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Review Article

Limestone Powder in Concrete Mixes: A Review of Mechanical Enhancements

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Abstract

The wide application of concrete as a construction material is also connected with a large environmental impact, mainly related to carbon dioxide (CO_2) emissions from the production of Portland cement. Hence, studies increasingly investigate alternative materials that could substitute concrete, mitigating its impacts on the environment without losing its mechanical performance. Limestone powder has recently been highly considered as a supplementary constituent of concrete. This review focuses on the effects of Limestone (LS) on the compressive, tensile, flexural strength, and elastic modulus of concrete. Data show that it is highly affected by factors like the size of particles, dosage (e.g., typically up to 15% replacement of cement by mass to enhance performance), and the method of application of LS in relation to its impacts on the mechanical properties of concrete. Specifically, finer LS particles can improve the compressive strength of concrete by filling the gaps and providing nucleation sites for hydration products. However, high LS concentration can cause a diluting effect that reduces compressive strength. On the other hand, LS may improve elastic modulus, tensile, and flexural strength when combined with other wastes like marble waste aggregate. These observations have explicated that LS is a workable and sustainable addition in view of performance improvement in concrete.

Keywords: Limestone, Limestone Powder, Concrete, Sustainable Solution, Construction Material

Introduction

Concrete is the most widely used construction material due to its durability, low maintenance costs, and the broad availability of basic resources [1]. Approximately 21 gigatons of concrete are produced annually worldwide [2], highlighting its indispensable role in infrastructure development. However, concrete production is associated with significant environmental impacts, primarily due to its contribution to global CO_2 emissions. About 25 billion kilograms of concrete are produced annually [3], with Portland cement as its fundamental constituent. The manufacturing of Portland cement requires an energy input of 4–5 GJ per ton, releasing substantial CO_2 emissions due to both fuel combustion and the thermal decomposition of limestone during the clinker production process [4]. It is estimated that 0.87 kilograms of CO_2 is emitted for every kilogram of Portland cement clinker produced, contributing to 7% of global annual CO_2 emissions [5, 6].

To address these environmental challenges, supplementary cementitious materials (SCMs) have been integrated into concrete mixes, enhancing its workability, mechanical properties, and durability while significantly reducing its ecological footprint [1]. For instance, substituting 50% of Portland cement with SCMs by mass could reduce global CO_2 emissions by 1 billion tons annually [7]. High-volume fly ash concrete has demonstrated both economic and environmental benefits in various projects [8]. However, the global production of fly ash, estimated at 0.8 billion tons annually, is insufficient to meet the demand, and not all produced fly ash meets the required specifications for use as SCMs [9]. These limitations necessitate the exploration of naturally occurring alternative materials for cement replacement.

Limestone powder has garnered considerable attention as a viable alternative due to its abundant availability, low cost, and beneficial properties. Research has revealed that limestone powder exhibits filler, nucleation, dilution, and chemical effects in cement-based materials. These effects depend on factors such as particle size, dosage, dissolution rate, polymorph, and the mineral composition of both the limestone powder and supplementary cementitious materials [10, 11].

Despite the promising advantages of limestone powder, several challenges remain unresolved. Key issues include determining the optimal particle size and dosage for maximizing mechanical performance, understanding its long-term effects on concrete durability, and evaluating its interactions with other materials under varying environmental conditions. This review aims to investigate the impacts of limestone powder on the mechanical properties of concrete and critically assess the findings from existing studies. By addressing these unresolved aspects, this review seeks to provide a clearer understanding of the potential for limestone powder to serve as a sustainable replacement material in concrete production.

Effect on Mechanical Strength

Effect on compressive strength

Finer LS particles can occupy the spaces between cement particles, boosting the packing density of the cementitious materials. For instance, introducing ultra-fine LS into concrete has been demonstrated to increase the compressive strength upto 50% of self-compacting concrete [12]. Additionally, concrete with tiny LS particles (5 µm) displayed greater compressive strength at various ages compared to concrete with larger LS particles (10 and 20 µm) [13].

When significant quantities of fine LS are used to substitute cement, a dilution effect develops, leading to a loss in compressive strength [14]. Generally, a rise in LS content correlates to a decrease in compressive strength [15], with the diluting effect being more significant at later ages [16]. This is because increased

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LS content decreases the quantity of cement, hence limiting the development of hydration products. Notably, when the LS concentration approaches 35%, the diluting impact dramatically accelerates [16]. Replacing cement with 15–45% LS has been found to diminish compressive strength, with strength losses ranging from 9% to 86% depending on the water-to-binder ratio and the age of the concrete [17].

Conversely, when LS is used to replace cement paste or fine aggregates, it may fill the spaces between aggregates and boost compressive strength. Replacing cement paste with LS has been found to greatly enhance the compressive strength of concrete even when the water-to-cement ratio (W/C) stays unchanged [18]. This enhancement is ascribed to LS boosting the precipitation of C-S-H, hence raising the hydration degree of cement through its nucleation impact. Additionally, the increased powder concentration and reduced water can prevent bleeding in concrete, strengthening the interfacial transition zones. Nikbin et al. [19] observed that increasing LS content from 25% to 100% resulted to compressive strength increases of 20% and 38% for W/C ratios of 0.6 and 0.47, respectively.

Another investigation on the impacts of limestone powder (LP) on mass concrete finds that substituting produced sand with LP can boost compressive strength, with the best strength attained at a 10% LP replacement (Fig. 1). This replacement outperformed the control group, notably after 60 and 90 days, where strength improvements of 5-7 MPa were recorded. However, substituting fly ash with more than 20% LP may significantly effect strength development at later phases, notably after 90 days. These findings imply that LP is a viable sustainable solution for enhancing the compressive strength of mass concrete [20].

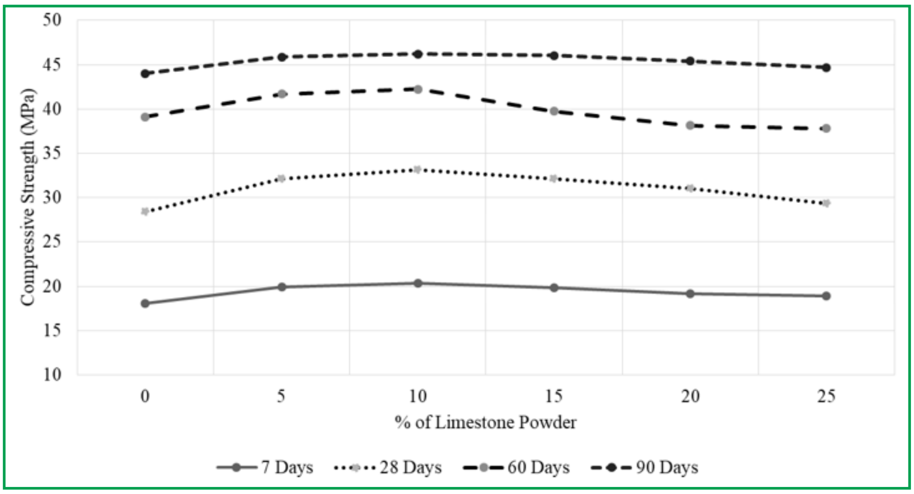

Figure 1. Variation in compressive strength of concrete with different percentages of limestone powder replacement [20]

Based on the aforementioned investigations, it may be extrapolated that employing LS to substitute cement paste or fine aggregates can boost compressive strength. However, there exists an ideal LS concentration for optimizing

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compressive strength when finer LS is utilized to replace cement. . Below this ideal amount, finer LS demonstrates a filler effect, while beyond it produces in a dominating diluting effect. Studies have demonstrated that substituting cement with up to 5% LS can boost the early compressive strength particularly at 7 and 28 days of concrete [21, 22]. Similarly, Schmidt [23] reported that utilizing up to 10% LS as a cement replacement increased compressive strength. Furthermore, Li et al. [24] showed that inserting 3.0% nano-$CaCO_3$ into ultra-high performance concrete (UHPC) with water-to-binder ratios of 0.16 and 0.17 resulted to compressive strength improvements of 17% and 11%, respectively.

Effect on flexural strength

Incorporating limestone powder (LS) into concrete mixes can enhance flexural strength when used in optimal amounts. For example, using up to 15% LS in high-strength concrete has been shown to improve flexural tensile strength [25]. Similarly, a mix with 18% limestone waste powder exhibited maximum resistance against flexural loads [26].

While moderate amounts of LS positively influence concrete properties, excessive use can lead to reduced mechanical performance (Fig. 2). For instance, replacing cement with 30% LS in ultra-high-performance concrete resulted in decreased flexural strength compared to mixes containing silica fume [27]. The synergy between LS and other materials significantly impacts flexural strength. Blends of LS and silica fume in steel fiber-reinforced concrete enhanced flexural fatigue performance by improving the microstructure [28]. Additionally, combining LS and marble powder improved flexural behavior in self-compacting concrete [29].

Curing periods and mix design play pivotal roles in determining flexural strength. Prolonged curing typically enhances performance, though the extent depends on the specific mix and curing conditions [30]. For example, using ultrafine LS in reactive powder concrete substantially increased flexural strength when applied in appropriate proportions [31].

When limestone powder (LS) is used to substitute cement, it largely shows filler and dilution effects, with its nucleation and chemical effects having limited impact on the flexural strength of concrete. However, using nano-limestone with a particle size of 15–80 nm to substitute cement has been found to increase the flexural strength of ultra-high-performance concrete (UHPC) [24]. Specifically, when 3% nano-limestone was added to UHPC with a water-to-binder ratio (W/B) of 0.16 and 0.17, the flexural strength rose by 40% and 30%, respectively. On the other hand, if the particle size of limestone is similar to that of cement, it tends to display a diluting effect. When LS is used to replace cement, the content of cementing ingredients reduces while non-cementing elements rise, causing to a fall in the flexural strength of concrete. As the LS concentration increases, the flexural strength drops [21], where concrete without LS had a flexural strength of 9.1 MPa, compared to 7.5 MPa and 7.3 MPa for concrete containing 5% and 10% LS, respectively.

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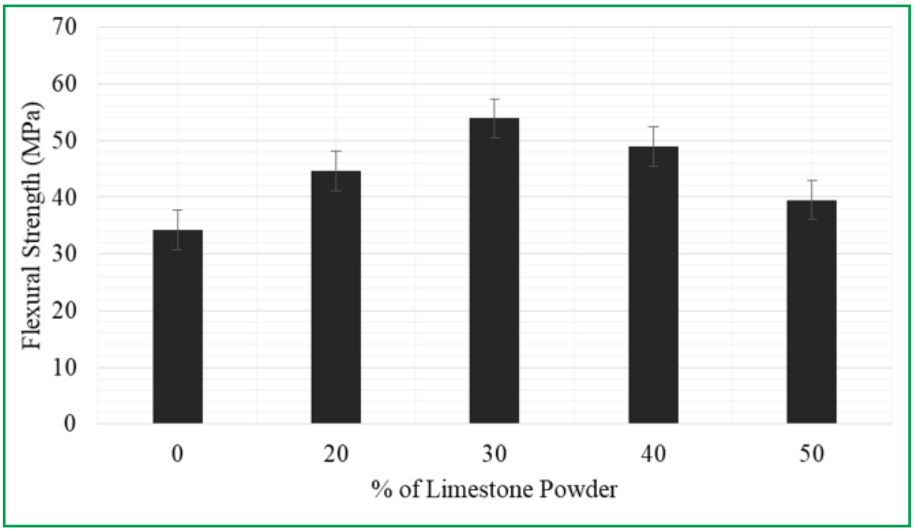

Figure 2. Variation in flexural strength of concrete with different percentages of limestone powder replacement [32]

The addition of limestone waste powder and marble waste aggregate into concrete has proven a considerable boost in its flexural strength. As the quantity of limestone waste powder rose, the concrete's resistance to flexural loads improved, with the best performance recorded at 18% usage. Similarly, the incorporation of marble waste aggregate resulted to a large improvement in flexural strength, reaching its peak at 60% use. These results emphasize the potential of employing these waste elements as useful additives in concrete to improve its flexural performance [26].

Effect on tensile strength

Incorporating limestone powder (LS) to replace cementitious paste [18] and fine aggregates [19] has also been proven to boost the tensile strength of concrete. Adding small amounts of limestone powder (usually between 10 and 15%) can make concrete stronger when it comes to tensile strength. This is because the microstructure is better and there are more places for water products to start forming, which leads to better tensile qualities [25, 32-35]. The tensile strength was seen to enhance as the LS concentration increased (Fig. 3). For example, when the LS content was raised from 25% to 100%, the tensile strength of concrete rose by 17% and 12% for water-to-cement ratios (W/C) of 0.6 and 0.47, respectively [58]. Li [18] noticed that integrating LS boosted compressive strength, and usually, elements that promote compressive strength also enhance tensile strength. Additionally, as the tensile strength of the matrix is lower than that of aggregate particles, integrating LS adds to an increase in tensile strength. When the replacement level of limestone powder exceeds 15-20%, there is often a decrease in tensile strength. This is attributed to the dilution effect, where the reduction in cement content outweighs the benefits provided by the limestone powder [36].

Combining limestone powder with other materials like slag or bamboo fibers can further improve tensile strength. For instance, a mix with 10% limestone powder and 10% slag showed favorable tensile strength results [35]. The tensile strength of concrete was considerably increased by the inclusion of limestone waste powder and marble waste aggregate. Experimental findings demonstrated that as the amount of limestone waste powder grew, the tensile strength improved, with best results at 18% utilization. Similarly, the tensile strength continued to improve with the increasing proportion of marble waste aggregate, reaching its peak at 60% usage. These results underline the usefulness of integrating limestone waste powder and marble waste aggregate in improving the tensile strength of concrete, contributing to its overall robustness and longevity [26].

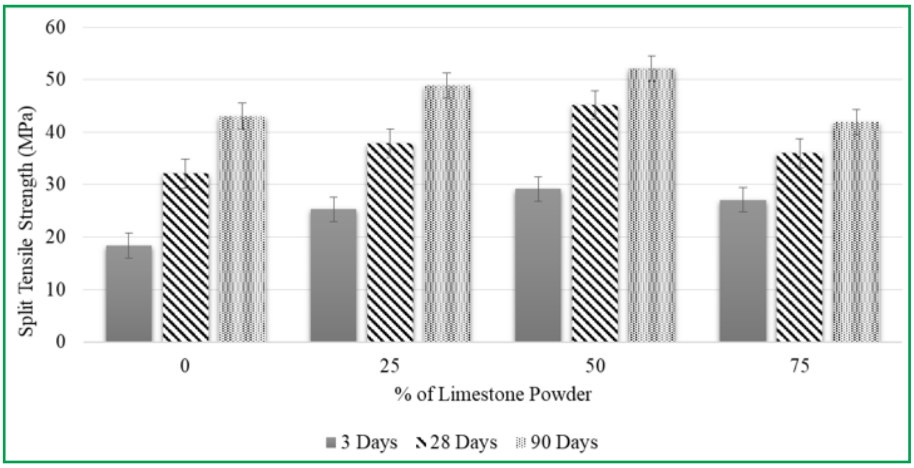

Figure 3. Variation in tensile strength of concrete with different percentages of limestone powder replacement [37]

Elastic modulus

As in Fig. 4, limestone powder replacement for cement paste or fine aggregate can give better packing density by filling the interstitial volumes between aggregate particles and improves the elastic modulus of concrete when LS is substituted for cementitious material [17] or fine particles [18] since LS is much harder compared with mortar. Li [17] and Nikbin [18] presented studies that indicated an enhanced elastic modulus with a greater LS content; limestone is stiffer than the cement matrix [17]. For example, it has been reported that the elastic modulus increases by 9% for a variation in LS content from 25% to 100% [18].

On the other side, cement substitution with LS has a dilution effect when LS replaces cement, and it would reduce the elastic modulus of concrete. Meddah et al. [16] observed that elastic modulus decreases as the fine LS is employed to replace cement up to 0% - 45%. The reductions were in the range of 5% - 33% and proportionated directly depending on LS content. Whereas the replacement of 15% cement with LS had a very negligible influence on the elastic modulus, much higher LS proportions than 15% resulted in an abrupt decrease in elastic modulus.

The size and composition of the particles in limestone powder affect how it affects the elastic modulus. The mechanical characteristics can be enhanced

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by smaller particle sizes and ideal content levels, while the elastic modulus is usually decreased by high replacement levels [38].

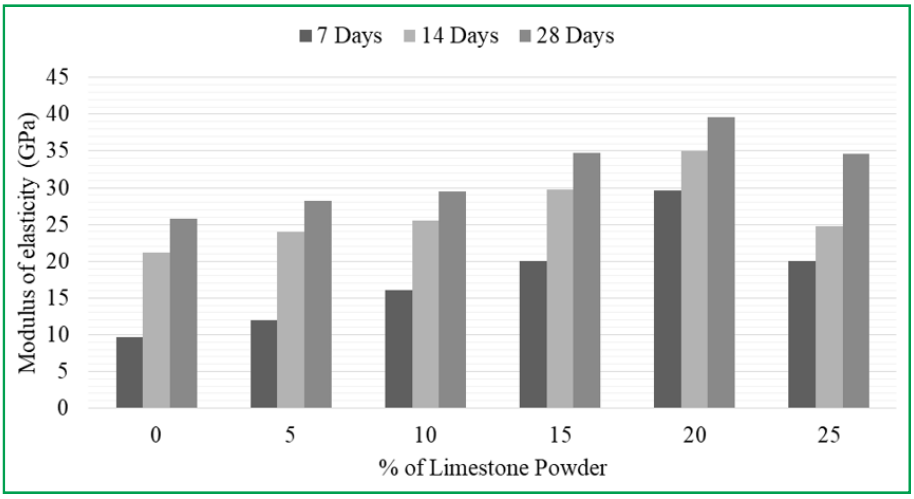

Figure 4. Modulus of elasticity using Limestone Powder [39]

Conclusions

This paper has examined the effects of limestone powder (LS) on the mechanical properties of concrete, including compressive, tensile, and flexural strengths, as well as the modulus of elasticity, with a focus on its sustainability implications.

The inclusion of fine LS particles enhances concrete's compressive strength by acting as a filler, reducing porosity, and providing nucleation sites for hydration products. However, excessive LS content can lead to a dilution effect, reducing strength. Similarly, LS improves tensile and flexural strengths by enhancing the interfacial transition zone and densifying the concrete matrix, though these benefits are also dosage-dependent. The modulus of elasticity is improved by LS's ability to optimize the microstructure and packing density, although excess LS may weaken the stiffness of the concrete.

Overall, LS contributes to improved mechanical performance when optimally dosed, with its eco-friendly characteristics offering a sustainable alternative for the construction industry. Proper dosage optimization is essential to balance the performance benefits and mitigate potential drawbacks, aligning with global efforts toward environmentally sustainable construction practices.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Md. Saniul Haque Mahi: writing- original draft preparation, resources. **Tanjun Ashravi Ridoy: c**onceptualization, supervision. **Md. Faiag Ahmed Nibir:** visualization. **Mohummad Shopon Sheikh:** formal analysis.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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