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Article

From Industrial Waste to Sustainable Infrastructure: Engineered Geopolymer Lightweight Aggregates for Low Carbon Concrete

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Abstract: The extensive consumption of natural aggregates and cement in concrete production has intensified concerns regarding resource depletion and environmental sustainability, creating a growing need for alternative construction materials derived from industrial by-products. This study investigates the feasibility of producing geopolymer lightweight aggregates (GLWA) from fly ash (FA), rice husk ash (RHA), ground granulated blast-furnace slag (GGBFS), and metakaolin (MK) through alkali activation and incorporating them into geopolymer lightweight aggregate concrete (GLWAC). Four aggregate formulations were developed and evaluated in terms of particle density, crushing strength, water absorption, and heavy metal leaching behavior. The resulting aggregates were subsequently used as coarse aggregates in lightweight concrete mixtures, and their effects on fresh, mechanical, and durability-related properties were examined through flowability, compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV), and electrical resistivity measurements.

The results demonstrated that aggregate composition significantly influenced both aggregate quality and concrete performance. The GGBFS-containing aggregate exhibited the highest particle density (1.52 g/cm³), crushing strength (48.0 kgf/cm²), and lowest water absorption (13%), leading to the highest compressive strength and UPV among the GLWAC mixtures. In contrast, the RHA-containing aggregate showed greater porosity and lower mechanical performance due to its higher water absorption. All geopolymer aggregates exhibited negligible heavy metal leaching, confirming their environmental compatibility. Furthermore, the developed GLWAC mixtures achieved satisfactory self-consolidating characteristics and durability performance, with electrical resistivity values indicating moderate-to-good resistance against ionic transport.

The findings demonstrate that engineered geopolymer lightweight aggregates produced from industrial residues can simultaneously enhance resource efficiency, reduce dependence on natural aggregates, and deliver balanced mechanical and durability performance, highlighting their potential for sustainable and low carbon concrete applications.

Keywords: geopolymer lightweight aggregate; fly ash; rice husk ash; GGBFS; metakaolin; sustainable concrete

1. Introduction

Concrete remains the most widely used construction material in modern infrastructure due to its ability to satisfy structural requirements while offering versatility, material availability, and cost-effectiveness. Rapid urbanization and the continuous expansion of public facilities have sustained a substantial global demand for cement-based materials. Within this context, concrete serves not only as a structural component but also as a central focus of innovation in construction materials engineering. Consequently, contemporary concrete research extends beyond compressive strength enhancement and increasingly emphasizes workability, durability, and constructability. This trend is evidenced by the sustained advancement of lightweight concrete, high-performance concrete (HPC), and self-consolidating concrete (SCC) technologies over the past several decades (IEA, 2023; Zhang and Gjørv, 1991; Hwang and Hung, 2005; Kim et al., 2010).

In addition to cement, natural materials such as sand, gravel, crushed stone, and limestone are consumed extensively to meet the growing demands of the construction industry. Aggregates constitute the largest volumetric fraction of concrete and therefore play a critical role in governing its density, workability, mechanical performance, and long-term serviceability. As a result, optimizing aggregate characteristics has become a key aspect of concrete design, particularly when lightweight yet structurally efficient materials are required. Innovations such as high-strength lightweight concrete, self-consolidating concrete, and high-performance concrete have largely emerged from the need to improve material efficiency while maintaining superior engineering performance. The continuously increasing consumption of cement and natural aggregates therefore highlights not only the scale of modern construction activities but also the importance of advancing concrete technology through innovative material design (Kılıç et al., 2003; Rossignolo et al., 2003; Kim et al., 2010; Gesoğlu et al., 2014).

Despite their engineering advantages, the extensive use of natural raw materials in conventional concrete production has raised significant environmental concerns. Cement manufacturing is associated with substantial energy consumption and greenhouse gas emissions, whereas the extraction of sand, gravel, and crushed stone intensifies pressure on riverine, coastal, and terrestrial ecosystems. At an industrial scale, these challenges extend beyond resource depletion and encompass ecological degradation and the growing environmental footprint of the construction sector. Continued reliance on virgin raw materials may therefore hinder the achievement of global low-carbon development targets. Accordingly, the identification of sustainable alternatives capable of reducing the consumption of natural resources has become a strategic priority in contemporary concrete technology (IEA, 2023; UNEP, 2026; USGS, 2025).

Among the various sustainability-oriented approaches, the utilization of industrial by-products and waste-derived materials has attracted considerable attention. Fly ash (FA), ground granulated blast furnace slag (GGFBS), and metakaolin (MK) have been extensively investigated owing to their high reactivity and their ability to enhance the strength and durability of cementitious systems. From a sustainability perspective, incorporating these materials supports circular economy principles by transforming industrial residues into value-added construction resources. Furthermore, aluminosilicate precursors and supplementary cementitious materials provide opportunities to reduce the consumption of primary raw materials while improving the performance of the binder matrix. This concept can also be extended to other silica-rich residues, including rice husk ash (RHA), provided that their suitability is verified through comprehensive material characterization and experimental validation (Sabet et al., 2013; Chindaprasirt et al., 2012; Gao et al., 2013; Nath and Sarker, 2014; Deb et al., 2014).

Among the emerging applications of industrial by-products, the production of geopolymer-based artificial aggregates has shown considerable promise. This approach utilizes materials such as fly ash, slag, and metakaolin to manufacture lightweight aggregate particles through pelletization processes, particularly via cold-bonding techniques conducted at relatively low temperatures. Compared with conventional sintering methods, cold bonding offers the advantages of lower energy demand and more effective utilization of inorganic waste streams. The resulting lightweight aggregates can subsequently be incorporated into concrete to reduce structural self-weight while maintaining adequate mechanical performance. Consequently, geopolymer aggregates should be viewed not merely as substitutes for natural aggregates but as engineered materials capable of significantly influencing both fresh and hardened concrete properties (Bui et al., 2012; van Deventer et al., 2007; Lo and Cui, 2004).

Recent advances in geopolymer aggregate technology indicate a transition from proof-of-concept studies toward the deliberate engineering of aggregate particles with tailored properties. Bui et al. (2012) demonstrated the feasibility of producing alkali-activated cold-bonded lightweight aggregates for high-performance concrete applications, while subsequent investigations revealed that alumina dissolution kinetics, SiO_2/Al_2O_3 ratios, metakaolin characteristics, and nano-SiO_2 modification strongly influence geopolymerization, setting behavior, and microstructural development. At the concrete level, aggregate water absorption, internal porosity, paste content, and the quality of the interfacial transition zone (ITZ) have been identified as critical parameters governing workability, strength development, and durability. Studies on self-consolidating lightweight concrete have further shown that fresh-state stability depends heavily on the compatibility between lightweight aggregates, paste volume, and pre-wetting strategies. Collectively, the current research frontier recognizes geopolymer aggregates as engineered particles whose performance must be optimized in conjunction with concrete mixture design rather than being evaluated independently (Hajimohammadi et al., 2010; Kuenzel et al., 2013; Chen et al., 2013; Gesoğlu et al., 2014; Deb et al., 2014).

Nevertheless, most existing studies have investigated geopolymer aggregate synthesis and concrete performance as separate research domains. Consequently, the interrelationships among precursor–activator composition, cold-bonding pelletization parameters, aggregate characteristics, and the behavior of both fresh and hardened concrete remain insufficiently understood. This limitation is significant because the successful production of lightweight aggregates does not necessarily guarantee the development of concrete exhibiting self-consolidating capability, high mechanical performance, and adequate durability. To address this gap, the present study proposes the development of geopolymer-based lightweight aggregates produced from fly ash, slag, and metakaolin for manufacturing lightweight concrete that simultaneously exhibits the characteristics of self-consolidating concrete and high-performance concrete. The novelty of this work lies in the integrated material design framework that links precursor selection, aggregate production, fresh concrete performance, mechanical properties, and durability indicators within a unified experimental approach (Bui et al., 2012; Hwang and Hung, 2005; Kim et al., 2010; Nath and Sarker, 2014; Xu et al., 2014).

2. Materials and methods

2.1.Materials

Geopolymer based lightweight aggregates were produced from fly ash (FA), rice husk ash (RHA), ground granulated blast-furnace slag (GGBFS), and metakaolin (MK). The chemical compositions of these precursor materials are presented in Table 1. FA contained 37.0% SiO_2, 14.0% Al_2O_3, 26.2% Fe_2O_3, and 15.2% CaO, whereas RHA was highly siliceous, with 85.2% SiO_2. GGBFS exhibited the highest CaO content at 61.83%, while MK contained a relatively high Al_2O_3 content of 32.7%. These precursor materials were activated using a 10 M sodium hydroxide solution and sodium silicate. For concrete production, cement, natural sand, water, superplasticizer, and either natural stone or geopolymer lightweight aggregate were used.

Table 1. Chemical Composition of Raw Materials

	Oxide	FA	RHA	GGBFS	MK
Chemical analysis (%)	SiO_2	37	85.2	21.9	56
	Al_2O_3	14	0.6	7.8	32.7
	Fe_2O_3	26.2	-	1.27	4.07
	CaO	15.2	3.01	61.83	0.45
	K_2O	2.25	7.93	0.06	1.53
	others	5.35	3.26	7.14	5.25

2.2.Preparation of geopolymer lightweight aggregates

Four aggregate formulations were prepared, namely F100R0S0M0, F70R30S0M0, F70R0S30M0, and F70R0S0M30. As listed in Table 2, F100R0S0M0 was produced from 100% FA, whereas the remaining mixtures were obtained by partially replacing FA with 30% RHA, 30% GGBFS, or 30% MK, respectively. The corresponding activator dosages were 174.2 and 266.8 g for the FA-only mixture, 206.3 and 315.9 g for the FA–RHA mixture, 172.2 and 263.6 g for the FA–GGBFS mixture, and 178.4 and 273.2 g for the FA–MK mixture, for 10 M NaOH and sodium silicate, respectively. The alkaline solution was used to activate the precursor blends and promote cold-bonded pellet formation, thereby producing geopolymer-based artificial lightweight aggregates. The physical properties of the produced aggregates were evaluated through bulk density, particle density, and water absorption measurements in accordance with ASTM C29/C29M and ASTM C127. Aggregate crushing strength was determined using a modified single-pellet compression test, with ASTM C131/C131M and ASTM C535 adopted as reference standards for aggregate mechanical resistance evaluation.

In the previous GLWAC study, geopolymer lightweight aggregates (GLWA) were manufactured through a cold-bonding pelletization process using alkali-activated industrial by-products as precursor materials. The produced aggregates were then incorporated into lightweight concrete mixtures as partial or complete replacements for conventional coarse aggregates. The resulting geopolymer lightweight aggregate concrete (GLWAC) was evaluated through fresh-state tests to assess its flowability, segregation resistance, and filling capacity, with slump flow and flow time measured in accordance with ASTM C1611/C1611M-21 and passing ability by J-ring measured according to ASTM C1621/C1621M-17 (2023). Mechanical and durability-related properties were subsequently determined to establish the suitability of the developed concrete for structural applications.

Table 2. Mix Proportions of Source Materials and Alkaline Activator Used for Various Aggregate Types

Aggregate ID	FA (%)	RHA (%)	GGBFS (%)	MK (%)	10 M NaOH	Sodium silicate
F100R0S0M0	100	-	-	-	174.2	266.8
F70R30S0M0	70	30	-	-	206.3	315.9
F70R0S30M0	70	-	30	-	172.2	263.6
F70R0S0M30	70	-	-	30	178.4	273.2

2.3.Concrete mixture design and methods

Five concrete mixtures were prepared, consisting of one control mixture with natural coarse aggregate and four lightweight aggregate concrete mixtures containing geopolymer-based artificial aggregates. The control mixture, CM1, had a water-to-cement ratio of 0.35 and contained 457.0 kg/m³ of cement, 829.0 kg/m³ of coarse aggregate, 923.0 kg/m³ of sand, 160.0 kg/m³ of water, and 3.5 kg/m³ of superplasticizer. The lightweight concrete mixtures, CM2 to CM5, were proportioned at a water-to-cement ratio of 0.40. CM2 contained F100R0S0M0, CM3 contained F70R30S0M0, CM4 contained F70R0S30M0, and CM5 contained F70R0S0M30 as the aggregate type. The detailed mixture proportions are summarized in Table 3. This mixture design was intended to compare the behavior of normal concrete and geopolymer-based lightweight aggregate concrete produced from different precursor combinations.

Table 3. Mix proportions for the light weight aggregate concrete and the control specimen

Concrete ID	w/c	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	Aggregate ID
CM1	0.35	457.0	829.0	923.0	160.0	3.5	Natural stone
CM2	0.40	406.8	591.7	887.6	164.8	7.3	F100R0S0M0
CM3	0.40	398.4	534.9	927.6	159.5	7.2	F70R30S0M0
CM4	0.40	384.1	644.4	726.7	154.4	6.9	F70R0S30M0
CM5	0.40	353.1	485.5	1031.7	142.0	6.4	F70R0S0M30

Fresh concrete properties were evaluated in terms of flowability, segregation resistance, and filling capacity, primarily using ASTM C1611/C1611M-21 for slump flow and T50 flow time and ASTM C1621/C1621M-17 (2023) for the J-ring test; if a separate conventional slump value is intentionally retained, it should be reported under ASTM C143/C143M-26a. The hardened concrete was further examined through compressive strength, splitting tensile strength, flexural bending strength, and specific strength, with compressive strength and splitting tensile strength determined according to ASTM C39/C39M-26 and ASTM C496/C496M-17, respectively. In addition, ultrasonic pulse velocity and electrical resistivity were determined according to ASTM C597 and ASTM C1876-25, respectively, to assess internal quality and durability-related performance. Accordingly, the experimental program was designed to examine whether the proposed geopolymer lightweight aggregate concrete could exhibit the characteristics of lightweight concrete.

3. Results and discussion

3.1. Test results of particle density, crushing strength, water absorption, and heavy metal performance for the GLWA

The physical properties of the geopolymer lightweight aggregates were evaluated through bulk density, relative density (particle density), water absorption, and crushing strength measurements. Bulk density was determined in accordance with ASTM C29/C29M, whereas relative density and water absorption were measured following ASTM C127. The crushing strength of individual aggregate pellets was assessed using a universal testing machine through a modified compression test procedure, since no ASTM standard specifically governs the direct crushing strength of artificial geopolymer lightweight aggregates; therefore, ASTM C131/C131M and ASTM C535 were adopted as reference standards for aggregate mechanical resistance evaluation.

Table 4. Physical Properties of the GLWA

Aggregate ID	Particle density	Crushing strength	Water absorption
	(g/cm^3)	(kgf/cm^2)	(%)
F100R0S0M0	1.38	33.50	14.00
F70R30S0M0	1.20	17.00	27.00
F70R0S30M0	1.52	48.00	13.00
F70R0S0M30	1.30	39.50	20.50

The results presented in Table 5 indicate that all geopolymer lightweight aggregates exhibited very low concentrations of hazardous elements, with most heavy metals remaining undetectable and only trace amounts of chromium and copper observed in several mixtures. These findings demonstrate that the geopolymer matrix effectively immobilized potentially harmful constituents through the formation of a stable aluminosilicate network. The differences in heavy metal concentrations among aggregate types can be attributed to variations in precursor chemistry and mixture composition, as shown in Tables 1 and 2, particularly the proportions of FA, RHA, GGBFS, and MK used during aggregate production. Simultaneously, the physical properties reported in Table 4 confirm that the same precursor combinations significantly influenced aggregate density, crushing strength, and water absorption. The superior performance of the GGBFS-containing aggregate highlights the beneficial role of calcium-rich phases in promoting aggregate densification and mechanical stability, whereas the RHA-containing aggregate exhibited a more porous structure due to its lower calcium availability. Overall, the results demonstrate that precursor selection governs both the environmental compatibility and engineering performance of geopolymer lightweight aggregates, enabling the production of sustainable aggregate materials with tailored properties

Table 5. Heavy metal content values for the GLWA

Aggregate ID	Pb	Cr	Cd	Zn	Cu	Ni
	(mg/L)					
F100R0S0M0	N.D.	N.D.	N.D.	N.D.	0.02	N.D.
F70R30S0M0	N.D.	N.D	N.D.	N.D.	0.01	N.D.
F70R0S30M0	N.D.	0.02	N.D.	N.D.	0.01	N.D.
F70R0S0M30	N.D.	0.05	N.D.	N.D.	N.D.	N.D.

N.D.; Pb < 0.015 mg/L; Cr < 0.009 mg/L; Cd < 0.021 mg/L; Zn < 0.074 mg/L; Cu < 0.089 mg/L; Ni < 0.112 mg/L

3.2. *Fresh properties of GLWAC*

The fresh-state properties summarized in Table 6 indicate that all GLWAC mixtures possessed adequate self-consolidating capability, as evidenced by slump flow values ranging from 580 to 650 mm and satisfactory J-ring performance. The absence of excessive reduction in flow spread and passing ability suggests that the mixtures were capable of flowing under their own weight while maintaining sufficient resistance to segregation and blocking. Although the incorporation of geopolymer lightweight aggregates slightly reduced workability compared with the control concrete, the measured values remained within the range generally accepted for self-consolidating lightweight concrete. These results demonstrate that the selected mixture proportions and superplasticizer dosages successfully produced lightweight concrete with the flowability, stability, and passing ability required for self-consolidating applications.

Table 6. Fresh state properties

Concrete ID	Unit weight	Slump test			J-ring test	
		Slump	Slump flow	Flow time	Passing ability	Flow spread
	(kg/m^3)	(mm)	(mm)	(sec)	(mm)	(mm)
CM1	2369	255	700	35	13	520
CM2	1980	245	630	36	15	570
CM3	1878	245	630	41	14	540
CM4	1889	250	650	39	14	545
CM5	1852.8	235	580	31	22	535

3.3. *Strength of GLWAC*

The compressive strength development of the control concrete and geopolymer lightweight aggregate concrete (GLWAC) mixtures is presented in Figure 1. It can be observed that all mixtures exhibited continuous strength gain with increasing curing age, indicating the progressive hydration of cement and gradual densification of the matrix structure. The control concrete (CM1) consistently produced the highest compressive strength, reaching approximately 44 MPa at 28 days, whereas all GLWAC mixtures showed lower values due to the porous nature and lower density of the geopolymer lightweight aggregates. Such behavior is commonly observed in lightweight aggregate concrete because the aggregate phase becomes the weakest component under compressive loading. Nevertheless, all GLWAC mixtures achieved sufficient strength for structural lightweight concrete applications, demonstrating the feasibility of utilizing geopolymer-based artificial aggregates as sustainable alternatives to conventional coarse aggregates.

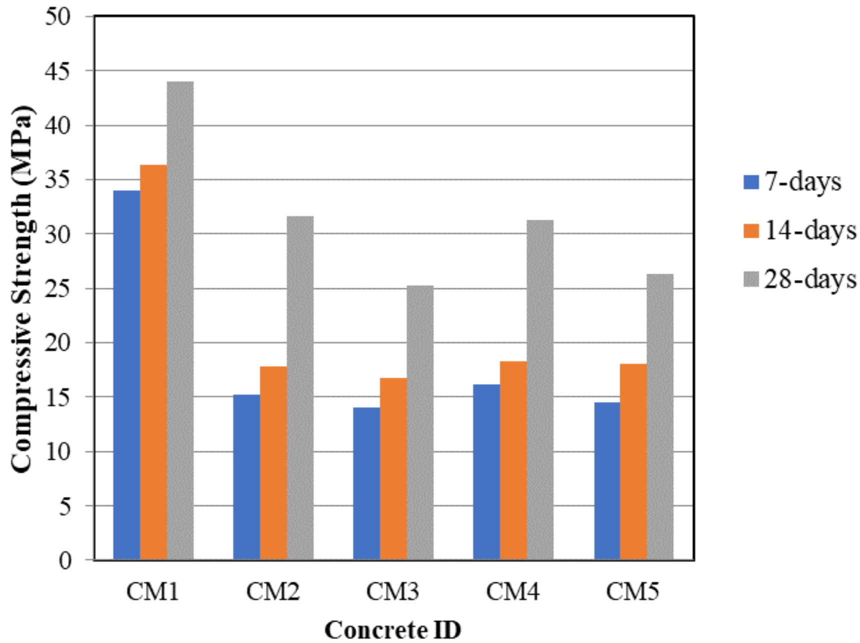

Figure 1. Compressive strength comparison of concrete

As shown in Figure 1, CM4 containing F70R0S30M0 exhibited the highest compressive strength among the lightweight concrete mixtures, followed by CM2, CM5, and CM3. This trend corresponds closely with the aggregate properties reported in Table 4, where F70R0S30M0 possessed the highest particle density (1.52 g/cm³), the highest crushing strength (48.0 kgf/cm²), and the lowest water absorption (13%). The incorporation of GGBFS appears to have enhanced aggregate densification through the formation of additional calcium-rich reaction products, thereby improving both aggregate integrity and the interfacial transition zone (ITZ) between aggregate and cement paste. Conversely, CM3 produced the lowest compressive strength because the corresponding F70R30S0M0 aggregate exhibited the highest water absorption (27%) and the lowest crushing strength (17.0 kgf/cm²), indicating a highly porous internal structure. The increased porosity likely reduced the effective load-bearing area and promoted stress concentration within the concrete, leading to lower compressive resistance.

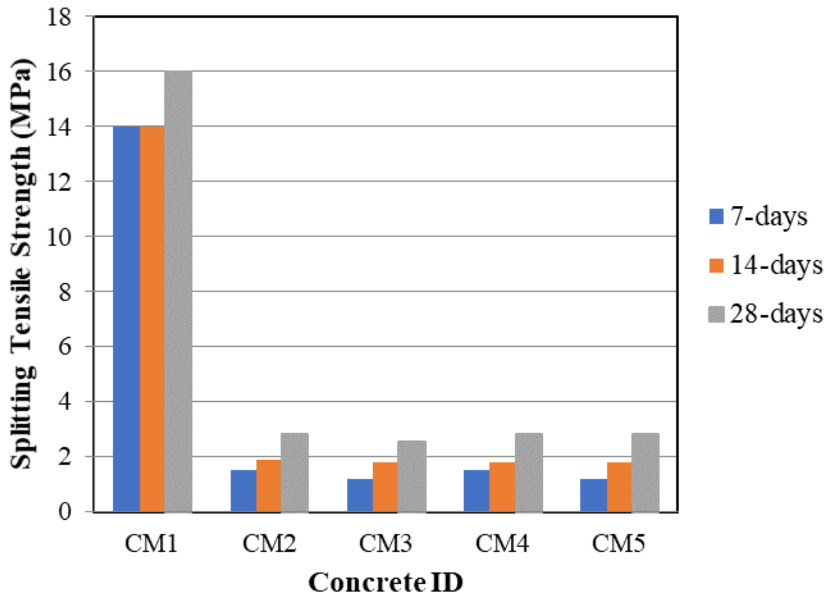

Figure 2. Splitting tensile strength of concrete

The splitting tensile strength results shown in Figure 2 generally followed the same trend as the compressive strength results, indicating that aggregate quality strongly influences crack resistance in GLWAC. The control concrete (CM1) exhibited the highest tensile strength at all curing ages, while CM4 again demonstrated the best performance among the lightweight concrete mixtures. The superior tensile behavior of CM4 can be attributed to the improved aggregate strength and denser ITZ provided by the GGBFS-modified geopolymer aggregate, which effectively delayed crack initiation and restricted crack propagation under tensile loading. In contrast, CM3 and CM5 exhibited lower splitting tensile strengths because their aggregates possessed higher porosity and weaker aggregate–paste interactions. Since tensile failure in lightweight concrete is primarily governed by crack propagation through the aggregate particles and surrounding ITZ, the results suggest that enhancing aggregate density and reducing water absorption are critical factors for improving both compressive and tensile performance. Overall, the findings from Figures 1 and 2 demonstrate that the incorporation of GGBFS is particularly effective in improving the mechanical performance of geopolymer lightweight aggregate concrete while maintaining its lightweight characteristics and sustainability benefits.

The ultrasonic pulse velocity (UPV) results presented in Figure 3 indicate that all concrete mixtures experienced a continuous increase in pulse velocity with curing age, reflecting the progressive densification of the cementitious matrix and the reduction of internal discontinuities. The control concrete (CM1) consistently exhibited the highest UPV values, increasing from 4385 m/s at 7 days to 4624 m/s at 28 days, which is indicative of a dense and homogeneous internal structure. Among the GLWAC mixtures, CM4 achieved the highest UPV value at 28 days (4220 m/s), followed by CM2, CM5, and CM3. This trend corresponds closely with the aggregate properties reported in Table 4, where F70R0S30M0 possessed the highest crushing strength (48.0 kgf/cm²) and the lowest water absorption (13%). The stronger and less porous aggregate structure promoted a denser aggregate–paste interface and reduced internal void content, thereby facilitating faster transmission of ultrasonic waves through the concrete matrix. In contrast, CM3 exhibited the lowest UPV values due to the high water absorption (27%) and low crushing strength (17.0 kgf/cm²) of the F70R30S0M0 aggregate, which likely increased internal porosity and wave scattering within the hardened concrete.

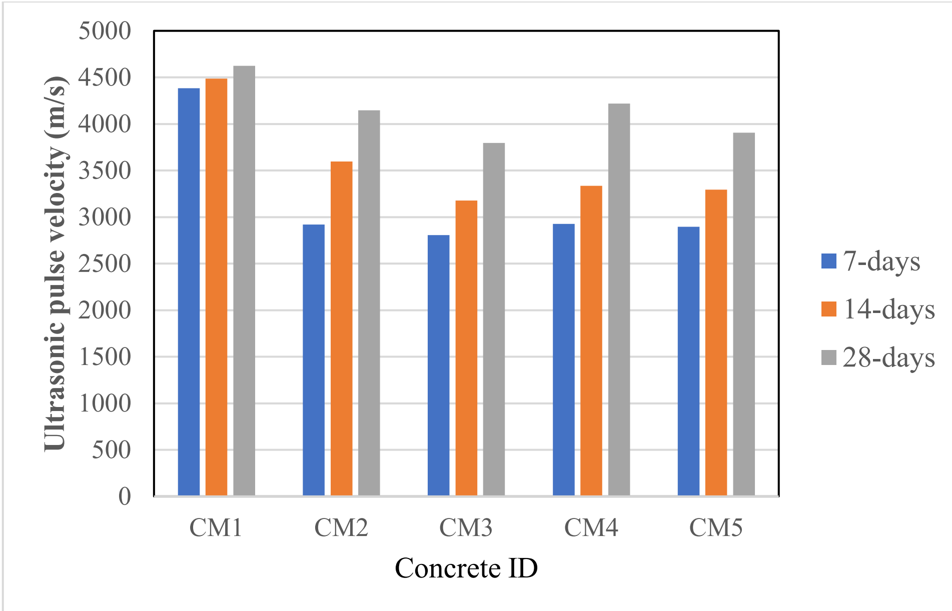

Figure 3. UPV test results of concrete

A similar tendency was observed in the electrical resistivity results shown in Figure 4. Electrical resistivity increased significantly with curing age for all mixtures, indicating the progressive refinement of pore structure and reduction in ionic mobility within the concrete. The control concrete exhibited the highest resistivity values, reaching approximately 18 kΩ·cm at 28 days, while the GLWAC mixtures showed lower but steadily increasing resistivity. Among the lightweight concretes, CM5 exhibited the highest electrical resistivity at 28 days (14 kΩ·cm), followed by CM2, CM3, and CM4. The relatively high resistivity of CM5 suggests that the incorporation of metakaolin contributed to the formation of a refined pore network and reduced pore connectivity, thereby restricting the movement of conductive ions through the concrete. According to established durability criteria, all GLWAC mixtures achieved electrical resistivity values above the threshold commonly associated with moderate-to-good resistance against reinforcement corrosion, indicating satisfactory durability performance despite the use of lightweight aggregates.

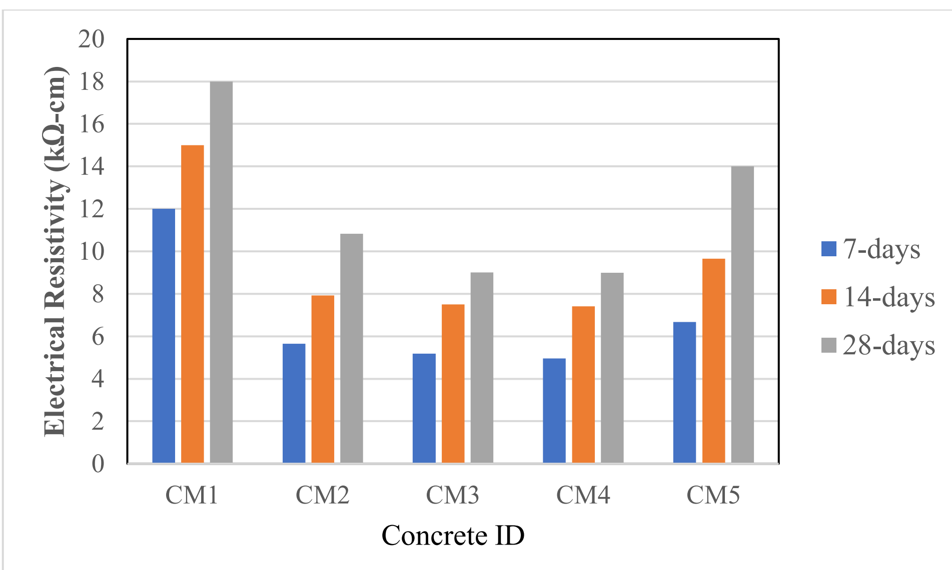

Figure 4. Electrical resistivity of concrete

The combined analysis of compressive strength, UPV, and electrical resistivity reveals a strong relationship between aggregate quality and overall concrete performance. Mixtures containing aggregates with higher crushing strength and lower water absorption generally produced higher compressive strengths and UPV values, confirming the importance of aggregate integrity and aggregate–paste bonding in controlling mechanical performance. However, electrical resistivity was influenced not only by aggregate porosity but also by the characteristics of the hydration and geopolymer reaction products governing pore connectivity. Consequently, while CM4 exhibited the highest compressive strength and UPV among the GLWAC mixtures, CM5 produced the highest electrical resistivity due to its denser pore refinement effect. These findings demonstrate that the incorporation of industrial by-products such as GGBFS and metakaolin can improve different aspects of concrete performance, where GGBFS predominantly enhances mechanical properties through aggregate strengthening, whereas metakaolin contributes more significantly to durability-related characteristics through microstructural refinement. Overall, the results confirm that geopolymer lightweight aggregates can simultaneously provide acceptable mechanical performance and durability while supporting the development of low-carbon and resource-efficient concrete materials.

4. Conclusion

The results demonstrate that the characteristics of geopolymer lightweight aggregates significantly influenced the fresh, mechanical, and durability performance of the developed concrete. Aggregates incorporating GGBFS (F70R0S30M0) exhibited the highest sparticle density, crushing strength, and the lowest water absorption, which translated into superior compressive strength and ultrasonic pulse velocity among the GLWAC mixtures. Conversely, aggregates containing RHA (F70R30S0M0) showed higher porosity and lower particle strength, resulting in reduced mechanical performance. The heavy metal leaching results confirmed that all geopolymer aggregates satisfied the environmental requirements for construction applications, while the fresh concrete properties demonstrated adequate flowability and stability for lightweight concrete production. These findings collectively indicate that the physical integrity of geopolymer aggregates governs the effectiveness of load transfer, microstructural development, and overall concrete performance.

The combined evaluation of compressive strength, splitting tensile strength, ultrasonic pulse velocity, and electrical resistivity revealed that geopolymer lightweight aggregates produced from industrial by-products can provide a balanced combination of structural efficiency and durability. While GGBFS-enhanced aggregates contributed predominantly to strength development through improved aggregate quality and aggregate–paste interaction, metakaolin-containing aggregates exhibited favorable durability characteristics through pore refinement and reduced ionic transport. The integrated assessment performed in this study establishes a direct linkage between precursor composition, aggregate engineering, and concrete performance, providing a comprehensive understanding of how geopolymer lightweight aggregates influence both mechanical behavior and long-term durability. The outcomes highlight the potential of utilizing fly ash, rice husk ash, GGBFS, and metakaolin as value-added resources for the production of environmentally responsible lightweight concrete capable of supporting future low-carbon construction practices.

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