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From Agricultural Waste to Construction Material: The Necessity of Controlled Water Curing for CLR-Concrete

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ABSTRACT

The sugar industry generates substantial agricultural waste, necessitating sustainable recycling pathways. This study explores the valorization of Carbonation Lime Residue (CLR), a waste from sugar beet processing, in concrete as a partial cement replacement. Given the critical impact of curing on performance, this research specifically investigates the effect of curing conditions on CLR-based concrete. Specimens with 0% to 40% CLR were prepared and subjected to two distinct curing regimes: stagnant water and controlled curing with periodic water replacement. Compressive strength was evaluated at 7, 28, 56, and 90 days, while the curing water was monitored for electrical conductivity (EC) and total dissolved solids (TDS). The results revealed that stagnant water curing led to a sharp decline in long-term strength, attributed to the leaching of impurities and a consequent harmful increase in water salinity. Conversely, controlled water curing with periodic refreshing prevented salt accumulation and facilitated a continuous strength gain for all mixes. A 20% cement replacement with CLR was found to be structurally viable under this proper curing method. This study conclusively demonstrates that controlled water curing is not merely beneficial but essential for producing durable green concrete from agricultural waste, effectively transforming it into a valuable construction material.

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1. Introduction

The agricultural sector is a cornerstone of global food security, yet it simultaneously generates significant volumes of organic and inorganic waste streams. The sugar industry, intrinsically linked to the cultivation of sugar beet, is a prime example, producing by-products that pose considerable disposal challenges. Integrating these agricultural residues into value-added applications, particularly in the construction industry, presents a promising pathway toward a circular economy, reducing environmental burden and conserving natural resources.

Today, despite the remarkable progress of science in human societies and the high speed of industrialization and the establishment of large and small factories to meet the needs of the community, which is very gratifying, the production of large volumes of waste from these industries and factories is damaging and concerning. On the other hand, many of these wastes contain chemical and industrial materials that, if released into the environment, are harmful to humans and other living organisms in their surrounding

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environment. These concerns have led most societies to remove waste and residues from their surroundings. One of the most practical options in waste management is recycling and optimal reuse, which, in addition to environmental benefits, can also generate income and lead to economic savings.

With the expansion of urbanization worldwide, the construction industry is a new and significant gateway for accepting recycled materials. Concrete is one of the most important and common building materials that, due to its advanced technology and expertise in its production, has opened its arms to accept industrial waste. Given the characteristics of concrete production and the flexibility in formulating its main constituent materials, concrete is one of the best platforms for testing and investigating industrial waste. On the other hand, using these materials as a substitute for cement, since cement itself is a major pollutant for the environment, significantly enhances the value of recycling.

During the production and operation process of sugar factories, a large amount of waste is generated, including pulp, molasses, and Carbonation Lime Residue (CLR). These wastes can be used as raw materials for producing other high-value products. Recently, several studies have investigated the use of molasses in the production of cement, mortar, and concrete [1-4]. Other research has focused on the reuse of pulp in other industries [5-14], especially the food industry [15-17]. However, currently, the biggest problem and waste of sugar factories is CLR. CLR is a mandatory by-product and waste of these factories, which is currently unused and generally accumulated in large volumes around the factories. Field surveys from several active sugar factories revealed that during peak operation periods, about 80 tons of CLR is obtained daily per factory [18]. The accumulation of this waste has caused environmental pollution in their surroundings and posed a serious disposal problem for sugar factories. Furthermore, follow-ups and warnings from Iran's environmental agencies have even led to the shutdown of some of these factories and their inclusion on the Environmental Protection Organization's blacklist As a result, sugar factories, to escape this issue and dispose of these materials, are sometimes forced to bury them, transfer them to other areas, or even dump them into nearby rivers. It is worth noting that unfortunately, due to the very high lime properties of these materials, this action causes irreparable damage to the environment, animals, and aquatic life in the areas. Dried Carbonation Lime Residue accumulated around sugar factories disperses as very fine powder in the surrounding environments. Furthermore, since sugar beet farms are usually located near most sugar factories, the dispersion of these materials clogs soil pores and disrupts plant growth processes.

Although CLR in sugar factories (due to the absorption of impurities from non-sugar contaminants during the sugar refining process) is different from original calcium carbonate, since these wastes have a lime origin, reviewing the results of studies where calcium carbonate replaced cement in concrete production can be beneficial [19-25]. Unfortunately, few studies on the recycling of CLR have been reported so far. Recently, research has been conducted on the effect of using this waste as a soil stabilizer [26], on various parameters of geopolymers [27-30], polymer concretes [31], cement [32], and ordinary Portland concrete [33-35]. A review of the literature indicates that Heidari et al. [33], Gharieb and Rashad [34], and Phuyal et al. [35] are among the limited researchers who have so far investigated the reuse of CLR waste in concrete production. Heidari et al. [33] investigated the effect of the method of using this waste on the mechanical properties of concrete through laboratory experiments. They used three different methods, including dissolving in mix design water, sieving, and grinding, to replace cement in concrete production with different percentages of CLR. Their experimental results demonstrated that the optimal method for utilizing CLR in concrete is to incorporate it in a ground form. Their findings indicated that replacing up to at least 20% of the cement by weight with this processed waste is feasible, resulting in only a minimal reduction in concrete strength. Gharieb and Rashad [34] also investigated the effect of replacing cement with CLR in different ratios between 5% and 25% by weight on the compressive strength, specific weight, water absorption, and porosity of concrete. Their laboratory test results showed that the best replacement ratio is 5%, and higher replacement ratios lead to a decrease in the compressive strength of concrete. The laboratory investigations of Phuyal et al. [35] showed that increasing the percentage replacement of cement with CLR in concrete production reduces the compressive, tensile, and flexural strengths of concrete. It is predicted that by introducing these materials into the construction industry and producing environmentally friendly green concrete, a large volume of this type of sugar factory waste can be consumed and recycled, and the problem of accumulating this waste, which has become problematic for their environment, can be completely or largely eliminated, providing profitability for both industries. However, to improve the efficiency, the best curing conditions for concrete produced with this type of waste must be investigated.

Effectively implementing any procedure or method to optimize concrete curing conditions requires sufficient expertise and a deep understanding of the process. To ensure the practical applicability of these methods, a comprehensive study is essential. Utilizing previous research significantly accelerates this process [36-40]. In general, the results of these studies highlight the critical importance of proper curing and its impact on the properties of hardened concrete. In other words, curing influences all characteristics of hardened concrete. For instance, the required duration for protecting and curing concrete depends on factors including the type of cementitious materials used, mix proportions, specified strength, the size and shape of the concrete element, and the ambient temperature and humidity during and after the curing period.

Therefore, given the significant role of curing in developing the strength and durability of concrete, and considering the lack of attention paid to this aspect in previous research on carbonated green concrete, the primary objective of current research is to identify the optimal curing conditions. This aims to facilitate the more practical utilization of sugar factory waste (CLR) as a partial replacement for cement in concrete production, ultimately paving the way for the processing and commercialization of this type of green concrete.

2. Materials and Proposed Research Methodology

In this research, Type II Portland cement produced by Ardestan Cement Factory located in Isfahan city (Iran) was used. Potable water available in the laboratory was also used, and the maximum water-to-cement ratio in the mixes was considered to be 0.35. The gradation of the used sand and gravel was evaluated based on National Standard No. 302 (Iran). Pea gravel and sand were obtained from the Noor complex mine, and crushed mountain almond gravel was obtained from the Paya Sang mine, all from Isfahan city (Iran). Waste Carbonation Lime Residue produced at the Naghsh-e Jahan Sugar Factory in Isfahan was used as a cement replacement in the production of carbonated green concrete. It is worth noting that the specifications of all used materials, including cement, water, aggregates, and CLR, are in accordance with the research presented by Heidari et al. [33].

To make the cylindrical concrete specimens containing different replacement percentages of 5%, 10%, 20%, 30%, and 40% as a substitute for part of the cement, this waste (whose appearance is shown in Figure 1) was first powdered using an industrial grinder to make its particle size more uniform and similar to cement [33]. The control specimens were prepared without adding any waste powder. For each mix design, 15 cylindrical specimens were made to determine the compressive strength at 7, 28, 56, and 90 days, noting that three extra molds were also kept for inspection and evaluation of the concrete when necessary. The reported compressive strength for each mix design was obtained by averaging the compressive strength of three specimens.

According to Standard Building Regulations, concrete curing is a process during which moisture loss from the concrete is prevented and the temperature of the concrete is maintained at a satisfactory level. While preliminary investigations highlight the importance of curing for concrete containing waste CLR, this subject remains still unexplored. To address this gap, two curing methods were evaluated: curing by the use of a pond with stagnant, non-replaceable water (Figure 2), and a pond equipped with water replacement system (Figure 3). A comparative analysis of the compressive strength results was then conducted.

Figure 1. Granulation and composition of CLR particles in nature

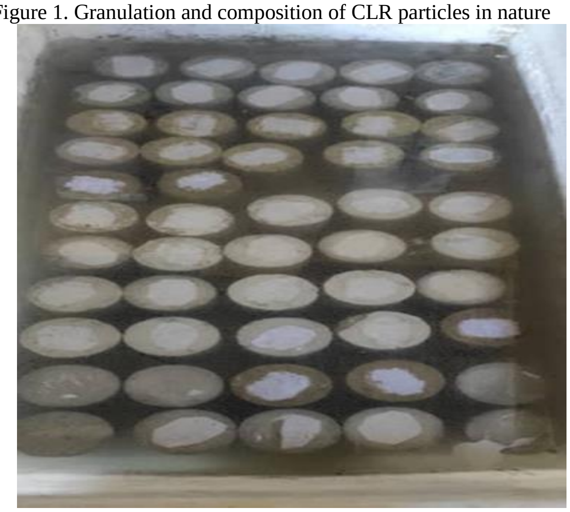

Figure 2. Sample storage pond with stagnant and non-replaceable water

3. Results and Discussion

3.1. Results of compressive strength of concrete specimens cured using a pond with stagnant, non-replaceable water

The results of compressive strength tests for concrete specimens cured in a pond with stagnant, non-replaceable water are shown in Figure 4. Scrutinizing the results easily shows that the strength of the specimens had an upward trend until the first 28 days after production, but after about two months, the compressive strength of the specimens decreased sharply; such that the compressive strength of the 56 and 90-day specimens decreased significantly. It is worth mentioning that the three additional specimens prepared in all mixes, which were made and kept for necessity, deteriorated after a 120-day period, and their strength decreased severely, to the extent that some specimens easily disintegrated with hand pressure, as can be seen in Figure 5.

Figure 3. Sample storage pond with temperature control and replaceable water

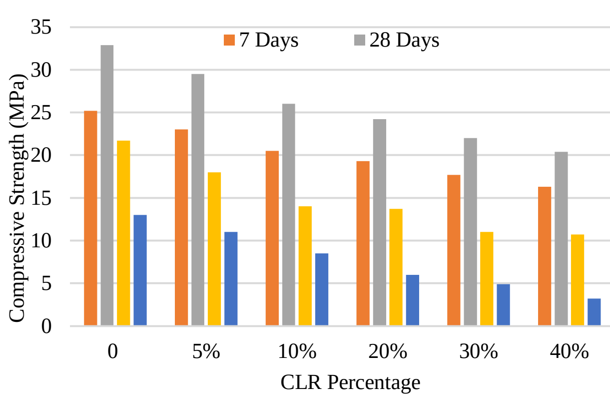

Figure 4. Compressive strength of concrete specimens containing different percentages of CLR cured using a pond with stagnant, non-replaceable water

It is reminded that at this stage, the produced specimens were placed next to each other in the pond with stagnant, non-replaceable water. Visual observations after one month indicated a change in the color of the water and the formation of sludge inside the pond. Visual inspection also indicated that a layer of white residue gradually formed on the surface of the specimens, as shown in Figure 6. The reason for this can be related to the presence of impurities and organic materials in the concrete specimens containing CLR and their seepage in contact with water.

Figure 5. Loss of strength and disintegration of concrete specimens cured using a pond with stagnant, non-replaceable water after 120 days.

Figure 6. Appearance changes of specimens cured using a pond with stagnant, non-replaceable water after one month

To investigate the cause of the severe strength reduction in specimens cured in the stagnant ponds, the pond water was analyzed. Water samples were collected from the curing ponds at five different intervals (30, 45, 60, 75, and 90 days) and subjected to chemical testing. The results of these analyses are presented in Figure 7.

Electrical Conductivity (EC) measures a solution's ability to conduct electricity, which is directly related to its ionic concentration. Total Dissolved Solids (TDS) represents the total concentration of dissolved inorganic salts and minerals in the water, often referred to as water hardness. A higher EC value indicates a greater concentration of ions, while a higher TDS value signifies increased mineral content and harder water. The significance of these parameters lies in their correlation with the corrosivity of water; a higher EC generally indicates a higher corrosion rate under similar conditions. Although EC and TDS are distinct parameters, they exhibit a strong and direct correlation. However, the exact ratio between TDS and EC varies for different water samples, depending on the specific composition and concentration of dissolved impurities.

Standard guidelines recommend that the TDS in concrete curing ponds should not exceed 1000 mg/L to prevent potential damage. However, as detailed Figure 7, the TDS in the stagnant curing ponds increased progressively over time. Within two months of introducing the specimens, the TDS surpassed the 1000 mg/L threshold, reaching over 3000 mg/L after three months—a level comparable to seawater salinity and detrimental to concrete made with Type II Portland cement. Therefore, it can be concluded that curing CLR-containing concrete in stagnant water ponds leads to a significant accumulation of salts in the water. This increase in salinity, which intensifies with prolonged curing duration, is the primary cause of the observed severe strength reduction in the specimens.

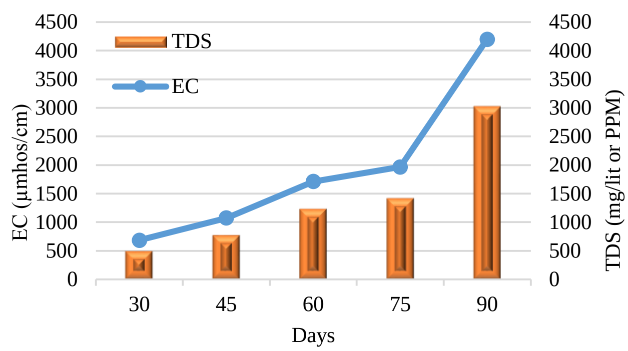

Figure 7. Results of water chemical tests after different intervals (pond with stagnant, non-replaceable water)

3.2. Results of compressive strength of concrete specimens cured using ponds equipped with temperature control and water replacement system

In response to the significant strength reduction observed in specimens cured in stagnant water, a controlled curing system was designed and implemented to mitigate the detrimental effects of salt accumulation. This system featured dedicated ponds equipped with temperature control and water replacement system, ensuring a stable and homogeneous curing environment. To maintain water quality, a protocol was established for complete water replacement every two weeks, or whenever visual inspection indicated cloudiness, thereby preventing the buildup of dissolved ions leached from CLR.

Using the same mix designs as the initial phase, a new set of cylindrical specimens was cast with CLR replacement levels of 0%, 5%, 10%, 20%, 30%, and 40% by weight of cement. These specimens were then subjected to the improved curing regime, and their compressive strength was evaluated at 7, 28, 56 and 90 days. The results, summarized in Figure 8, demonstrate a markedly different and more favorable trend compared to stagnant water curing.

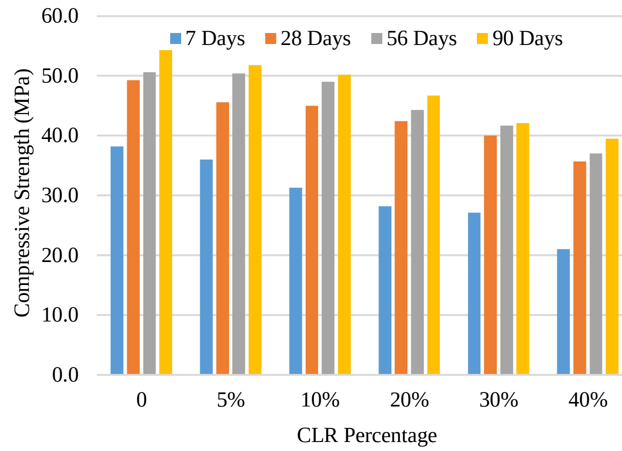

Figure 8. Compressive strength of concrete specimens containing different percentages of CLR cured using a pond equipped with temperature control and water replacement system.

The compressive strength development under controlled curing conditions is shown in Figure 8. The data indicate consistent strength gain for all mixes throughout the 90-day curing period. As expected, incorporating CLR generally led to a reduction in compressive strength compared to the control specimens (0% CLR), attributable to cement dilution and the lower reactivity of CLR. However, a significant finding emerges that at replacement levels up to 20%, the strength reduction remained relatively modest. For instance, the 20% CLR mix achieved approximately 42 MPa at 28 days and 44 MPa at 56 days, compared to the control's 49 MPa and 50 MPa, respectively—representing a strength retention of about 86-88%. This suggests that replacement ratios up to 20% are structurally viable for many applications.

Furthermore, the results reveal an important long-term trend; while the control mix showed minimal strength gain beyond 28 days, the CLR-containing mixes exhibited continued strength development between 28 and 90 days. This sustained hydration suggests a possible pozzolanic or filler effect from the processed CLR that compensates for the initial cement dilution and contributes to long-term strength development.

The stark contrast between the two curing methods is undeniable. The controlled curing environment, characterized by water periodic replacement, successfully prevented the spike in water salinity (as measured by TDS and EC) that was detrimental in the stagnant ponds. Consequently, all specimens cured under controlled conditions remained sound and intact throughout the testing period, with no signs of the deterioration that plagued their stagnant-water counterparts. This compelling evidence allows us to conclude that the severe strength loss previously observed was not an inherent property of CLR-concrete, but rather a direct consequence of an unsuitable curing method. Therefore, the adoption of a managed curing regime, which controls water chemistry through periodic replacement, is not merely beneficial but essential for realizing the full structural potential of green concrete incorporating waste Carbonation Lime Residue.

4. Conclusion

This study demonstrates a viable pathway for recycling agricultural waste from the sugar industry into construction materials. By investigating the use of Carbonation Lime Residue (CLR) in green concrete, it was established that the curing method is the critical factor determining its structural viability. Specimens were subjected to two distinct curing regimes: stagnant water and controlled curing with periodic water replacement. Evaluation of compressive strength results and chemical analysis of the water yielded the following key findings:

- Stagnant Water Curing: Curing in ponds with stagnant water led to a severe decline in strength at later ages (56 and 90 days). Chemical analysis of the water revealed a progressive increase in salinity resulting from the leaching of impurities from the CLR. This highly corrosive environment not only halted strength development but also caused progressive deterioration of the specimens, to the extent that 120-day specimens completely lost their integrity and could be disintegrated by hand.
- Controlled Curing with Periodic Water Replacement: In contrast, curing under controlled conditions (with periodic water replacement) resulted in a consistent and sustained increase in strength up to 90 days for all mix designs. Although incorporating CLR at levels up to 40% led to an overall reduction in strength compared to the control, the reduction for replacements up to 20% was limited (approximately 14% at 28 days). More importantly, mixes containing CLR exhibited a significant rate of strength gain between 28 and 90 days. For instance, the 20% CLR mix showed only a 12% reduction in strength compared to the control at 90 days. This behavior indicates a possible prolonged pozzolanic or filler effect from the processed CLR, which continues at later ages and compensates for the initial strength loss due to cement dilution.

This study clearly demonstrates that the curing method is a critical factor determining the performance of green concrete containing CLR. Curing in stagnant water is entirely unsuitable due to the creation of a corrosive, and high-salinity environment. Conversely, a managed curing regime with regular water replacement to control the chemical quality of the water is essential for achieving durable strength development and realizing the full potential of this green concrete. Consequently, a replacement level of up to 20% CLR, when coupled with proper curing, presents a viable and reliable option for structural applications.

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