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Production of Green Concrete Using Waste Carbonation Lime Residue from Sugar Factory

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ABSTRACT

This research investigates the possibility of producing green concrete using Carbonation Lime Residue (CLR), a waste by-product from the Naghsh-e Jahan Sugar Factory in Isfahan (Iran). The primary objective is to recycle this industrial waste by utilizing it as a partial replacement for cement in concrete production, aligning with waste management goals, environmental preservation, and economic benefits. Concrete samples were prepared with different percentages of CLR replacement (0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40%) for cement, maintaining a constant water-to-cement ratio of 0.35. These samples were subjected to compressive strength tests (at 7, 28, and 56 days) and tensile strength tests (Brazilian method). The results indicated that both compressive and tensile strengths decrease with an increase in the replacement percentage. This reduction is primarily attributed to the presence of impurities and sugary substances in the CLR, as confirmed by SEM and EDX analyses. However, it was observed that up to a 25% replacement level, the reduction in compressive and tensile strengths was less than respectively 15% and 10%. This level of reduction is considered acceptable given the environmental and economic advantages derived from utilizing this waste material. Therefore, using waste CLR as a cement replacement in concrete up to 25% is deemed a practical and effective solution, particularly for non-structural applications or in regions near sugar factories, contributing to sustainable development and a circular economy.

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1. Introduction

Nowadays, with the industrialization of societies, one of the major challenges faced by countries is the presence of waste and by-products from various factories. Improper management of these wastes can cause irreparable damage to the environment, whereas with precise management, they can be converted into raw materials for other industrial uses [1].

Recycling is one of the most practical options in waste management, consistently attracting attention due to its economic savings and environmental benefits. Annually, millions of tons of waste are generated in the country, posing not only a serious disposal problem but also increasing environmental pollution in various areas, consequently posing a risk to the health of residents. Industrial wastes are among these materials, and the lack of timely and appropriate use of these vast resources leads to environmental pollution.

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Preliminary field investigations revealed that significant amounts of waste from sugar factories accumulate daily, occupying considerable space. The management and disposal of Carbonation Lime Residue (CLR) entail high costs. On the other hand reusing these compounds can not only address the disposal challenges faced by sugar factories but also yield economic benefits.

The recycling of waste CLR from sugar factory is not yet common practice in Iran. Utilizing this waste as a partial replacement for cement in concrete production could be a suitable strategy for achieving three objectives: 1) waste disposal (without the need for landfilling), 2) achieving positive properties in concrete, and 3) realizing economic benefits.

2. Literature Review

The use of any waste material in concrete requires sufficient and specialized knowledge about it. Comprehensive study is needed to ensure the durability and safety of consumed waste in concrete, and leveraging past research accelerates this process. Most studies conducted on sugar factory waste are limited to agricultural and livestock industries [1-8], with no significant research in the construction industry except for specific cases. CLR essentially consists of calcium carbonate (lime) along with impurities. Given that these wastes have a calcareous origin, it is possible to utilize previous research conducted on the effects of using lime in concrete production [9-13].

To date, limited research has been reported on the recycling of CLR. Karimi-Dehkordi et al. [14] studied the use of CLR, referred to as lime waste, in concrete production. They concluded that incorporating this sugar factory by-product into concrete is an effective strategy for promoting sustainable development, as it reduces costs, preserves the environment, aids waste management, and contributes to structural strength. Karimi-Dehkordi and Heydari [15] in another study investigated the use of CLR as a sand replacement in concrete. Through laboratory tests, they stated that despite a minimal reduction in compressive strength and no significant change in water absorption, lime waste can still be a suitable option for use in concrete, especially in areas near sugar factories. In addition, Heydari et al. [16] assessed how different application methods of CLR affect the mechanical performance of concrete. They tested three distinct approaches: dissolving the CLR in the mixing water, sieving, and grinding. Their findings identified grinding as the most effective method for utilizing CLR as a cement replacement in concrete. The results demonstrated that using the ground waste to replace up to 20% of cement by weight is feasible, resulting in only a minimal strength reduction.

While previous studies have mainly explored the agricultural use of sugar factory waste or provided qualitative assessments of its potential in concrete, a significant research gap still remains. Specifically, a systematic laboratory investigation into using CLR from the Naghsh-e Jahan Sugar Factory in Isfahan (Iran) as a partial cement replacement has been lacking. The current study addresses this gap by focusing experimentally on this local waste material. It aims to advance the current qualitative understanding to a quantitative level by supplying precise data on the effects of replacing cement with CLR at various percentages (0–40%). This research introduces a novel replacement material and defines an optimal replacement threshold of 25% to minimize compressive strength loss, while also employs microstructural analysis (SEM/EDX) to clarify the fundamental mechanisms responsible for the strength reduction. By achieving these goals, this work could provides, for the first time with robust scientific support, a viable pathway to recycle this waste material, thereby transforming an environmental liability into a valuable economic resource for the construction industry.

3. Materials and Methods

To investigate the effect of using lime waste from the Naghsh-e Jahan Sugar Factory as a partial cement replacement on concrete properties, a mix design based on a water-to-cement ratio of 0.35 was adopted. CLR was used to replace cement at different percentages of 0%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40%. The concrete specimens were subjected to compressive (with curing times of 7 to 56 days) and tensile strength experiments.

3.1. Materials Used

Portland cement Type II from Ardestan Cement Plant located in Isfahan (Iran) was used in this research. Potable water from the laboratory was also used. The water pool was meticulously maintained, with the water always being clear and meeting the required standards. Furthermore, the entire pool water was drained and replaced with fresh municipal water every two weeks, adhering to all necessary standards during sampling and curing. The gradation of the used aggregates was evaluated according to Iranian National Standard No. 302 [17]. Coarse gravel and sand were obtained from the Noor Complex mine, and fine gravel was obtained from the Paya Sang mine, all sourced from Isfahan (Iran). It is worth noting that the specifications of the materials used, including cement, water, and aggregates, are consistent with those presented in the research by Heydari et al. [16]. Additionally, a polycarboxylate ether superplasticizer was used in the construction of some molds as needed.

The waste CLR accumulated at the Naghsh-e Jahan Sugar Factory in Isfahan (Figure 1) was used after drying and exposure to the open air. To better characterize this waste, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analysis was performed on the powdered CLR. This analytical technique is used for elemental determination. The results of analysis, presented in Table 1, specify the precise elemental composition of the powdered CLR. The ICP-MS method is recognized as one of the most advanced and reliable methods for determining the concentration of trace and major elements due to its exceptionally high sensitivity, precise quantitative accuracy, and ability to measure multiple elements simultaneously. In this method, the sample in solution form is injected into a very high-temperature plasma, leading to complete atom ionization. The produced ions are then separated based on their mass-to-charge ratio in the mass spectrometer, and the concentration of each is measured.

Figure 1. CLR accumulated on-site at the Naqsh-e Jahan sugar factory, Isfahan (Iran)

Based on the data in Table 1, the element Calcium (Ca) is the main constituent, with the highest concentration (over 10%), consistent with the calcium carbonate nature of this waste. Following that, the elements Sulfur (S) with a concentration of 3938 ppm and Magnesium (Mg) with a concentration of 3684 ppm rank next. The significant presence of sulfur may indicate residual sulfate compounds from the sugar syrup purification process. Other elements with relatively higher abundance in this sample include Iron (Fe) at 1039 ppm, Aluminum (Al) at 470 ppm, Sodium (Na) at 295 ppm, and Zinc (Zn) at 25 ppm.

The precise identification and quantification of these impurities are crucial for predicting and justifying their effects on the mechanical properties and durability of concrete. Specifically, the significant presence of sulfur (S) indicates soluble sulfates, which can participate in reactions with calcium aluminate phases in cement to form ettringite. While ettringite is a normal hydration product, its delayed or excessive formation in hardened concrete can lead to destructive expansion and cracking. Furthermore, the detectable levels of alkali elements such as sodium (Na) and potassium (K) are of concern due to their potential to increase the pore solution alkalinity. This elevated alkalinity can accelerate the alkali-silica reaction (ASR) when reactive aggregates are present, leading to detrimental expansion and loss of strength over time. Therefore, the chemical composition revealed by ICP-MS provides a fundamental explanation for the observed reduction in mechanical strength and highlights potential durability risks that must be considered in future mix designs and applications.

Table 1.
Results of the ICP-MS chemical analysis performed on the CLR from the Naqsh-e Jahan sugar factory, Isfahan (Iran)

Element	**Ag**	**Al**	**As**	**Ba**	**Be**	**Bi**
DL	0.1	100	0.1	1	0.2	0.1
Unit: ppm	<0.1	470	2.1	2	<0.2	<0.1
Element	Ca	Cd	Ce	Co	Cr	Cs
DL	100	0.1	0.5	1	1	0.5
Unit: ppm	>10%	<0.1	5	<1	16	<0.5
Element	Cu	Dy	Er	Eu	Fe	Gd
DL	1	0.02	0.05	0.1	100	0.05
Unit: ppm	11	0.09	<0.05	<0.01	1039	0.62
Element	Hf	In	K	La	Li	Lu
DL	0.5	0.5	100	1	1	0.1
Unit: ppm	<0.5	<0.5	<100	<1	3	<0.1
Element	Mg	Mn	Mo	Na	Nb	Nd
DL	100	5	0.1	100	1	0.5
Unit: ppm	3684	44	<0.1	295	<1	<0.5
Element	Ni	P	Pd	Pr	Rb	S
DL	1	10	1	0.05	1	50
Unit: ppm	3	191	<1	<0.05	<1	3938
Element	Sb	Sc	Se	Sm	Sn	Sr
DL	0.5	0.5	0.5	0.02	0.1	1
Unit: ppm	<0.5	<0.5	<0.5	<0.02	2.9	288
Element	Ta	Tb	Te	Th	Ti	Tl
DL	0.1	0.1	0.1	0.1	10	0.1
Unit: ppm	0.32	0.13	<0.1	<0.1	56	<0.1
Element	Tm	U	V	W	Y	Yb
DL	0.1	0.1	1	1	0.5	0.05
Unit: ppm	<0.1	0.4	9	<1	0.7	0.4
Element	Zn	Zr				
DL	1	5				
Unit: ppm	25	<5				

3.2. Mix Design and Specimen Preparation

The basic concrete mix design was performed according to the National Method for Concrete Mix Design (Third Edition) [18]. Cylindrical concrete specimens (100 mm diameter × 200 mm height) were fabricated with varying replacement levels of cement by powdered CLR. Prior to mixing, the industrial waste was ground using an industrial mill to achieve a uniform particle size comparable to cement, following the findings of Heydari et al. [16]. Subsequently, predetermined amounts of the resulting powder (at levels of 5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40% by weight) were used as a partial replacement for cement in the mix design, achieved by reducing the weight of cement corresponding to each percentage. A control specimen (0% CLR) was also prepared. All specimens were cured in a water tank at 23 ± 2°C in accordance with ASTM C192 until the time of testing. The compressive strength test was conducted at 7, 28, and 56 days using a calibrated compression testing machine with a capacity of 2000 kN, following the procedure outlined in ASTM C39. The tensile strength was determined at 28 days using the Brazilian splitting test method as per ASTM C496. For both tests, the loading rate was maintained as specified in the respective standards. The reported values for compressive and tensile strengths for each mix are the average of results from three separate specimens. The compositions and exact quantities of materials used, including Portland Cement (PC), Carbonation Lime Residue (CLR), Water, Sand, Fine Gravel (Fine G.), and Coarse Gravel (Coarse G.), are provided in Table 2.

4. Results and Discussion

4.1. Compressive Strength

Table 3 and Figure 2 show the results of compressive strength tests on concrete specimens containing different percentages of ground CLR (from 0% to 40%) from the Naghsh-e Jahan Sugar Factory in Isfahan at ages of 7, 28, and 56 days. All reported strength values are expressed as mean ± standard deviation, based on three replicate specimens for each mix. The test results clearly demonstrate an inverse relationship between the waste replacement percentage and concrete strength. While the control specimen (0% CLR) developed compressive strengths of 38.2, 49.3, and 50.6 MPa at 7, 28, and 56 days, respectively, increasing the CLR content led to a consistent decline in performance. For instance, 28-day strength dropped to 42.4 MPa with 25% replacement and further to 37 MPa with 40% replacement. Of particular importance, however, is the rate of this strength loss. Up to the 25% replacement level, the reduction in compressive strength remains within an acceptable margin, and specimens retain adequate structural performance. This key observation strongly supports the economic and environmental viability of utilizing this waste material. The primary cause of the strength reduction is attributed to sugary impurities within the CLR, which are known to retard cement hydration and inhibit the formation of robust cementitious compounds. Furthermore, the presence of organic and mineral impurities can disrupt paste cohesion and introduce microscopic weak points into the concrete matrix.

Table 2.
Mix proportions of concrete with different percentages of CLR (kg per m³ of concrete)

Mix code	PC	CLR	Water	Sand	Fine G.	Coarse G.
CLR0	400	0				
CLR 5	380	20				
CLR10	360	40				
CLR 15	340	60				
CLR 20	320	80	152	1075	400	250
CLR 25	300	100				
CLR 30	280	120				
CLR 35	260	140				
CLR 40	240	160				

For a deeper understanding of the reasons for strength reduction at the microscopic level, SEM (Scanning Electron Microscopy) and EDX (Energy Dispersive X-ray Spectroscopy) analyses were performed on the control specimen and the specimen containing 40% CLR. A comparison of the SEM images of the control specimen and the specimen containing 40% waste (Figure 3) reveals significant structural differences.

The SEM images clearly show that the cementitious matrix in the control specimen is very dense and integrated, whereas in the specimen containing waste, more porosity is observed. These fine pores act as stress concentration points and lead to a reduction in mechanical strength. It is also observed that in the control specimen, there is a strong and coherent bond between the cement paste and the aggregates, whereas in the 40% specimen, a weak Interfacial Transition Zone (ITZ) is evident, where there is less adhesion, and this area cracks easily and facilitates crack propagation. Close examination of the SEM images also reveals that the presence of large, plate-shaped Calcium Hydroxide (CH) crystals is distinctly more pronounced in the specimen containing waste. Although CH is a natural product of hydration, its accumulation as large crystals is considered a weakness in the structure and weakens the bond between components.

Table 3.
Compressive strength results of concrete mixes incorporating ground CLR from Naghsh-e Jahan Sugar Factory, Isfahan (Iran)

CLR (%)	7 Days (Mpa)	Reduction compred to 0%	28 Days (Mpa)	Reduction compred to 0%	56 Days (Mpa)	Reduction compred to 0%
0	38.2±0.88	-	49.3±0.48	-	50.6±0.83	-
5	36±0.79	5.7	47±0.70	4.6	50±0.22	1.2
10	33±1.02	13.6	46±0.17	6.7	49±0.63	3.1
15	30±1.24	21.4	43±0.37	12.8	45.7±0.62	9.7
20	29±0.41	24	42.9±0.29	13	45±0.34	11.1
25	28.5±0.34	25.4	42.4±0.34	14	44.5±0.17	12
30	27.7±0.26	27.4	41±0.37	16.8	42±0.67	17
35	25.9±0.59	32.2	39±0.79	20.9	41±0.40	19
40	24±0.42	37.1	37±0.37	24.9	40±0.49	20.9

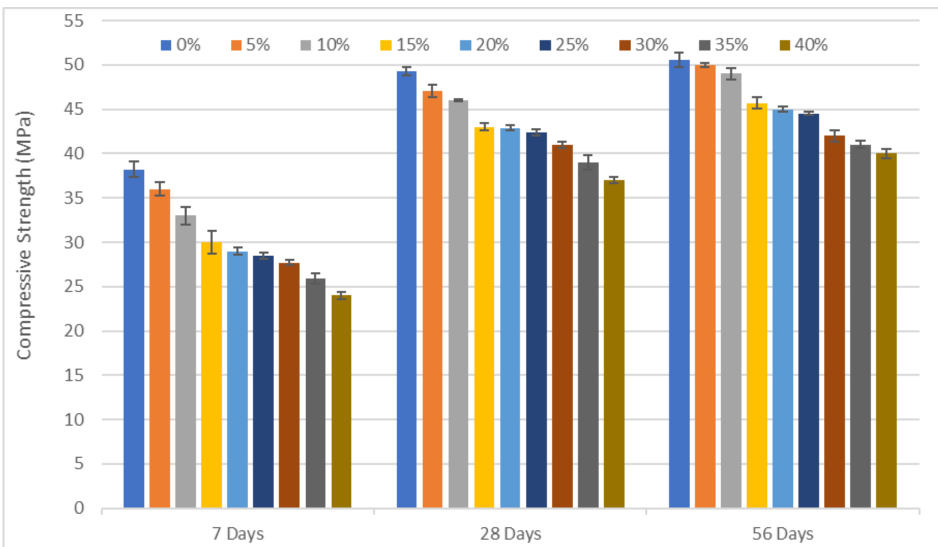

Figure 2. Compressive strength results of concrete specimens incorporating ground CLR from Naghsh-e Jahan Sugar Factory, Isfahan (Iran)

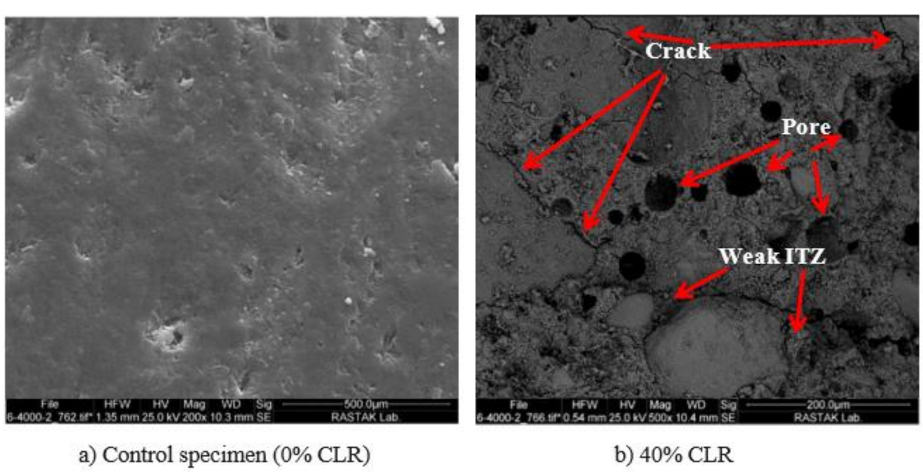

Figure 3. SEM analysis results of 28 days-concrete specimens with: a) 0% CLR and b) 40% CLR

The quantitative results of the EDX analysis listed in Table 4 well confirm the presence of chemical elements related to impurities in the specimen containing waste. The weight percentage of calcium in the specimen containing 40% CLR (34.44%) is much higher than in the control specimen, which itself confirms the calcium carbonate origin of this material. The presence of 1.78% carbon in the 40% specimen, which is not observed in the control specimen, may indicate residual organic and sugary materials in the waste. The identification of elements such as sulfur (2.18%) and potassium (1.38%), which are absent in the control specimen, confirms the presence of mineral and chemical impurities originating from the sugar factory production process. These elements play a role in the formation of harmful compounds like ettringite. It is also noted that the presence of sulfate impurities in the waste has led to the formation of needle-shaped ettringite crystals. These crystals can expand in the presence of moisture and create internal cracks, leading to the ultimate reduction in strength. Therefore, by carefully examining the SEM and EDX results, it can be understood that the presence of sugary and mineral impurities in the CLR leads to the creation of a porous, weak, and heterogeneous microstructure in the concrete. This structural weakness, manifested as weak bonding with aggregates, increased porosity, and the formation of undesirable crystals (CH and ettringite), is the main justification for the reduction in measured mechanical strengths in the compressive and subsequent tensile tests.

Table 4.
EDX analysis results for the control specimen and the specimen containing 40% CLR

	Control specimen		**40% CLR**	
Element	**Weight %**	**Atomic %**	**Weight %**	**Atomic %**
O K	48.04	61.77	38.92	57.73
SiK	46.34	33.94	13.45	11.37
AlK	5.62	4.28	2.28	2.00
CaK	-	-	34.44	20.39
FeK	-	-	5.28	2.24
NaK	-	-	0.24	0.25
MgK	-	-	0.05	0.05
S K	-	-	2.18	1.61
K K	-	-	1.38	0.84
C K	-	-	1.78	3.52

4.2. Tensile Strength

As observed in Table 5 and Figure 4, the Brazilian tensile strength test results revealed a trend similar to the compressive strength findings: as the percentage of CLR increased, tensile strength decreased. All reported tensile strength values are presented as mean ± standard deviation, calculated from three replicate specimens for each mix. The control specimen (0% CLR) exhibited the highest tensile strength at 4.39 MPa. This value declined to 4.19 MPa with 15% CLR replacement and further to 4.06 MPa at 25% replacement. Although tensile strength consistently decreased with higher CLR content, the rate of reduction was more gradual compared to the decline in compressive strength. This milder reduction may be attributed to the fine particles of the CLR, which, despite impairing primary chemical bonds, could help distribute stress more evenly within the concrete matrix.The decrease in tensile strength is primarily due to sugary and organic impurities in the CLR, which disrupt cement hydration and inhibit the formation of strong binding compounds, such as C-S-H. This leads to a weakened bond between the cement paste and aggregates, reducing resistance to tensile loads. Furthermore, as shown in the SEM images, a weakened Interfacial Transition Zone (ITZ) forms around aggregates in CLR-containing specimens. This zone serves as an initiation point and pathway for crack propagation—a vulnerability particularly evident in the Brazilian test, where direct tensile stress is applied. Despite a tensile strength reduction of approximately 7.5% at 25% CLR replacement, the absolute strength values remained above 4 MPa. Therefore, using CLR up to this level may be suitable for non-structural applications or structures with lower safety requirements, provided that other mechanical and durability properties are thoroughly evaluated.

Table 5.
Brazilian tensile strength results of concrete specimens incorporating ground CLR from Naghsh-e Jahan Sugar Factory

CLR (%)	**Failure load (N)**	**Tensile Strength (Mpa)**	**Reduction compred to 0%**
0%	138000	4.39±0.09	-
15%	131500	4.19±0.06	4.5
25%	127500	4.06±0.06	7.5

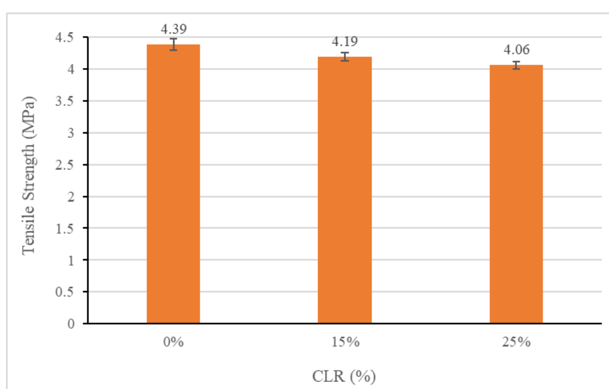

Figure 4. Brazilian tensile strength results of concrete specimens incorporating ground CLR from Naghsh-e Jahan Sugar Factory.

5. Conclusion

This study demonstrates the viability of utilizing Carbonation Lime Residue (CLR), a waste by-product from sugar factories, as a partial cement replacement in concrete production. The research was motivated by the environmental challenges posed by the massive accumulation of non-recycled CLR, which contributes to pollution and degrades landscapes and agricultural lands. The experimental results indicate that replacing up to 25% of cement with CLR leads to a reduction of less than 15% in compressive strength and less than 10% in tensile strength. While this strength reduction is attributed to impurities and sugary substances in the CLR, the decline remains within acceptable limits for many applications. Given the significant benefits in waste management, economic savings, and environmental preservation, the use of CLR in concrete represents a practical and effective strategy for promoting sustainable development in the construction industry, particularly for non-structural applications or in regions near sugar production facilities.

6. Limitations and Future Work:

This study focused on the fundamental mechanical properties (compressive and tensile strength) of concrete incorporating CLR. It is acknowledged that for practical implementation, a more comprehensive evaluation is required. Key properties such as workability, setting time, long-term durability (including sulfate resistance, chloride penetration, and water absorption), and dimensional stability were not within the scope of this initial investigation. These aspects are critically influenced by the chemical impurities present in CLR (e.g., sulfur, alkalis) and warrant detailed examination in future research. Therefore, while the results demonstrate the mechanical viability of using up to 25% CLR, it is strongly recommended that subsequent studies thoroughly assess these fresh, hardened, and durability properties before field application in specific environments, particularly where exposure to sulfates or moisture is a concern.

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