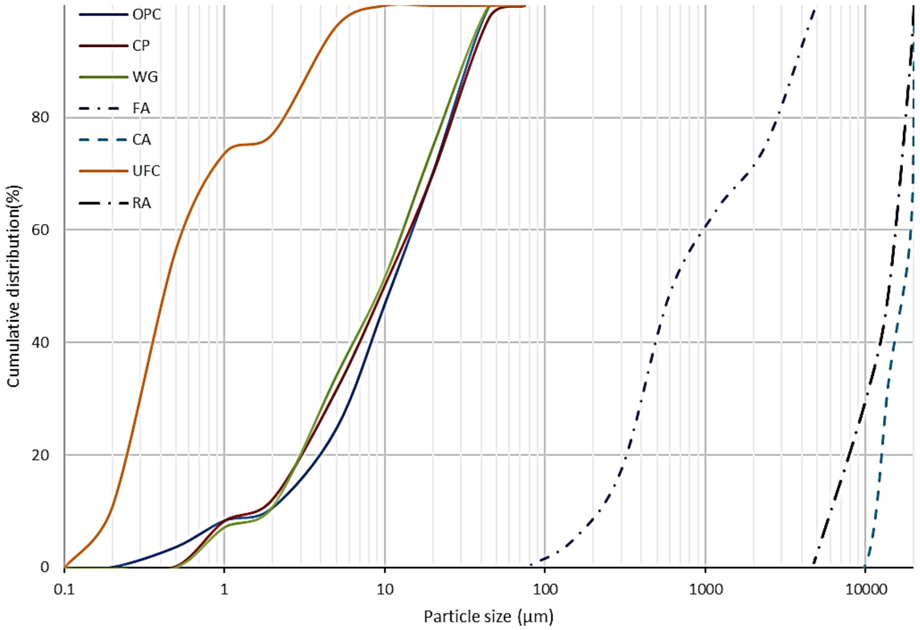

Figure 1: The distribution of particle sizes for OPC, WG, CP, UFC, NF, NC, and RA.

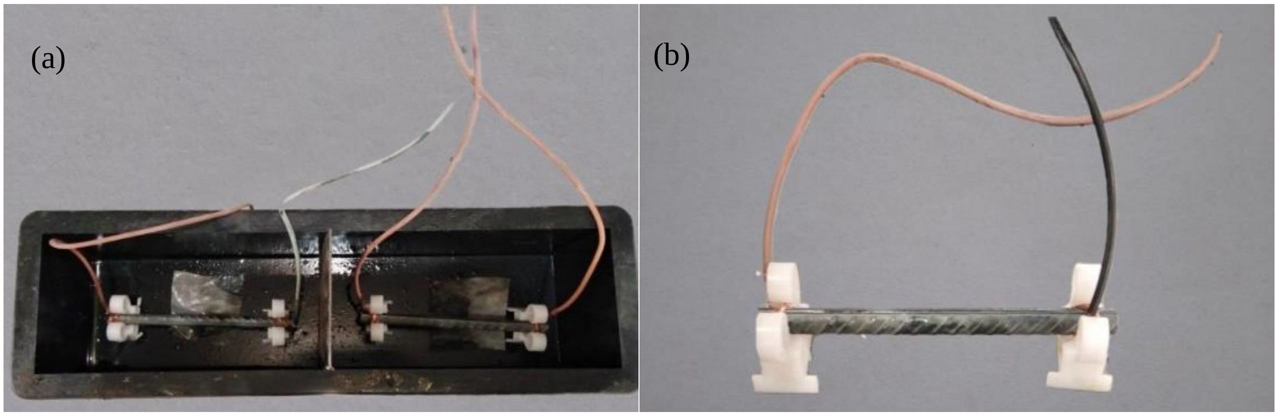

Figure 2: (**a**) Steel rebar tied with copper wires and (**b**) Plastic prismatic mould with rebar fixed in it.

2.2. Mixing Proportion, Sample Preparation and Testing

In this research, four concrete mixes containing 25% ceramic coarse aggregate (RA) were designed with different cement (OPC) replacement ratios of window glass powder (WG), wall ceramic powder (CP), and ultrafine cerium oxide (UFC) as shown in **Table 2**. The water-to-binder ratio in the mix design was fixed at 0.5, and superplasticizer was added at 1.6% of cementitious materials to improve the workability of concrete mixes. Concrete samples of different dimensions were prepared according to the test used. Samples of dimension (100 mm×100mm×100mm) in size were prepared to measure the compression according to BS 1881-Part 116 [52], porosity and water absorption as per ASTM C642 [53], and electrical resistivity as per ASTM C1876 [54]. Prismatic specimens of (10 mm×10mm×20mm) in size were prepared and reinforced with a 15mm long and 10mm diameter rebar to test the accelerated corrosion using the Empress current technique according to ASTM G1 [55] with the concrete cover thickness of 20 mm. Each steel bar was weighed and marked to determine the mass loss due to corrosion after the experiment and connected with a copper wire soldered to the end of the variable resistor to ensure proper electrical conductivity and then fixed before pouring the concrete mixture into the plastic prismatic mold. Cubic samples were treated with tap water by immersing them in water tanks at 25 °C for 28 and 90 days. Nine samples were prepared for each mix.

Table 2 : Proportions of the mixture.

Mixes	OPC	WG	CP	UFC	NC	NF	RA	SP	W
RA-C	375	0	0	0	750	250	250	1.6	0.5
RA-WG10UFC0.5	335.625	37.5	0	1.875	750	250	250	1.6	0.5
RA-CP0UFC0.5	335.625	37.5	0	1.875	750	250	250	1.6	0.5
RA-CP10WG10UFC0.5	298.125	37.5	37.5	1.875	750	250	250	1.6	0.5

*RA-C: recycled wall ceramic coarse aggregate concrete; WG: waste window glass powder; CP: ceramic wall waste powder; UFC: ultrafine cerium oxide powder; NC: natural coarse aggregate, and NF: natural fine aggregate

The prismatic specimens were treated by immersion in water for 28 days only, after which they were withdrawn from the water and permitted to air dry for 24 hours, following which they were partially submerged in a 5% sodium chloride solution as shown in **Fig. 3a** on a copper mesh. The steel rod of each specimen was attached to a DC power source as illustrated in **Fig. 3b**. Copper mesh is the cathode while hardened steel in the column is the anode. Based on Faraday's law [52], the corrosion rate, the current and time for the steel rods were determined. The current applied to all specimens was 14 mA for 26 days, during which the solution height and temperature were maintained at 25 °C and 50 mm below the top surface of the specimens, respectively. Following 26 days of testing, the samples were meticulously broken to retrieve the embedded rebar without causing damage, as seen in **Fig. 4a**. After removal, the rebar was meticulously cleaned utilizing a sandblasting apparatus, as seen in **Fig. 4b**. The rebar's weight post-sandblasting was recorded.

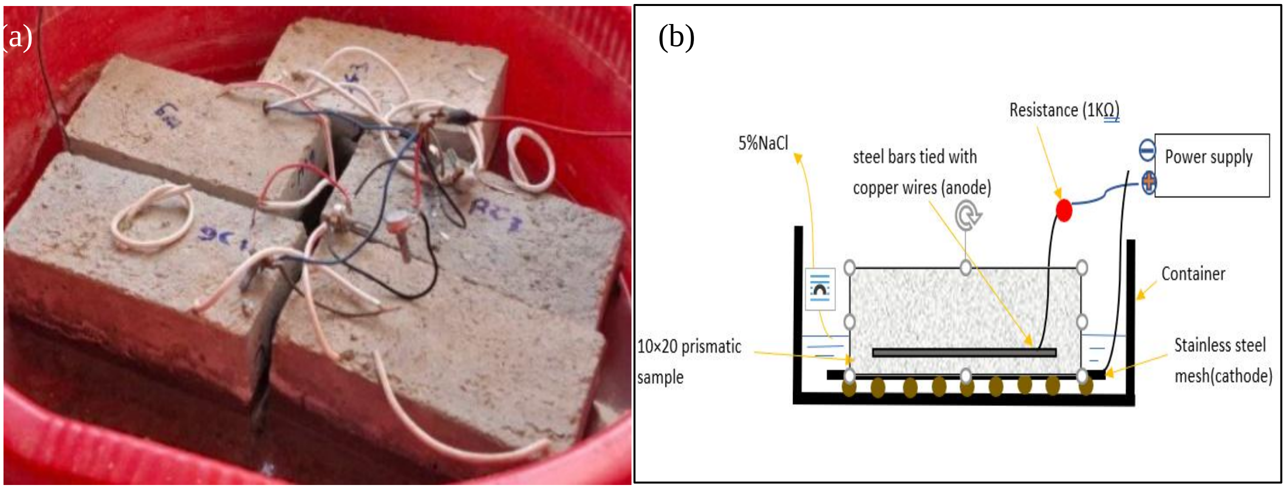

Figure 3: (**a**) Corrosion prismatic specimen partially submerged in a 5% sodium chloride solution and (**b**) Graphic representation of accelerated corrosion test.

Figure 4: (**a**) Rebars before sandblasting, (**b**) The rebars after sandblasting.

The mass loss and corrosion rate attributable to corrosion were computed according to the American Society for Testing and Materials (ASTM G1) as demonstrated by **Eq. (1)** and **Eq. (2)**:

$$\boldsymbol{Mass\ Loss\ (W)\ (g/cm^2) = \frac{(M_i - M_f)}{A}} \tag{1}$$

$$\boldsymbol{Corrosion\ Rate\ (mm/y)\ = \frac{K\times W}{(A\times T\times D)}} \tag{2}$$

where: M_i = mass before exposure (g), M_f = mass after exposure (g), K = constant for the necessary unit (8.76×10^4), W = mass loss (g), A = exposed surface area (cm²), T = exposure time (hours), and D = alloy density (g/cm²). Additionally, tests were carried out on freshly mixed concrete (before hardening), involving a slump test using the ASTM-C 143 standard for all concrete mixtures [22] and setting time measurement of cement pastes with and without cement replacement using WG, CP, and UFC performed according to ASTM C191 [56].

3. Results and Discussion

3.1. Setting Time

Fig. 5 shows the results of the impact of the WG, CP, and UFC on the initial (IST) and final (FST) setting times. The intervals for the IST and FST were 122 – 128 minutes and 170–194 minutes, respectively. The paste, entirely composed of 100% OPC, showed the lowest initial and final setting times recorded at 120 and 170 minutes, respectively. In contrast, the paste containing 10% CP, 10% WG, and 0.5% UC showed the longest setting times, with initial and final values reaching 128 minutes and 194 minutes, respectively. The observed behavior may be explained by a reduction in CaO and the rise in SiO_2 concentration due to the inclusion of 10% window glass powder and 10% wall ceramic powder, resulting in a slower chemical reaction rate and extended setting duration

[43, 44]. This leads to slower chemical reaction and an increase in the time needed for the hardening process by negating the impact of the ultrafine CeO_2 particles, which accelerated the hydration and hardening process [48].

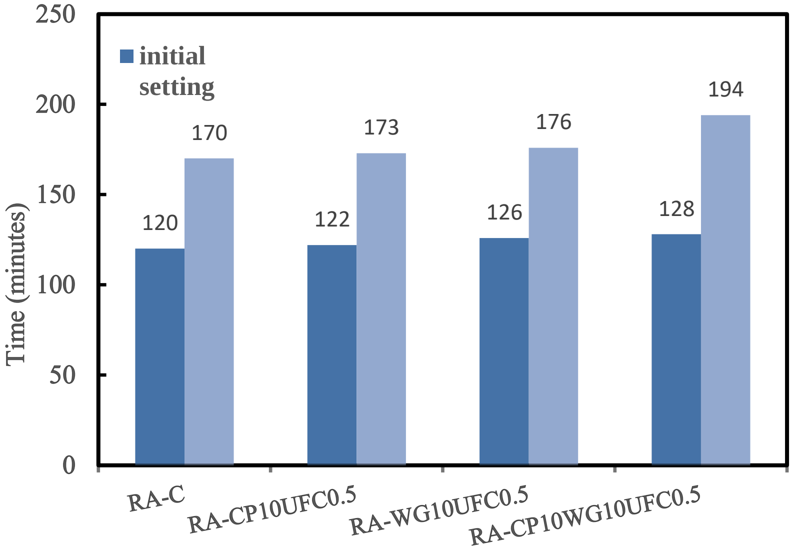

Figure 5: Effect of WG, CP, and UFC on initial and final setting time.

3.2. Slump Tests

The workability of all concrete mix batches was determined utilizing a slump test. **Fig.6** shows the slump test values of RA-C, RA-WG10UF0.5, RA-CP10UF0.5, and RA-CP10WG10UF0.5 mixes were defined as (100, 10**2**, 108, and 120mm), respectively. The slump test results show that the slump of the RA-WG10UFC0.5, RA-CP10UFC0.5, and RA-CP10WG10UFC0.5 concrete mixes was higher than that of the reference mix. The maximum slump value was recorded in the RA-CP10WG10UFC0.5 mix. This performance may stem from the synergistic effects of ceramic and glass powder, the smooth exterior of CP that reduces friction and improves particle range of motion, and the low water absorption of WG because of the vitreous nature of glass powder particles, which enhances the fluidity of the mixtures, despite the water absorption of UFC particles that diminishes the water content [48].

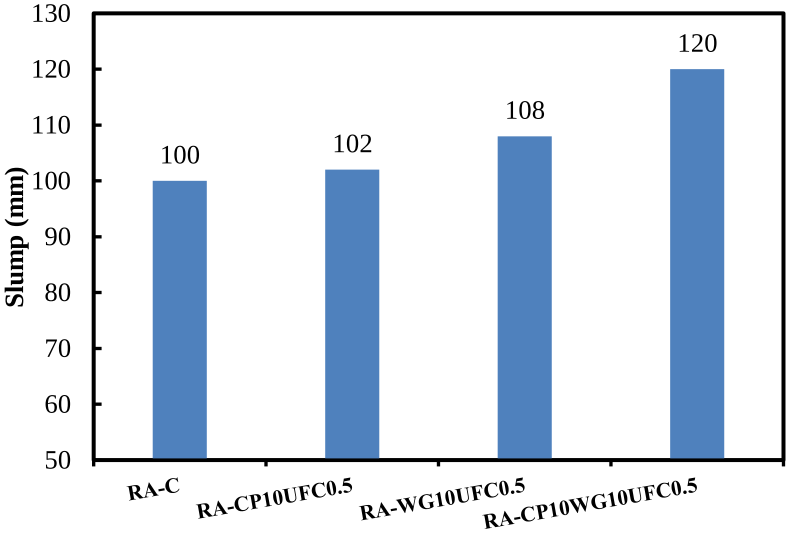

Figure 6: Slump value from RA-C, RA-WG10UFC0.5, RA-CP10UFC0.5, and RA-CP10WG10UFC0.5 concrete mixes.

The inclusion of glass and ceramic powder seems to influence the settling rate more than cerium oxide, enhancing the concrete mixture's flexibility. This effect is evident in certain mixtures through their lower paste volume and reduced viscosity. The decrease in viscosity facilitates the pouring of concrete mixes, highlighting the importance of viscosity as a key parameter in mix design. Accordingly, it is possible to declare that the inclusion of glass and powder of ceramic into ceramic aggregate concrete (RA), in addition to improving the workability of the material it also decreases the water quantity necessary to achieve the appropriate level of workability [46, 57].

3.3. Compressive Strength

It usually provides a thorough evaluation of concrete quality since the components of the water-cement paste directly affect the concrete's compressive strength [38]. **Fig.7** shows the compressive strength results. As shown in the figure, all ternary and quaternary mixtures significantly improved compressive strength at all days compared to the RA-C (reference mix). The ternary mix RA-WG10UFC0.5 exhibited the highest compressive strength at 28, 90, and 180 days, outperforming the reference sample across all time points; accordingly, the compressive strength increased by 31.6%, 22.3%, and 27.4%. The strength improvement of this mixture could be attributed to the effect of the filler provided by fine glass particles. With an average particle size of 9.549 µm, WG particles are noticeably finer than the cement particles, which have an average particle size of 10.96 µm, allowing them to fill voids more effectively and enhance the mix's density. Moreover, ultra-fine cerium oxide particles with an average particle size of 350 nm can fill the pores and improve the properties of concrete. Furthermore, the pozzolanic interaction of WG and UFC with Ca $(OH)_2$ in the cement paste results in the creation of C-S-H, which occupies the interfacial transition zone (ITZ) and increases the compressive strength of the RA-WG10UFC0.5 mix [47, 58].

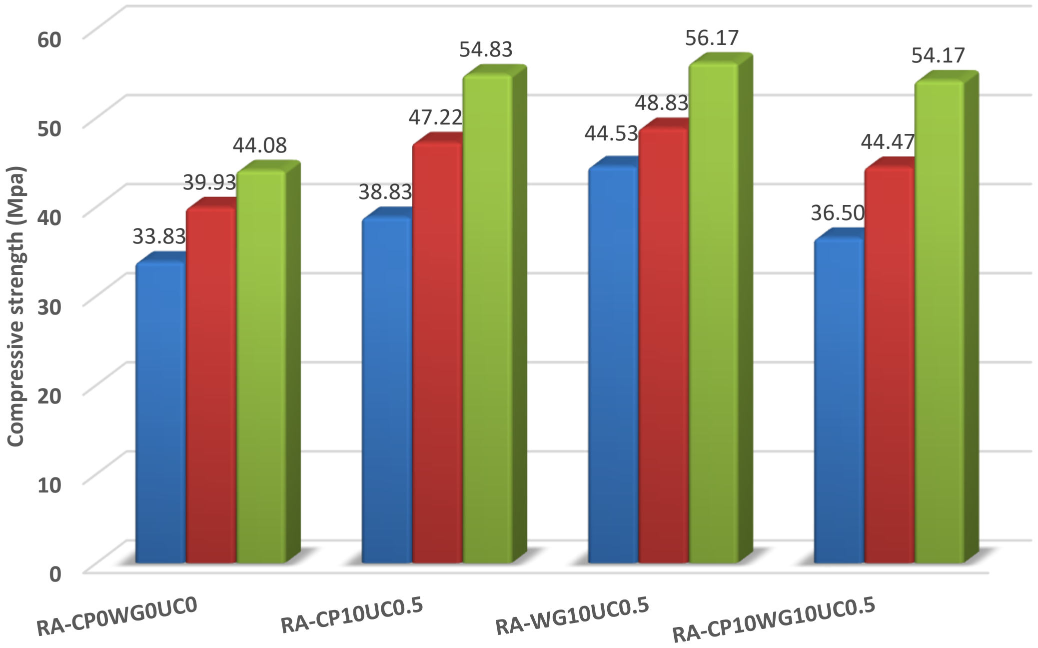

Figure 7: The compressive strength of concrete mix RA-C, RA-WG10UFC0.5, RA-CP10UFC0.5, and RA-CP10WG10UFC0.5 concrete mixes at 28, 90, and 180 days.

3.4. Total Water Absorption

Fig. 8 shows the total water absorption of the control mix along with the formulations. The presence of glass, ceramic powder, and ultrafine cerium oxide decreased the total absorption of ceramic aggregate concrete (RA). The total absorption of the ternary mixes RA-WG10UFC0.5, RA-CP10UFC0.5, and the quaternary mix RA-CP10WG10UFC0.5, was less than that of the reference mix, specifically, the reductions were 29.1%, 32.23 and 25.32% on 28 days; 34.5%,35.3%, and 42.1% at 90 days; and 35.2%, 39.2% and 45.1% in 180 days. RA-WG10UFC0.5 mix recorded the lowest total water absorption at 28 days. This may be due to the filling effect of glass and cerium oxide particles, which are finer than OPC. Additionally, their pozzolanic reaction, which consumes calcium hydroxide and creates C-S-H, C-A-H, and C-A-S-H-gel phases, as well as the formation phases C-Ce-H, C-Ce-A-H, and C-Ce-A-S-H gel, which fills the micropores and reduces the absorbency, was responsible for the RA-WG10UFC0.5 mix's performance [47, 59]. However, at later curing ages, 90 and 180 days, the RA-CP10WG10UFC0.5 mix recorded lower water absorption. Concrete's pore structure is improved, and the percentage of permeable pores is decreased by the pozzolanic reaction when the curing time is prolonged in the presence of CP and WG. As a result, the water absorption decreases [60].

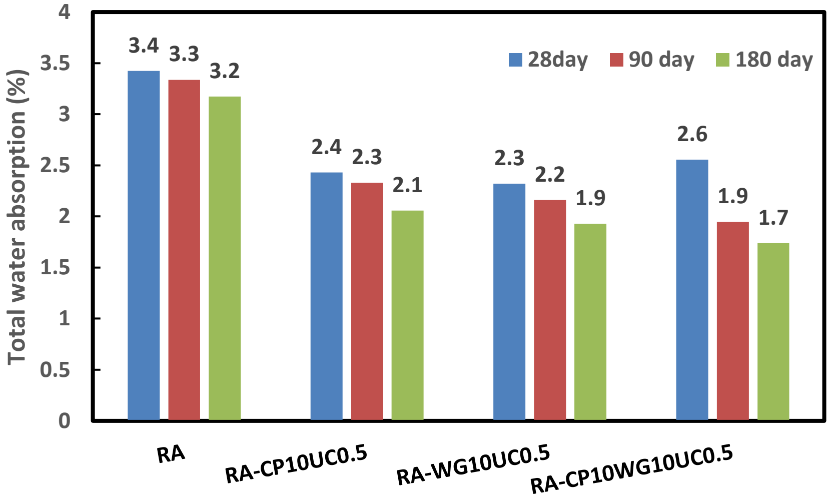

Figure 8: Total water absorption results from RA-C, RA-WG10UFC0.5, RA-CP10UFC0.5, and RA-CP10WG10UFC0.5 concrete mixes at 28,90, and 180 days.

3.5. Percentage of Permeable Voids

The percentage of permeable pores results are shown in **Fig. 9**. These results align with the water absorption data across different replacement levels, although the values differ. This variation is anticipated since the volume of the moisture that enters through the pores directly affects the level of water absorption. The findings demonstrated that at all specified ages, the permeable void ratios for the RA-WG10FUC0.5, RA-CP10FUC0.5, and RA-CP10WG10FUC0.5 mixtures were lower than those of the control combination. The lowest void ratio at 28 days was in RA-WG10UFC 0.5 mixtures containing 10% glass powder and 0.5% ultrafine cerium oxide powder, where voids decreased by 26.7%. The penetration of small WG and UFC particles between the cement particles, as well as the low content of soluble calcium hydroxide and its conversion into a solid - calcium silicate hydrate (CSH) - due to the pozzolanic reaction of the glass and ultra-fine cerium oxide powder, contributed to filling the voids or reducing their volume [61, 62].

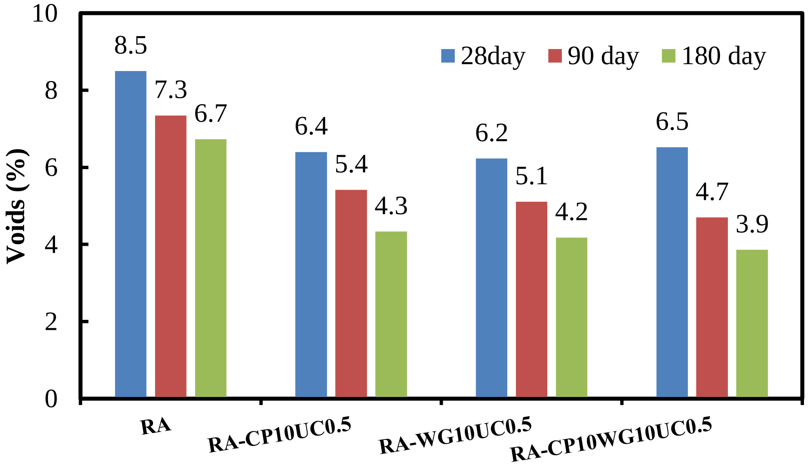

Figure 9: Percentage of permeable void results from RA-C, RA-WG10UFC0.5, RA-CP10UFC0.5, RA-CP10WG10UFC0.5 concrete.

At the late age of 90 and 180 days, the quaternary RA-CP10WG10UFC0.5 mixture showed a lower percentage of permeable pores compared to the reference mixture (RA-C) and binary mixtures (RA-WG10UFC0.5 and RA-CP10UFC0.5). The pozzolanic reaction is responsible for enhancing the pore structure of concrete and lowering the percentage of permeable pores that occur due to the prolonged curing period in the presence of CP and WG. CP particles not only performed as fillers within the capillary pore structures, but also contributed to this effect through their pozzolanic activity [62].

3.6. Bulk Electrical Resistivity

Electrical resistivity correlates with certain performance characteristics of concrete and serves as an effective tool for quality assurance in both fresh and hardened concrete [63]. Moreover, the corrosion of reinforced concrete buildings relies on concrete resistivity. Concrete with high resistivity provides less reinforcing corrosion risk. In practical applications, impedance was measured using a 1000 Hz DER EE LCR meter that was manufactured in Taiwan. The analysis was conducted on saturated 100-mm cube samples placed between two metal plates [64]. **Fig. 10** shows that at all ages, the bulk resistivity of all ternary and quaternary samples containing ultrafine cerium oxide was higher than that of the reference sample. At 28 days, the electrical resistivity of RA-WG 10UFC 0.5, RA-CP10UFC 0.5, and RA-CP 10WG10UFC 0.5 mixtures was higher than the electrical resistivity of the RA-C mixture by 4.23%, 21.46%, and 1.7%. At 90 days, it was higher by 14.38%, 15.64%, and 23.70%; while at 180 days, the resistivity values were higher by 30.49%, 39.53%, and 54.7%, respectively. Previous research has shown that adding WG, CP, and UFC to concrete lowers the connected pore network, which makes the concrete less conductive. This is why the electrical resistivity increases. In addition, the pozzolanic activity of WG, CP, and UFC assists in smoothing the pores and microstructure of concrete, making it more difficult for ions to pass through, thus reducing the conductivity of concrete [65-67]. According to these findings, the electrical resistivity was not negatively impacted by substituting WG, CP, and UFC for cement, even though the cement concentration was reduced. The electrical resistivity characteristics of the quaternary RA mixture, which includes 10% WG, 10% CP, and 0.5% UFC, are greater than 21 Kohm.cm. ACI 222r-01 identifies this as having "extremely high" levels of corrosion protection [68].

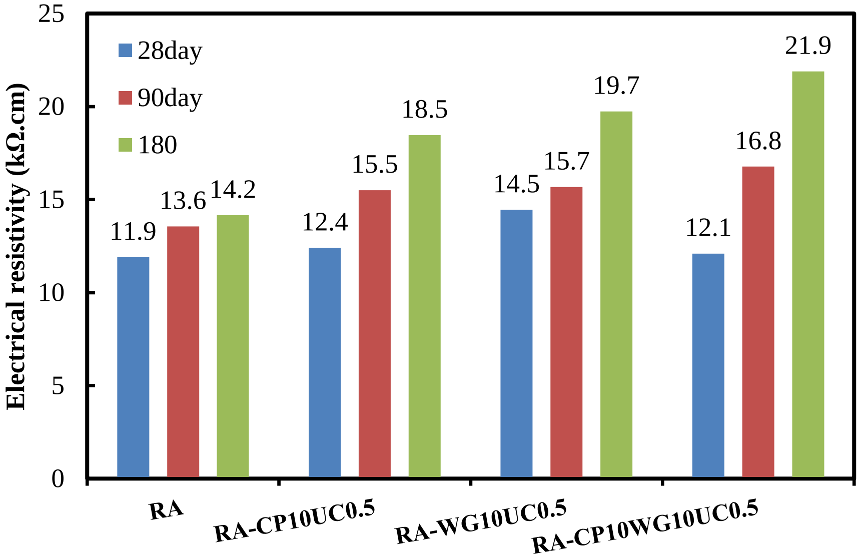

Figure 10: Electrical resistivity results from RA-C, RA-WG10UFC0.5, RA-CP10UFC0.5, and RA-CP10WG10UFCO.5 concrete mix at 28, 90 and 180 days.

3.7. Accelerated Corrosion Test

Fig. 11 illustrates the outcomes of weight loss and corrosion rate, indicating a reduction in the steel bar's mass loss and corrosion rate with the substitution of OPC by CP, WG, and UFC. The corrosion rates and weight losses for RA-CP10UFC1, RA-WG10UFC0.5, and RA-CP1WG10UFC0.5 are (3.186, 2.848, and 4.042) mm/y and (0.170, 0.149, and 0.234) g/cm², respectively, which are lower than the corrosion rate and mass loss of those observed in the reference mixture by (35.45%, 42.31% and 18.11%) and (38.46%, 46.15% and 15.38%). The findings indicate that the RA mixture, including 10% WG and 0.5% UFC, exhibited minimal mass loss and corrosion rate, aligning with the outcomes of the electrical resistance test at 28 days conducted in this study.

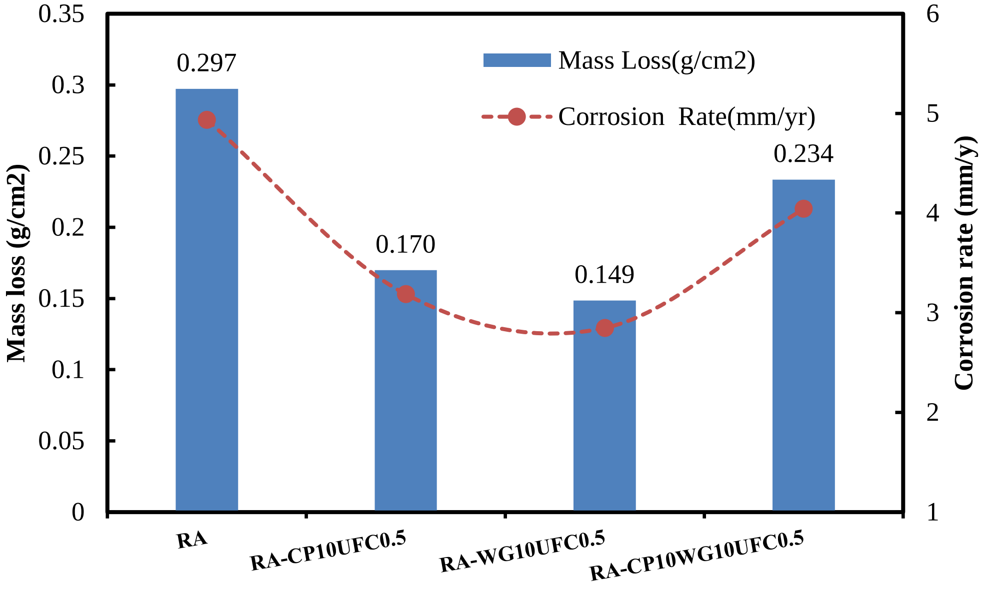

Figure 11: Mass loss and corrosion rate of RA-C, RA-WG10UFC0.5, RA-CP10UFC0.5, RA-CP10WG10UFC0.5 concrete mixes.

The findings are noteworthy as they demonstrate that the binder composed of WG and UFC exhibits lower permeability to chloride diffusion than OPC and, on the other hand, reduces the corrosion rate and mass loss. Thereby suggesting that partial cement substitution with WG and UFC enhances the corrosion resistance of steel reinforcements in comparison to those reinforced with OPC. The main contributing factors are the more complex transport path and the denser microstructure formed through the pozzolanic reaction of glass powder and ultrafine cerium oxide, which may potentially prolong the lifespan of reinforced concrete structures exposed to chloride attack [31, 67]. The corrosion of ceramic concrete specimens is manifested by brown spots on the surface and longitudinal cracks, as shown in **Fig. 12**. The corrosion susceptibility depends on the binder used in the concrete formulation.

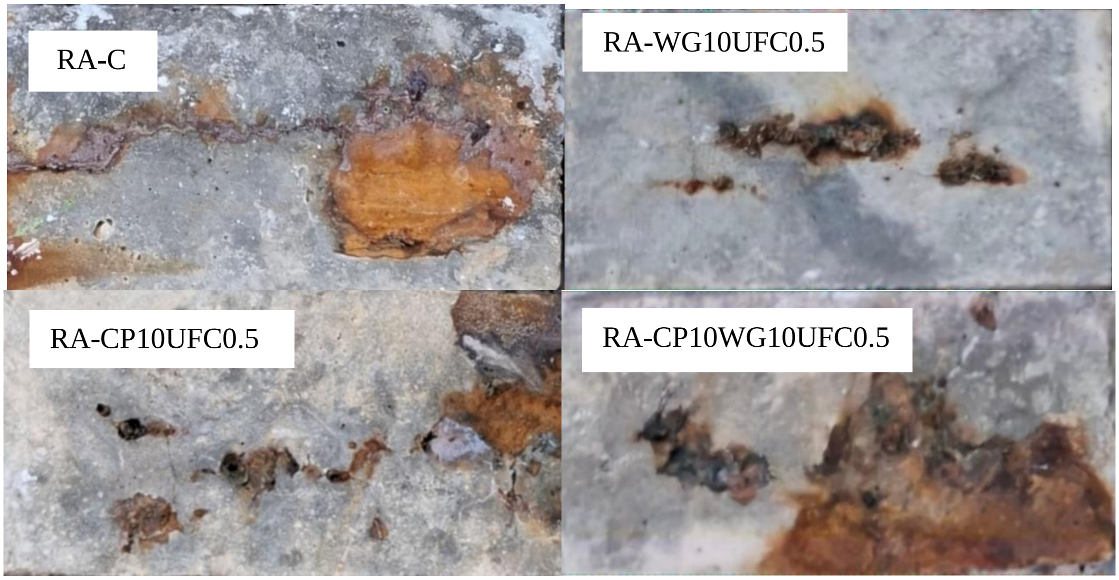

Figure 12: The longitudinal, corrosion-induced splitting crack in different specimens.

Crack width measurement shown in **Fig. 13**. The crack width measurement of RA concrete containing WG and UFC revealed a very low crack width compared to the reference mixture, which showed a 60% reduction compared to the crack width of the reference specimen. The RA-WG10UFC0.5 concrete specimen has a dense microstructure, forming an excellent protective barrier for steel reinforcement. As a result, the formation of longitudinal fractures along the lateral surface area of the specimen is prevented.

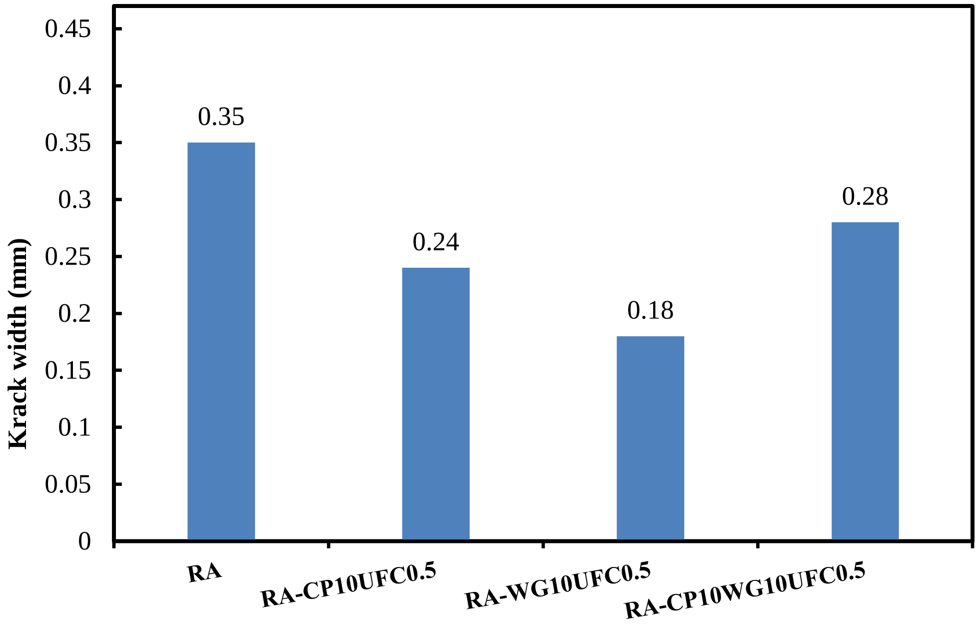

Figure 13: Crack width for different concrete specimens.

4. Conclusion

This study developed environmentally friendly and corrosion-resistant concrete by combining RA derived from waste wall ceramics, WG derived from waste window glass, CP derived from waste wall ceramics, and UFC derived from grinding micro-sized cerium oxide (D50 = 20µm). A summary of the study's key findings is presented below:

1- The slump flow value of the binary and quaternary mixes was higher than that of the reference mix, and the highest slump value (120 mm) was recorded for the quaternary mix (RA-CP10WG10UFC0.5).

2- The initial and final setting times of ternary and quaternary mixes were higher than those of the reference mix. The highest initial and final setting times were recorded in quaternary mixed (RA-CP10WG10UFC0.5), 128 and 194 minutes, respectively.

3- The compressive strength of the ternary and quaternary mixes was higher than that of the reference mix. The highest compressive strength at 28, 90, and 180 days was obtained in the ternary mix (RA-WG10UFC0.5), containing 10% WG and 0.5% UFC, where its value was 44.53, 48.83, and 56.17MPa.

4- Water absorption and void ratio exhibited a similar trend. The highest absorption and void ratio was observed in RA-C (reference blend), while the lowest absorption and void ratio was observed at 28 days for the ternary blend containing 10% WG and 0.5% UFC. At 90 and 180 days, the quaternary mix (RA-CP10WG10.5UFC) recorded the lowest absorption and void ratios compared to the reference and binary mixes.

5- The electrical resistance values of the ternary and quaternary mixes were much higher than those of the reference mix at all specified ages. The highest electrical resistance value was recorded at 28 days in the ternary mixture (RA-WG10UFC0.5). As for the later ages (90 and 180 days), the highest value was recorded in the quaternary mixture (RA-CP10WG 10 UFC0.5).

6- The accelerated corrosion results indicated that the binary and ternary mixtures showed lower corrosion rates, mass losses, and crack widths than the reference mixture. The RA concrete mixture containing 10% WG and 0.5 UFC had a lower corrosion rate, mass loss, and crack width, which was expected due to its low permeability and high electrical resistivity.

Conflict of Interest

The authors declare that they have no conflict of interest.

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