# THE EFFECTS OF LIMESTONE POWDER PARTICLE SIZE ON THE MECHANICAL PROPERTIES AND THE LIFE CYCLE ASSESSMENT OF PRECAST/PRESTRESSED CONCRETE

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**Abstract**: The major environmental impact of concrete comes from $CO_2$ emissions during cement production. The main goal of this research was to develop an optimized cement replacement in order to reduce energy consumption and $CO_2$ emissions. This was tested by incorporating limestone powder in concrete to meet construction specifications. This study utilized limestone powders with different particle sizes that replaced a part of Portland cement in different replacement levels to produce precast/prestressed concrete. Due to the dilution effect associated with partially replacing cement, there is a reduction in the physical properties of concrete. Conducting a life cycle assessment permitted optimization of the concrete in a way that minimized environmental impact with a minimal reduction in concrete strength. Test results showed that concretes with higher limestone powder content minimized the percentage lost in strength.

**Keywords: Limestone powder, Fineness, Life Cycle Assessment, Particle Size, Cement Replacement.**

## 1. INTRODUCTION

Concrete is one of the most widely used construction materials and its production impacts the environment in a number of ways. The acquisition and quarrying of large quantities of raw materials and aggregates depletes natural resources in the effort to meet the demand for concrete. Most of the energy and resources are consumed in the cement manufacturing process when a large rotary kiln is fueled by pulverized coal at 1450 degrees Celsius (Neville, 2011). Due primarily to calcination of the limestone, approximately 1.6 metric tons of raw materials are required to make 1 metric ton of cement; which is released as $CO_2$ (Nisbet, Marceau, & VanGeem, 2002). The manufacturing of cement is not very efficient, and roughly 40% of raw materials are lost in the production process. As the focus on sustainable construction is increasing in North America, replacing a portion of the ordinary Portland cement (OPC) with pozzolanic, or environmentally friendly filler materials, can be used to reduce the effects on the environment. By optimizing the mixture design in precast/prestressed concrete, positive effects on the life cycle environmental impact of concrete can be achieved (Proske, Hainer, Rezvani, & Graubner, 2014). The use of fly ash has been a proven replacement for cement. But as the use of natural gas for power generation gains popularity, the availability of fly ash is diminished because less coal is burned at power plants. Power generation from coal as fuel has been reduced by 9% in the United States from 2011 to 2015 (U.S. Energy Information Administration, 2016). Only in recent years have U.S. standards incorporated the use of inter-ground calcium carbonate ($CaCO_3$), or limestone, in ASTM standards and specifications for Portland cement. The performance of these limestone blended cements with ASTM C150 cements has recently been documented in a study (Hossack, Thomas, Barcelo, Blair, & & Delagrave, 2014). Even with ASTM standards allowing the use of Portland limestone cements, the manufacture of these cements is limited and not widely available in the United States. The introduction of limestone to concrete can be done like other pozzolanic materials by incorporating the limestone directly with the mixing design. This is an alternative to inter-grounding the limestone with the cement, and the limestone can then be mixed with the concrete while batching. By replacing part of the cement with limestone, it will provide an additional surface for precipitation of hydration, while also decreasing the amount of water needed to keep the concrete workable (Bonavetti, Donza, Menendez, Cabrera, & Irassar, 2003). Replacing cement with limestone when batching precast/prestressed concrete means the limestone and cement are manufactured separately and that their physical properties are different. The particle size, surface area, or distribution of the limestone may differ and, therefore, needs to be controlled. By implementing limestone powder as a replacement for cement, the environmental effect can be reduced. The environmental effects of replacing cement with limestone powder will differ based on the particle size used because finer limestone powder requires additional milling. Using limestone powder with a particle distribution of about 8 μm, generates approximately 24.5 kilograms of $CO_2$ per ton produced, whereas a finer particle size of about 4.5 μm generates about 90.7 kilograms of $CO_2$ per ton. (HuberCrete, 2015). That is only 3.4% to 12.5% of the $CO_2$ emissions compared to manufacturing a ton of cement, making it very sustainable.

To investigate how these characteristics affect the performance of the physical properties on concrete and its environmental impacts, different particle sizes of limestone powder are utilized. The level of replacement of cement are also a driving factor that affects the physical properties and the life cycle assessment of the resulting concrete.

### 1.1 Research Significance

The objective of this study was to experimentally analyze the effect that $CaCO_3$, or limestone powder, has on the fresh and hardened properties, based on the level of replacement of cement and the particle size used in the concrete mix designs. The purpose of this study was to develop information, specifically concerning $CaCO_3$ and the effects it has on the mechanical properties. This will enable the concrete industry to utilize $CaCO_3$ as a cement replacement to offset some of the environmental effects that are associated with cement manufacturing. Separate grinding of the limestone and clinker provides greater opportunity to optimize the particle size distribution, and to ascertain what levels of $CaCO_3$ and particle size used are advantageous for the physical properties and environmental effects.

## 2. EXPERIMENTAL PROCEDURES

### 2.1 Materials

In this study, Type I OPC (meeting ASTM C150 specifications) was used and replaced partially with Limestone powders that differ in particle size. The percentages of limestone replacement were 10%, 20%, and 30% by weight of the cement. The particle sizes were of 4.5 μm, 8 μm, and 15 μm limestone powder and a specific gravity of 2.7. The concrete mixture consisted of natural river gravel with specific gravity of 2.57, and river sand with fineness modulus of 2.68 and a specific gravity 2.61. The binder to water ratio of 0.40 was maintained in all batches and was calculated from the total amount of cement and limestone used.

### 2.2 Mixture Proportions

In each series, 15 specimens of 3" x 6" cylinders were produced. Three different cement intervals and different particle sizes of limestone were introduced (4.5 μm, 8 μm, and 15 μm). The mixture design is shown in Table 1. The concrete was mixed in accordance to ASTM C192, and the limestone powder was added to the drum mixer before adding the cement. Once the concrete has been mixed, the fresh concrete was tested for concrete temperature, workability, density, and air content. The concrete mixtures were then cast into 3" x 6" cylinder molds that were rodded to create uniform specimens for testing.

Table 1 Mix design of concrete with different limestone finesse

| Mix Design (kg/m$^3$) | Control | α -10 | β-10 | γ-10 | α-20 | β-20 | γ-20 | α-30 | β-30 | γ-30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Cement (kg/m$^3$) | 348 | 313 | 313 | 313 | 278 | 278 | 278 | 244 | 244 | 244 |
| Limestone Powder (kg/m$^3$) | 0 | 35 | 35 | 35 | 70 | 70 | 70 | 104 | 104 | 104 |
| Water (kg/m$^3$) | 139 | 139 | 139 | 139 | 139 | 139 | 139 | 139 | 139 | 139 |
| River Gravel (kg/m$^3$) | 1018 | 1018 | 1018 | 1018 | 1018 | 1018 | 1018 | 1018 | 1018 | 1018 |
| River Sand (kg/m$^3$) | 715 | 715 | 715 | 715 | 715 | 715 | 715 | 715 | 715 | 715 |
| W/B | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 |

*α - 4.5 μm *β - 8 μm *γ - 15 μm

## 3. RESULTS

### 3.1 Fresh Concrete Properties

Table 2 Fresh properties of concrete with different limestone finesse

| Batch Data | Control | α-10 | β-10 | γ-10 | α-20 | β-20 | γ-20 | α-30 | β-30 | γ-30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Concrete Temp. (°C) | 25.8 | 25.0 | 24.8 | 25.0 | 24.8 | 25.7 | 25.7 | 25.0 | 24.8 | 25.0 |
| Slump (cm) | 10.2 | 6.4 | 8.9 | 8.3 | 19.1 | 17.8 | 8.3 | 17.8 | 7.6 | 15.2 |
| Density (kg/m$^3$) | 2360.5 | 2361.8 | 2361.8 | 2356.6 | 2302.2 | 2309.9 | 2361.8 | 2325.2 | 2325.2 | 2325.2 |
| Air Content (%) | 2.40% | 2.20% | 2.30% | 2.20% | 2.10% | 2.25% | 2.20% | 2.25% | 2.10% | 2.00% |

*α - 4.5 μm *β - 8 μm *γ - 15 μm

The workability of the concrete in the fresh state was measured by conducting a slump test. The results for slump slightly increased as a result of limestone powder present in the concrete. Table 2 presents the density of the fresh limestone powder concrete that affects the material's elastic modulus and compressive strength. The decrease in density depends upon the difference in the specific gravity of cement and limestone powder. Replacing the cement with limestone powder will affect the density, and since the density affects the compressive strength of concrete, it will result in lower strength (Neville, 2011). The air content of fresh concrete containing limestone powder is considered to be important due to the relation it has with the durability and porosity. Table 2 shows the test results for air content that has not been modified with any air entraining admixtures. The air content decreased slightly with higher levels of limestone powder present in the concrete. This indicated that the presence of limestone powder in concrete has positive effects on the durability and porosity.

## 3.2 Hardened Concrete Properties

Table 3 Average Compressive strength of concrete with different limestone finesse

| Mix Design (MPa) | 1 Day | 7 Day | 14 Day | 28 Day | 90 Day | 28 Day Tensile |
|---|---|---|---|---|---|---|
| Control | 21.0 | 39.5 | 45.2 | 45.6 | 52.0 | 6.1 |
| α-10 | 18.5 | 33.2 | 37.2 | 39.2 | 44.3 | 5.6 |
| β-10 | 18.5 | 33.6 | 37.0 | 40.8 | 43.4 | 5.6 |
| γ-10 | 18.4 | 35.2 | 39.1 | 40.1 | 45.0 | 5.4 |
| α-20 | 14.6 | 29.3 | 33.2 | 37.6 | 39.6 | 4.8 |
| β-20 | 13.8 | 31.6 | 34.9 | 37.1 | 41.4 | 5.0 |
| γ-20 | 17.9 | 32.1 | 34.4 | 38.2 | 42.0 | 4.8 |
| α-30 | 13.3 | 28.2 | 31.5 | 36.0 | 38.4 | 4.3 |
| β-30 | 12.7 | 29.7 | 33.2 | 37.0 | 39.3 | 4.6 |
| γ-30 | 11.9 | 29.9 | 32.3 | 35.8 | 39.3 | 4.5 |

### 3.2.1 Compressive Strength

The compressive strength of concrete, commonly considered to be its most important characteristic (especially when limestone powder is used to replace cement because it adversely affects the compressive strength), also gave good overall of the quality of the concrete and the structure of the hydrated cement paste. Table 3 shows the calculated average MPa from 3 specimens at 1 day, 7 days, 14 days, 28 days and 90 days.

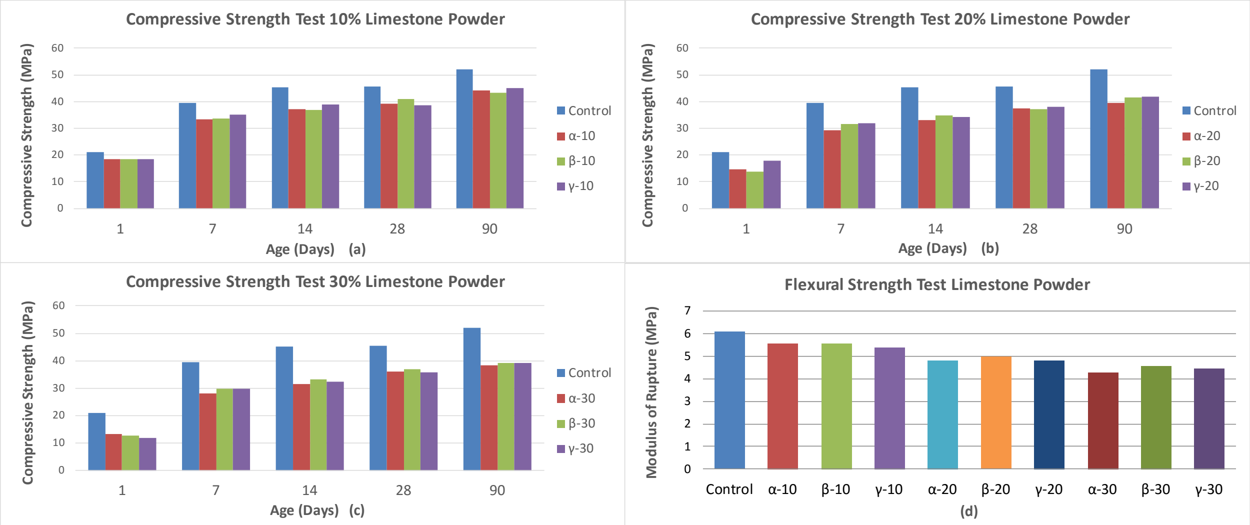

Fig. 1 Effects of Limestone Powder on Compressive Strength and Flexural Strength.

Figure 1.a illustrates the test results of the compressive strength of concrete with a 10% replacement limestone powder compared to the control that does not contain limestone powder. As expected, the replacement of the limestone adversely affected the compressive strength. A 10% replacement of cement on average reduced compressive strength

by 13% at 28 days and 15% at 90 days, compared to the control. Based on Figure 1.a, the particle size of the limestone powder does not have much of an effect on the concrete strength ranging from 39.2 MPa to 40.8 MPa at 28 days and 43.4 MPa to 44.3 MPa at 90 days. A 20% replacement of cement in Figure 1.b reduced the compressive strength even more with an average of 19% at 28 days and 21% at 90 days. The results follow the same pattern as a 10% replacement, demonstrating that the particle size of the limestone powder had little effect on concrete strength ranging from 37.1 MPa to 38.2 MPa at 28 days and 39.6 MPa to 42.0 MPa at 90 days. Figure 1.c illustrates the test results of a 30% replacement limestone powder compared to the control. There was an average loss of compressive strength of 21% at 28 days, and 25% at 90 days. Particle size of the limestone powder still had little effect on strength, even at a larger volume of limestone powder in the concrete, ranging from 35.8 MPa to 37.0 MPa at 28 days, and 38.4 MPa to 39.3 MPa at 90 days.

### 3.2.2 Flexural Strength

The flexural strength of concrete was tested using the third-point loading test method in accordance with ASTM C78 standard. The modulus of rupture for concrete beams was calculated at an aging period of 28 days. The flexural strength in Figure 1.d and Table 3 illustrates how different levels and particle size of limestone powder in concrete affects the flexural strength of concrete. As expected, replacement of the limestone adversely affects the flexural strength. A 10% replacement of cement reduced the average flexural strength by 10%, at a 20% replacement the reduction of strength was 20%, and a 27% reduction was observed at a 30% replacement. As in the case of compressive strength, the particle size of the limestone powder did not have a significant effect on the flexural strength.

### 3.3 Statistical Significance

Data collected on the effect of the particle size of limestone produced with compressive strength at 28 days and 90 days were assessed for statistical significance using analysis of variance (ANOVA). Analysis of variance is used to substantiate whether the measured variation was statistically significant. This inferential statistical method apportions the total variation in the results into that caused by the random variation and that caused by each factor. A conventional level of significance 0.05 was used for the analysis. This approach can test the hypothesis of whether particle size of limestone affects the concrete strength. Table 4 and 5 illustrated the analysis of the effect particle size and replacement percentage have on compressive strength.

Table 4 Analysis of variance of compressive strength at 28 days

| *Source of Variation* | *Sum of Squares* | *Degrees of freedom* | *Mean Square* | *F-value* | *P-value* | *F-critical* |
|---|---|---|---|---|---|---|
| Particle Size | 200034.03 | 2 | 100017.02 | 2.85 | 0.08 | 3.55 |
| Replacement % | 1166198.52 | 2 | 583099.26 | 16.60 | 0.00 | 3.55 |
| Interaction | 256670.51 | 4 | 64167.63 | 1.83 | 0.17 | 2.93 |
| Error | 632259.91 | 18 | 35125.55 | | | |
| Total | 2255162.98 | 26 | | | | |

To test if the effect on compressive strength at 28 days is significant, the null hypothesis, $H_o$, is that the particle size does not affect the compressive strength of concrete. The alternative hypothesis, $H_1$, is that the particle size does affect the compressive strength of concrete. Table 4 represents the F-values, along with p-values for the ANOVA of the concrete strength, at 28 days. Since the rejection criteria of the F-value of 2.85 is not greater than 3.55, the null hypothesis was not rejected. Thus, the particle size does not significantly affect the compressive strength of concrete at a level of 0.05. Since $16.60 > 3.55$, the null hypothesis is rejected. Consequently, the replacement percentage of limestone does significantly affect compressive strength.

Table 5 Analysis of variance of compressive strength at 90 days

| *Source of Variation* | *Sum of Squares* | *Degrees of freedom* | *Mean Square* | *F-value* | *P-value* | *F-critical* |
|---|---|---|---|---|---|---|
| Particle Size | 160602.07 | 2.00 | 80301.04 | 1.94 | 0.17 | 3.55 |
| Replacement % | 2622096.30 | 2.00 | 1311048.15 | 31.62 | 0.00 | 3.55 |
| Interaction | 143406.59 | 4.00 | 35851.65 | 0.86 | 0.50 | 2.93 |
| Error | 746383.33 | 18.00 | 41465.74 | | | |
| Total | 3672488.30 | 26.00 | | | | |

Test results of the 90 day compressive strength were analyzed with similar hypotheses as before. Table 5 represents the F-values, along with p-values for the ANOVA of the concrete strength at 90 days, and results are the same as the 28 day test. Since the rejection criteria of the F-value of 1.94 is not greater than 3.55 the null hypothesis is not rejected. Thus, the particle size does not significantly affect the compressive strength of concrete at a level of 0.05. Since 31.62 > 3.55, the null hypothesis is rejected. Consequently, the replacement percentage of limestone does significantly affect compressive strength.

## 4. LIFE CYCLE ASSESSMENT OF LIMESTONE POWDER IN CONCRETE

Materials from the mix design and emission data in Table 6, are from the PCA report on the life cycle assessment of different mix designs (Nisbet, Marceau, & VanGeem, 2002). Data for the production of limestone powder emissions were attained from the manufacturer (HuberCrete, 2015). The environmental impact was assessed based on the carbon dioxide equivalents ($CO_2e$), found in the U.S. Environmental Protection Agency Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) in order to obtain the emission factors (Bare, Norri, Pennington, & McKone, 2012). There are several benefits of conducting a life cycles assessment (LCA), including the ability to evaluate the environmental affect materials and operations have in concrete production, identifying pollution shifts between operations, and providing benchmarks for improvement. This allows for comparison between limestone replacement levels and the different particle sizes and their associated environmental impacts. To accurately conduct a LCA, an inventory of all inputs and outputs are documented with a life cycle inventory (LCI). This study includes a LCI of the $CO_2e$ emissions in kg to only produce a m³ concrete. The transportation emissions are based on a round-trip haul distance of 100 km for the cement and limestone, and a distance of 50 km for aggregates to and from the quarry.

Table 6 $CO_2e$ Emission of a m³ of concrete with transportation and production operations

| $CO_2e$ kg/m³ | Control | α-10 | β-10 | γ-10 | α-20 | β-20 | γ-20 | α-30 | β-30 | γ-30 |
|---|---|---|---|---|---|---|---|---|---|---|
| Cement | 845.7 | 761.1 | 761.1 | 761.1 | 676.5 | 676.5 | 676.5 | 592.0 | 592.0 | 592.0 |
| Limestone Powder | 0.0 | 10.6 | 2.9 | 1.4 | 21.1 | 5.7 | 2.9 | 31.7 | 8.6 | 4.3 |
| Water | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| River Gravel | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 |
| River Sand | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 |
| Transportation | 29.6 | 29.6 | 29.6 | 29.6 | 29.6 | 29.6 | 29.6 | 29.6 | 29.6 | 29.6 |
| Production | 38.9 | 38.9 | 38.9 | 38.9 | 38.9 | 38.9 | 38.9 | 38.9 | 38.9 | 38.9 |
| Total $CO_2e$ kg/m³ | 927.8 | 853.8 | 846.1 | 844.7 | 779.8 | 764.4 | 761.6 | 705.8 | 682.7 | 678.4 |
| $CO_2e$ Reductions | 0.0% | 8.0% | 8.8% | 9.0% | 16.0% | 17.6% | 17.9% | 23.9% | 26.4% | 26.9% |

*α - 4.5 μm *β - 8 μm *γ - 15 μm

Table 6 illustrates the $CO_2e$ of environmental impact for each material component, as well as for the transportation and production operations. The table clearly indicates the high degree of environmental impact from cement manufacturing in concrete production. Based on the control mix design, the manufacturing of cement accounts for 91% of the $CO_2e$ emissions. The main source of the emission is the operation of the kiln where $CO_2$ emissions are very high due to the calcination process, in which $CaCO_3$ is broken down to release $CO_2$.

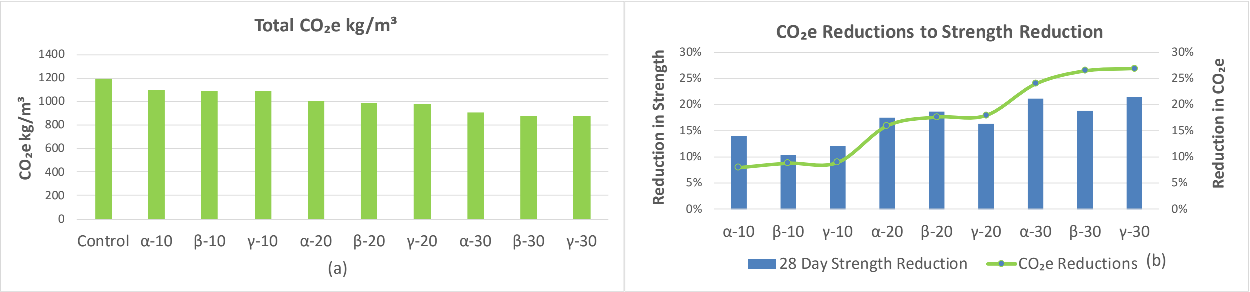

Fig. 2 $CO_2e$ Emission of Concrete Mix Designs

Figure 2.a shows the direct relation $CO_2e$ emission has in the replacement of cement with limestone powder. As the levels of replacement increase and the particle size of the limestone powder increases, the $CO_2e$ emissions of the mix designs decrease. Figure 7 indicates that for every 10% of cement that is replaced with limestone powder, the $CO_2e$ emissions decreased by 8% to 9%, depending on the particle size.

Higher levels of limestone powder replacement, however, adversely affect the compressive strength of concrete. Figure 2.b compares the benefits of the reduction in $CO_2e$ emissions and the adverse effects on the compressive strength. Figure 2.b also indicates at what level of percentage replacement the benefits of $CO_2e$ emissions are greater than loss of strength. At a 10% replacement of cement, the compressive strength was reduced by an average of 13% at 28 days, and $CO_2e$ emissions by 9.5%. With the loss of strength exceeding the emissions, this percentage of replacement is not very efficient. A 20% replacement of cement has an average of a 17% reduction in compressive strength at 28 days, while $CO_2e$ emissions is reduced by 17.2%. This indicates that at a 20% replacement level of cement, the benefits of the reduction of $CO_2e$ emissions from using limestone powders in concrete starts to surpass the loss in strength. At a 30% replacement, the reduction of $CO_2e$ emissions are greater than the loss of compressive strength, with an average 5.7%, making it the most effective level of cement because the environmental benefits outweigh the reduction of the compressive strength.

## 5. CONCLUSIONS

This study was conducted to evaluate the effects high volume limestone powder with different particle sizes and levels of cement replacement have on the characteristics of concrete when blended during batching. Results from this experiment indicate that introducing limestone powder in high volumes has positive effects on concrete and the environment. Based on the established parameters, concentrations of limestone powders at higher levels are more effective. However, the use of limestone powder as a cement replacement adversely affects the compressive strength.

- The use of limestone as cement replacement in concrete has little effect on the fresh properties.
- The level of cement replaced with limestone does affect the compressive strength negatively as levels increase. But at higher levels of limestone powder in concrete, the percentage of strength loss is less significant.
- The particle size of limestone used has little or no effect on the compressive strength of concrete at all levels of replacement that were conducted in this study.
- The effectiveness of limestone powder in concrete increase at higher levels of cement replacement. This is mostly likely due to effective particle packing and efficient particle distribution of the limestone powder.
- The replacement of cement with limestone powder significantly reduces emissions. This reduction in emissions is directly related to the level of replacement.
- The loss of compressive strength at low level replacement is greater than the benefits of emission reductions. But at higher replacement levels, the benefits of emissions reductions outweigh the loss in compressive strength.

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