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Effect of Acid Rain on Physical and Mechanical Properties of Concrete Containing Micro-Silica and Limestone Powder

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Abstract

Concrete is among the widely used materials in all industries and mineral and civil activities worldwide, highlighting its significance. Most natural and non-natural phenomena can influence the concrete's physical and mechanical properties, causing many irreparable damages. Acid rain is a natural inevitable phenomenon, particularly in industrial zones with high pollution percentages. This work investigates the effect of acid rain on the concrete specimens containing micro-silica and limestone powder. To this end, the concrete specimens are divided into six groups. Throughout this paper, CN represents the concrete without micro-silica and limestone powder under no-rain conditions, CO is the concrete without micro-silica and limestone powder under normal rain conditions, CA is the concrete without micro-silica and limestone powder under acid rain conditions, CMLN is the concrete containing micro-silica and limestone powder under no-rain conditions, CMLO is the concrete containing micro-silica and limestone powder under normal rain conditions, and CMLA shows the concrete containing micro-silica and limestone powder under acid rain conditions. The measured physical properties are the effective porosity, dry density, water absorption, and velocity of longitudinal waves. The mechanical properties including the Brazilian tensile strength, uniaxial compressive strength, triaxial compressive strength, cohesion, and internal friction angle are also measured. For the samples of CN and CMLN, they are tested under no rainfall conditions, whereas the samples of CA and CMLA are tested after 20 cycles of acid rain (pH = 2). The samples of CO and CMLO are also tested after undergoing 20 normal rain cycles (urban water with pH = 7). In each test cycle, there is 1 hour of rain and 1 hour of no rain. The results obtained show that adding micro-silica and limestone powder improves its properties so that the decrease in the effective porosity, longitudinal wave velocity, dry unit weight, water absorption, Brazilian tensile strength, uniaxial compressive strength, cohesion, and internal friction angle of the specimens of CMLA is less than those for the specimens of CA.

1. Introduction

Most Materials have been improved a lot in the recent years, making them perform better in different areas. Concrete is one of the materials that has evolved with advances in technology. Concrete is a widely used material in the civil and mining projects. Simply speaking, concrete is a mixture of different percentages of water, cement, and fine- and coarse-grain aggregates. Due to the scientific and technological advances, some materials have partially replaced cement in concrete in order to respond to the market and environmental demands. For instance, from the environmental viewpoint, one of the benefits of replacing part of cement is the use of mineral wastes or tailings as alternative for the cement manufacturing processes, and from an economical viewpoint, it can also reduce the warehouse and storage costs. These materials are valuable for creating highly stable concrete or

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improving the intrinsic properties of concrete in acidic media where sulfate ions may attack it.

Either as atmospheric precipitations or underground flows, water may adversely affect surface or underground concrete structures such as buildings and equipment with a concrete body and maintenance wells with a concrete coating. Acid rains cause chemical reactions in the concrete structure by changing its pH (power of hydrogen). These reactions cause cracking, developing pores in the concrete, changing physical properties, and reducing concrete mechanical properties. This is why various experiments and numerous research works have been conducted to test how to produce a higher-quality concrete.

Acid rains are caused by air pollution. Sulfate (SO_4^{2-}) is among the pollutants found in contaminated atmospheres. These are mostly formed after combining hydrogen ions with sulfuric acid solutions. Acid rains cause rocks and concrete to dissolve and degrade [1-4].

Numerous studies have been conducted about the properties of concrete containing micro-silica or micro-silica and limestone powder. Some studies are reviewed below.

Binici et al. have replaced part of cement in concrete with marble and limestone powders. The aim was to use available marble and limestone mineral tailings, which are useful and efficient for the environment and the economy. The research work showed that concretes with limestone and marble powder had less water absorption and porosity than the control concrete. The most optimal compressive strength was observed for the concrete containing 10-12% limestone powder relative to cement [5].

Adel Mohammed et al. have studied the effect of limestone powder as a replacement for part of cement in concrete. According to their results, the concrete's compressive strength increased by increasing the limestone powder content. The concrete containing 15% limestone powder showed the highest compressive strength [6].

Ghalenoei et al. have investigated the effect of marble powder wastes and silica as partial cement substitutes on concrete durability and compressive strength. In this experimental study, the durability of 16 concrete mix designs containing marble powder (0, 5, 10, and 20 wt% relative to cement) and microsilica (0, 2.5, 5, and 10 wt% relative to cement) as partial cement substitutes were investigated. A constant water/cement material ratio of 0.45 was used. According to their results, the durability and strength of concrete containing marble powder decreased at replacement ratios larger than 10%. However, satisfactory results were obtained for the replacement ratios up to 10% marble powder. The replacement ratios of 5% and 10% micro-silica compensated for the reduced durability of concrete containing high marble powder contents while improving the durability properties of the specimens containing marble powder wastes [7].

Gong et al. have studied the effect of micro-silica and nano-silica on the mechanical properties of foam concrete. The compressive and flexural strengths of concrete containing 15% micro-silica increased by 22% and 24%, respectively, when compared to concrete that did not contain micro-silica. The compressive and flexural strengths of concrete containing 4% nano-silica increased by 33% and 30%, respectively, as compared to concrete without nano-silica [8].

Singniao et al. have investigated how partial replacement of Portland cement with micro-silica and limestone powder affect the UHPC (ultra-high performance concrete) properties. In these mixtures, part of cement was replaced with 10%, 15%, and 20% of micro-silica and 15% and 20% of limestone powder. For all mixtures, a constant water/cement ratio of 0.2 and a steel fibre content of 2 Vol.% were considered. The specimens were cured by water vapour for 3 days. Their results showed that micro-silica increased both the compressive and flexural strengths. Adding limestone powder, on the other hand, reduced the compressive and bending strengths [9].

Mansouri et al. have investigated the effect of ceramic waste powder (CWP), micro-silica (MS), and steel fibres (SF) on self-compacting mortar. CWP replaced 10% and 20% of cement, and MS replaced 1% and 5% of cement. Moreover, 0.5% and 1% SF were added relative to cement. According to their results, CWP reduced the mechanical properties of self-compacting mortar by about 20%, and increased its permeability by about 14%. In contrast, the micro-silica particles improved the mechanical properties of self-compacting mortar so that the compressive strength increased by about by 30% by adding MS [10].

Previous research works on the properties of concrete containing micro-silica and limestone powder have shown that this concrete has a less porosity and a higher tensile strength and uniaxial compressive strength than concrete without micro-silica and limestone powder.

There are studies on the effect of acidic media on the physical and mechanical properties of rocks such as those conducted by Singh et al. [11], Vazquez et al. [12], Gibeaux et al. [13], and

Hosseini and Fakhri [14]. According to the findings of these studies, acid rains degrade rocks.

The followings are the reviews of two studies on the effect of acidic media on the physical and mechanical properties of concretes:

Mahdikhani et al. [15] have investigated the effect of acid rain on the durability and mechanical properties of concrete containing nano-silica. According to their findings, in acidic media, the concrete specimens containing nano-silica had a higher compressive strength than those without nano-silica. The degradation of specimens accelerated by increasing the solution acidity, which resulted in an increased water absorption and porosity of the specimens.

Yang [16] has studied the changes in the concrete structure exposed to acid rains. According to their results, the cracks and pores in the concrete gradually increase due to sulfate ion attacks caused by acid rains.

According to the published works, few studies have investigated the effect of acid rain on the physical properties, Brazilian tensile strength, and uniaxial compressive strength of concrete containing micro-silica. In this research work, in addition to studying the effect of acid rain on the physical properties, Brazilian tensile strength, and uniaxial compression strength, the effect of acid rain on the triaxial compressive strength, cohesion, and internal friction angle is also investigated, which is one of the advantages of this work.

2. Materials

The materials used in this work were gravel and lime sand. Table 1 shows the composition of gravel and sand according to the XRF (X-ray fluorescence) analysis. The screen analysis revealed that gravel and sand used in this work met the requirements of the Iran's National Standard No. 302 [17].

Table 1. XRF analysis of sand and gravel samples.

Sample	Unit	Sio_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	CaO	MgO	SO_3	P_2O_5	MnO	TiO_2	L.O.I
Sand	%	49.6	12.2	7.6	2.7	3.3	13.1	2.1	< 0.1	0.2	0.2	1	7.7
Gravel	%	7.3	1.6	1	0.4	0.5	49.3	0.9	< 0.1	< 0.1	< 0.1	< 0.1	38.8

The final mix designs of concretes including the concrete without fibres, micro-silica, and limestone powder and concrete containing micro-silica and limestone powder were offered after evaluating several mix designs through trial and error. The mix designs are listed in Tables 2 and 3.

The physical and mechanical properties including the effective porosity, velocity of longitudinal waves, water absorption, unit weight, tensile strength, uniaxial compressive strength, triaxial compressive strength, cohesion, and internal friction angle were studied.

Table 2. Mix design of concrete without fibres, micro-silica, and limestone powder.

Content per 1 m3 concrete	Content per 1 m3 concrete
350	350
1150	1150
700	700
0.4	0.4
2.8	2.8

The specimens were prepared using the polyvinylchloride (PVC) pipes with an inner diameter of 59 mm. The mixture was poured into the mould and then removed after 24 h, and stored in the laboratory up to 28 days in saturated lime water [18]. The specimens were removed from lime water after 28 days and cut into the desired lengths by a cutter and prepared for the Brazilian and uniaxial compressive strength tests. Along with the cut, the uniaxial compressive specimens were also polished.

3. Effect of acid rain on rock properties

For the samples of CN and CMLN, they were tested under no rainfall conditions, whereas the samples of CA and CMLA were tested after 20 cycles of acid rain (pH = 2). The samples of CO and CMLO were also tested after undergoing 20 normal rain cycles (urban water with pH = 7). In each test cycle, there was 1 hour of rain and 1 hour of no rain. Figure 1 displays the acid rain simulator, which includes two water pumps, a pan holding acidic water (pH = 2) to simulate acid rain, tap water (pH = 7) to simulate normal rain, a tub for placing the specimens, water pipe supports, and adjustable nozzles that sprayed acid rain on the specimens in the tub. The water pH was constantly monitored by a pH-meter, and sulfuric acid was used to reach pH = 2. Two pumps were used in this system, one to transfer water from the pan to the nozzles, and the other to discharge the remaining water in the tub and transfer it to the pan and circulate water in a closed cycle.

Table 3. Mix design of concrete containing micro-silica and limestone powder.

Components	Content per 1 m3 concrete
Portland cement, type 2 (kg)	297.5
Sand (kg)	1150
Gravel (kg)	700
Water/cement ratio	0.4
Superplasticizer (kg)	2.8
Micro-silica (kg)	35

The physical properties including the effective porosity, dry unit weight, water absorption, and longitudinal wave velocity, as well as the mechanical properties including the Brazilian tensile strength, uniaxial compressive strength, and triaxial compressive strength were determined based on the ISRM (International Society for Rock Mechanics) standard.

3.1. Effective porosity

The dimensions of the specimens were precisely measured by callipers to calculate their volumes in order to determine the effective porosity. After that, the specimens were saturated in water for 1 h under a vacuum pressure of less than 800 Pa, and the saturated mass was calculated. The specimens were then placed in a 105 °C oven for 6-7 h before being measured. Equation 1 was used to calculate the effective porosity [19].

$$n(e) = \frac{V_{ve}}{V} \times 100 \qquad (1)$$

where:

V_{ve}: Volume of interconnected voids, V: Total volume

V_{ve} = (Saturated mass-dry mass)/ρ_{water}

For each case, five specimens were tested in order to determine the effective porosity. The mean results for the concrete specimens are shown in Table 4.

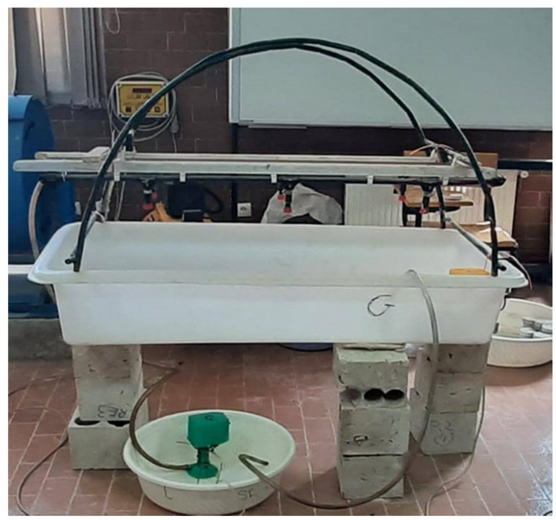

Figure 1. Acid rain system.

Table 4. Mean effective porosity of concrete specimens.

Specimen type	Effective porosity (%)
Concrete without micro-silica and limestone powder under no rain conditions	10.76
Concrete without micro-silica and limestone powder under normal rain conditions	11.08
Concrete without micro-silica and limestone powder under acid rain conditions	11.67
Concrete containing micro-silica and limestone powder under no rain conditions	7.04
Concrete containing micro-silica and limestone powder under normal rain conditions	7.24
Concrete containing micro-silica and limestone powder under acid rain conditions	7.73

3.2. Longitudinal wave velocity

In order to measure the longitudinal wave velocity, the transducers were placed on the designated locations, and the transmitter was pushed on the specimen with a pressure equivalent to 10 N/cm^2, and then the wave passage time was recorded [20]. The wave motion distance, the centre-to-centre distance of transducers, was also measured. In order to obtain the lost time between the specimen and the transducers, the transducers were placed on each other, and after that the displayed time was deducted from the recorded times. The longitudinal wave velocity in the specimens was calculated using Equation 2 [20].

$$V_P = \frac{L}{t} \times 1000 \qquad (2)$$

where:

L: Sample length (mm), t: Wave passage time (μs)

For each case, five specimens were tested in order to determine the longitudinal wave velocity. Table 5 shows the mean results for the concrete specimens.

Table 5. Mean longitudinal wave velocity in concrete specimens.

Specimen type	PV (m/s)
Concrete without micro-silica and limestone powder under no rain conditions	4097.1
Concrete without micro-silica and limestone powder under normal rain conditions	4060.6
Concrete without micro-silica and limestone powder under acid rain conditions	3991.5
Concrete containing micro-silica and limestone powder under no rain conditions	4159.7
Concrete containing micro-silica and limestone powder under normal rain conditions	4135.4
Concrete containing micro-silica and limestone powder under acid rain conditions	4093.9

3.3. Dry unit weight and water absorption

The dry unit weight and the water absorption were calculated using Equations. 3 and 4, respectively [19].

$$\gamma_{dry} = \frac{W_S}{V} \quad (3)$$

$$WA = \frac{B-A}{A} \text{x}100 \quad (4)$$

where γ_{dry} represents the dry unit weight, W_s is the dry weight, V is the total volume, B is the mass of specimen immersed in water after 48 h, A is the dry mass, and WA shows water absorption. Tables 6 and 7 represent the mean results for the concrete specimens.

Table 6. Mean dry unit weight of concrete specimens.

Specimen type	γ_dry (kN/m3)
Concrete without micro-silica and limestone powder under no rain conditions	21.68
Concrete without micro-silica and limestone powder under normal rain conditions	21.59
Concrete without micro-silica and limestone powder under acid rain conditions	21.45
Concrete containing micro-silica and limestone powder under no rain conditions	22.32
Concrete containing micro-silica and limestone powder under normal rain conditions	22.27
Concrete containing micro-silica and limestone powder under acid rain conditions	22.18

Table 7. Mean water absorption of concrete specimens.

Specimen type	WA (%)
Concrete without micro-silica and limestone powder under no rain conditions	4.75
Concrete without micro-silica and limestone powder under normal rain conditions	4.99
Concrete without micro-silica and limestone powder under acid rain conditions	5.30
Concrete containing micro-silica and limestone powder under no rain conditions	3.09
Concrete containing micro-silica and limestone powder under normal rain conditions	3.19
Concrete containing micro-silica and limestone powder under acid rain conditions	3.31

3.4. Tensile strength

The Brazilian test was performed in order to determine the Brazilian tensile strength of the specimens. The tensile strength was calculated using Equation 5 [21].

$$\sigma_t = 0.636\frac{P}{D.t} \quad (5)$$

where P represents the load at failure (N), D is the specimen diameter (mm), t is the specimen thickness (mm), and σ_t is the tensile strength (MPa). Table 8 shows the mean results for the concrete specimens. The Brazilian test on the concrete specimens is shown in Figure 2.

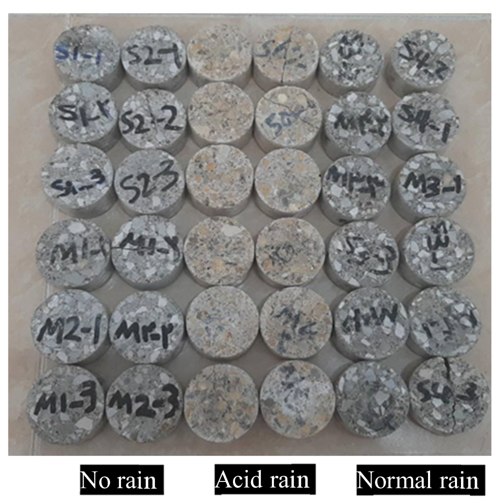

Figure 2. Colour changes by acid rain

Table 8. Mean Brazilian tensile strength of concrete specimens.

Specimen type	σ_t (MPa)
Concrete without micro-silica and limestone powder under no rain conditions	3.74
Concrete without micro-silica and limestone powder under normal rain conditions	3.57
Concrete without micro-silica and limestone powder under acid rain conditions	3.29
Concrete containing micro-silica and limestone powder under no rain conditions	5.11
Concrete containing micro-silica and limestone powder under normal rain conditions	4.99
Concrete containing micro-silica and limestone powder under acid rain conditions	4.78

3.5. Uniaxial compressive strength

The uniaxial compressive test was performed in order to determine the uniaxial compressive strength of the specimens [22]. Table 9 shows the mean results for the concrete specimens.

3.6. Triaxial compressive strength, cohesion, and internal friction angle

The triaxial compressive test was performed in order to determine the triaxial compressive strength, cohesion, and internal friction angle. The test instrument includes the four distinct sections of the Hook's test cell, axial load jack, confining pressure pump, and specimen removal jack. The tests were performed based on the ISRM standard [23] and under a confining pressure of 2.5 and 5 MPa. At each confining pressure, 5 tests were performed the on samples of each type of concrete. Table 10 presents the average results for the concrete specimens.

Figures 3 to 5 show the test results.

Table 9. Mean uniaxial compressive strength of concrete specimens.

Specimen type	σ_C (MPa)
Concrete without micro-silica and limestone powder under no rain conditions	27
Concrete without micro-silica and limestone powder under normal rain conditions	24.41
Concrete without micro-silica and limestone powder under acid rain conditions	21.17
Concrete containing micro-silica and limestone powder Under no rain conditions	35.43
Concrete containing micro-silica and limestone powder under normal rain conditions	33.87
Concrete containing micro-silica and limestone powder under acid rain conditions	31.51

Table 10. Mean triaxial compressive strength of concrete specimens.

Specimen type	Confining pressure (MPa)	Triaxial compressive strength (MPa)
Concrete without micro-silica and limestone powder under no rain conditions	2.5	49.67
Concrete without micro-silica and limestone powder under no rain conditions	5	60.79
Concrete without micro-silica and limestone powder under normal rain conditions	2.5	47.55
Concrete without micro-silica and limestone powder under normal rain conditions	5	55.67
Concrete without micro-silica and limestone powder under acid rain conditions	2.5	38.45
Concrete without micro-silica and limestone powder under acid rain conditions	5	49.12
Concrete containing micro-silica and limestone powder under no rain conditions	2.5	55.12
Concrete containing microsilica and limestone powder Under no rain conditions	5	69.37
Concrete containing micro-silica and limestone powder under normal rain conditions	2.5	53.43
Concrete containing micro-silica and limestone powder under normal rain conditions	5	66.57
Concrete containing micro-silica and limestone powder under acid rain conditions	2.5	49.63
Concrete containing micro-silica and limestone powder under acid rain conditions	5	61.15

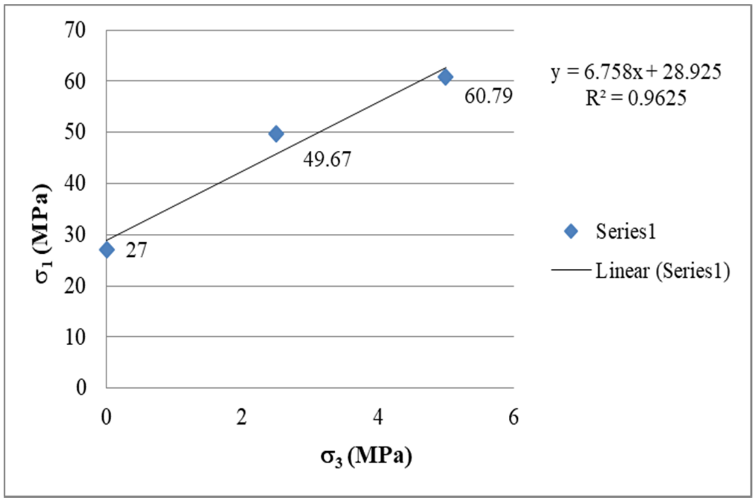

Figure 3. Failure envelope for concrete without micro-silica and limestone powder under no rain conditions.

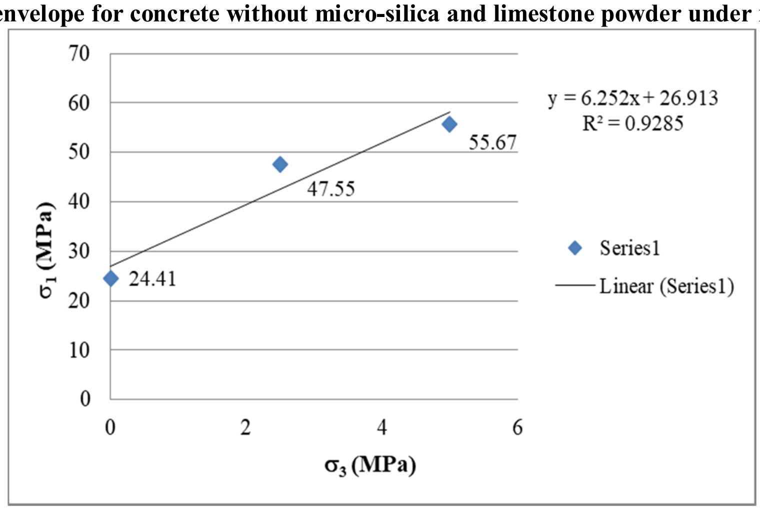

Figure 4. Failure envelope for concrete without micro-silica and limestone powder under normal rain conditions.

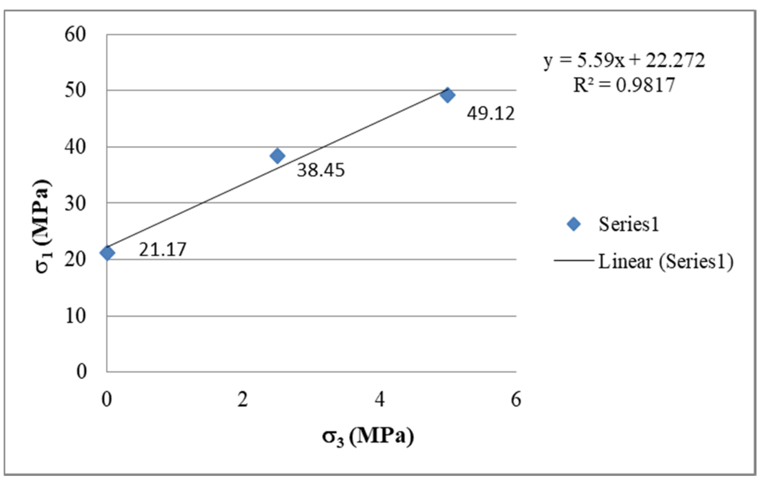

Figure 5. Failure envelope for concrete without micro-silica and limestone powder under acid rain conditions.

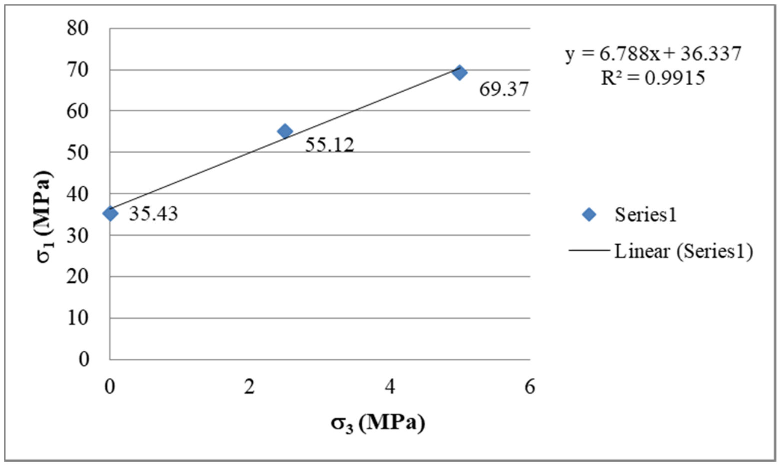

Figure 6. Failure envelope for concrete containing micro-silica and limestone powder under no rain conditions.

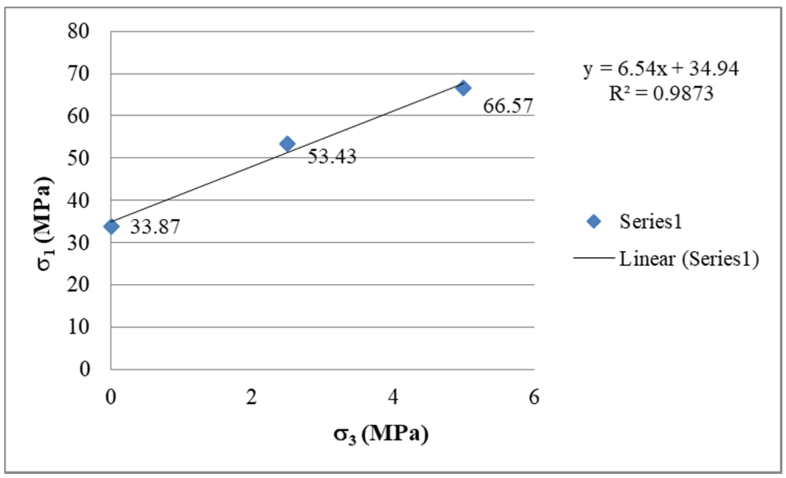

Figure 7. Failure envelope for concrete containing micro-silica and limestone powder under normal rain conditions.

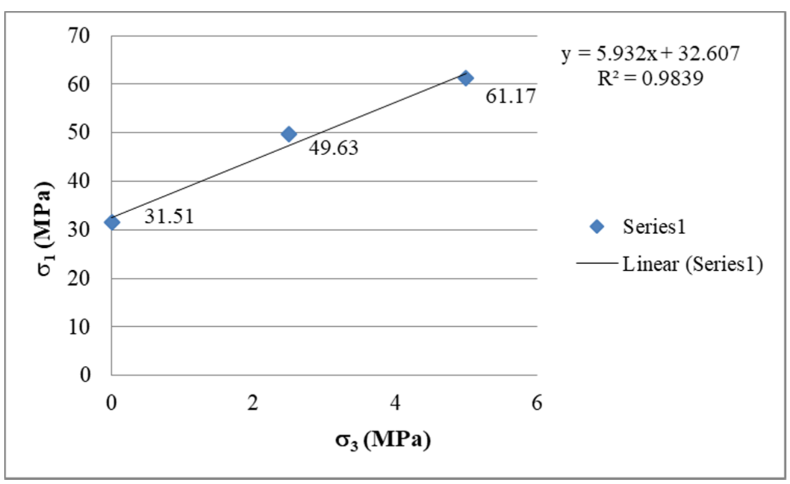

Figure 8. Failure envelope for concrete containing micro-silica and limestone powder under acid rain conditions.

The internal friction angle and cohesion of the concrete specimens were calculated using Equations. 6 and 7, respectively [24].

$$\emptyset = \sin^{-1}\frac{m-1}{m+1} \tag{6}$$

$$C = b\frac{1 - \sin\emptyset}{2\cos\emptyset} \quad (7)$$

where $\emptyset$ represents the internal friction angle (°), C is the cohesion (MPa), m is the axial stress-confining pressure curve slope, and b is the intercept of the axial stress-confining pressure curve. Table 11 shows the cohesion and internal friction angle of the concrete specimens.

Table 11. Cohesion and internal friction angle of concrete specimens.

Specimen type	C (MPa)	$\emptyset$ (°)
Concrete without micro-silica and limestone powder under no rain conditions	5.56	47.92
Concrete without micro-silica and limestone powder under normal rain conditions	5.38	46.40
Concrete without micro-silica and limestone powder under acid rain conditions	4.71	44.15
Concrete containing micro-silica and limestone powder under no rain conditions	6.97	48.01
Concrete containing micro-silica and limestone powder under normal rain conditions	6.83	47.29
Concrete containing micro-silica and limestone powder under acid rain conditions	6.69	45.36

4. Discussion

In order to analyse the results obtained, the concrete properties were depicted on the following diagrams. Figure 9 shows the effective porosity of the concrete specimens. On all diagrams, CN represents the concrete without micro-silica and limestone powder under no rain conditions, CO is the concrete without micro-silica and limestone powder under normal rain conditions, CA is the concrete without micro-silica and limestone powder under acid rain conditions, CMLN is the concrete containing micro-silica and limestone powder under no rain conditions, CMLO is the concrete containing micro-silica and limestone powder under normal rain conditions, and CMLA shows the concrete containing micro-silica and limestone powder under acid rain conditions.

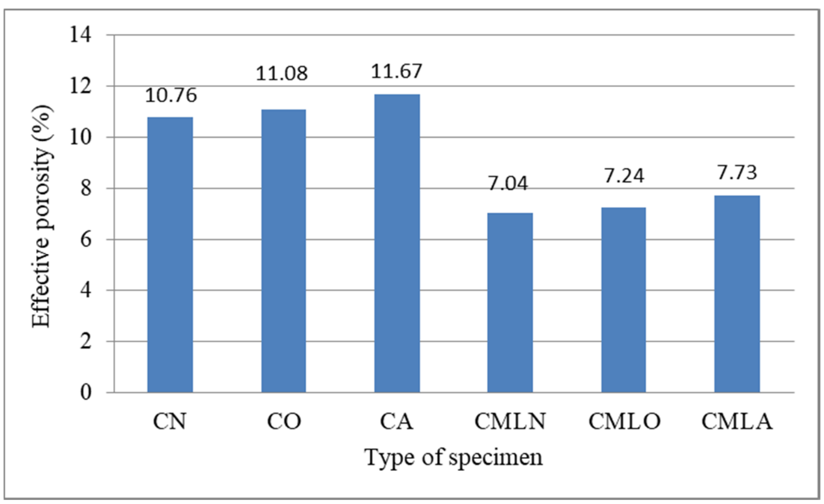

Figure 9. Effective porosity of concrete specimens.

Micro-silica and limestone powder fill the concrete pores, resulting in a lower effective porosity than concrete without micro-silica and limestone powder.

For this reason, the CMLN concrete specimens have a lower effective porosity than the CN concrete specimens. As a result, normal rain and acid rain have less of an effect on concrete the specimens containing micro-silica and limestone powder than on those that do not. Compared to no rain conditions, acid rain increased the effective porosity of concrete specimens containing micro-silica and limestone powder by 4.83%. Under acid rain, the effective porosity of the concrete specimens lacking micro-silica and limestone powder increased by 8.45% when compared to the same specimens under no rain conditions. These results are consistent with those reported by Mahdikhani et al. [15]. Figure 10 shows the longitudinal wave velocity of the concrete specimens. As shown in this figure, rain reduces the longitudinal wave velocity, which is consistent with the increased effective porosity.

According to the results obtained, acid rain has a greater effect on the longitudinal wave velocity in the specimens lacking micro-silica and limestone powder. Compared to no rain conditions, the acid rain lowered the velocity of longitudinal waves by 2.57% in the specimens without micro-silica and limestone powder, and compared to no acid rain conditions, acid rain reduced the velocity of longitudinal waves by 1.58% in the specimens containing micro-silica and limestone powder.

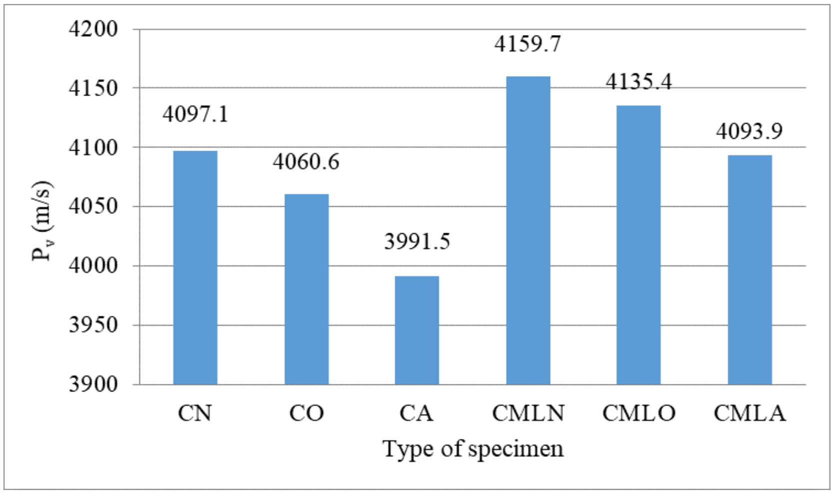

Figure 10. Longitudinal wave velocity in concrete specimens.

Figures 11 and 12, respectively, show the dry unit weight and water absorption of the concrete specimens. As shown, the dry unit weight decreases but water absorption increases by rain, which is consistent with the results of Mahdikhani et al. [15]. Compared to no rain conditions, acid rain reduced the density by 1.06% and increased water absorption by 15.97% in the specimens without micro-silica and limestone powder. In comparison to no rain conditions, acid rain reduced the density by 0.63% and increased water absorption by 7.12% in the specimens containing micro-silica and limestone powder.

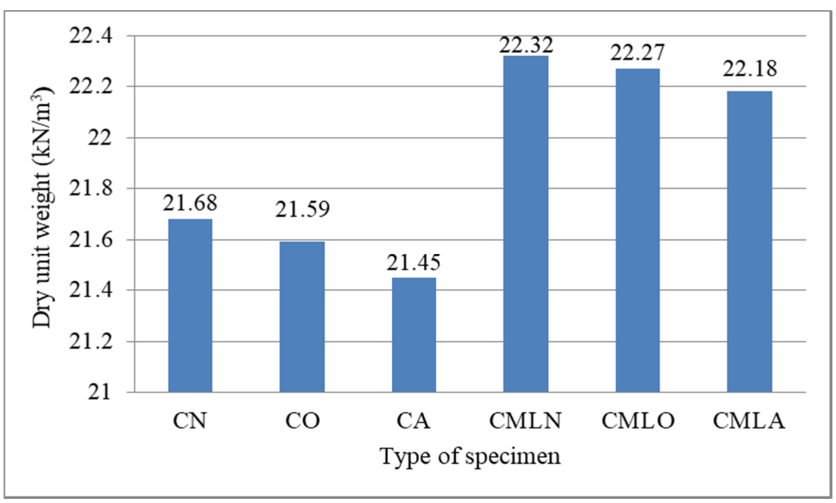

Figure 11. Dry unit weight of concrete specimens.

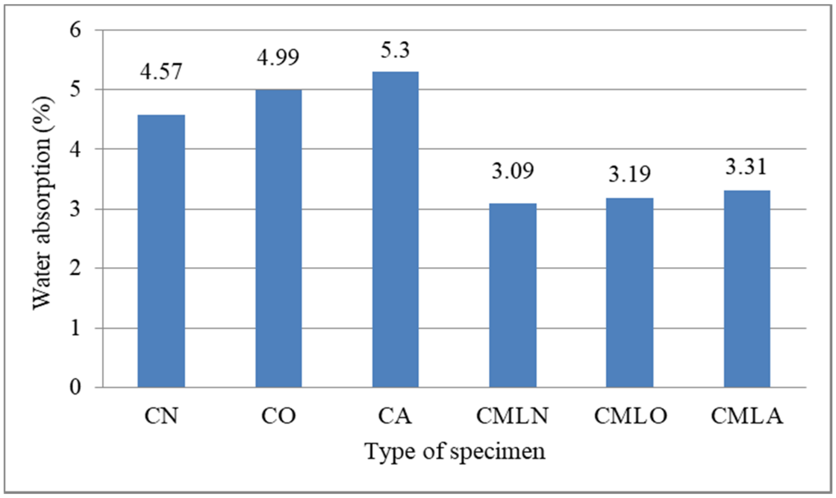

Figure 12. Water absorption of concrete specimens.

As illustrated, adding micro-silica and limestone powder decreases water absorption compared to the concrete specimens that do not include micro-silica and limestone powder. These changes are consistent with the effective porosity variations. These results are consistent with those reported by Hosseini and Fakhri in 2021 [14].

Figure 13 displays the Brazilian tensile strength of the concrete specimens. As shown in this figure, the Brazilian tensile strength increases by adding micro-silica and limestone powder.

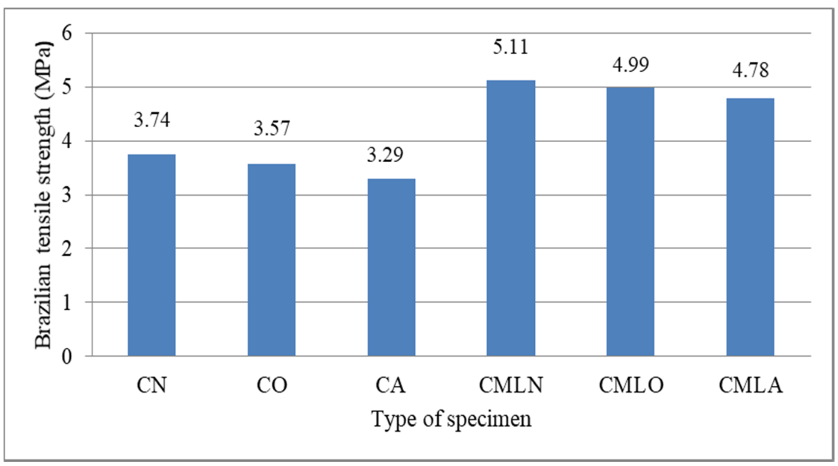

Figure 13. Brazilian tensile strength of concrete specimens.

The results obtained show that the Brazilian tensile strength of the CA samples decreased by 12.03% when compared to the CN samples, while the CMLA samples declined by 6.45% when compared to the CMLN samples.

Figure 14 shows the uniaxial and triaxial compressive strength of the concrete specimens at the confining pressures of 0 MPa, 2.5 MPa, and 5 MPa. As shown, CMLN has a higher triaxial compressive strength than CN. Thus in comparison to CN, the triaxial compressive strength of CMLN increases by 10.97% and 14.11% at the confining pressures of 2.5 MPa and 5 MPa, respectively. As shown in this figure, the uniaxial and triaxial compressive strength increase by adding micro-silica and limestone powder.

The results of the uniaxial compression test showed that the uniaxial compressive strength of the CA samples fell by 21.59% when compared to the CN samples, while the CMLA samples decreased by 11.06% when compared to the CMLN samples.

In comparison to CMLN, the triaxial compressive strength of CMLA at the confining pressures of 2.5 MPa and 5 MPa, respectively, decreased by 9.9% and 11.84%.

At the confining pressures of 2.5 MPa and 5 MPa, respectively, the triaxial compressive strength of CA droped by 22.5% and 19.19% compared to CN.

Figures 15 and 16 show the cohesion and internal friction angles of the concrete specimens.

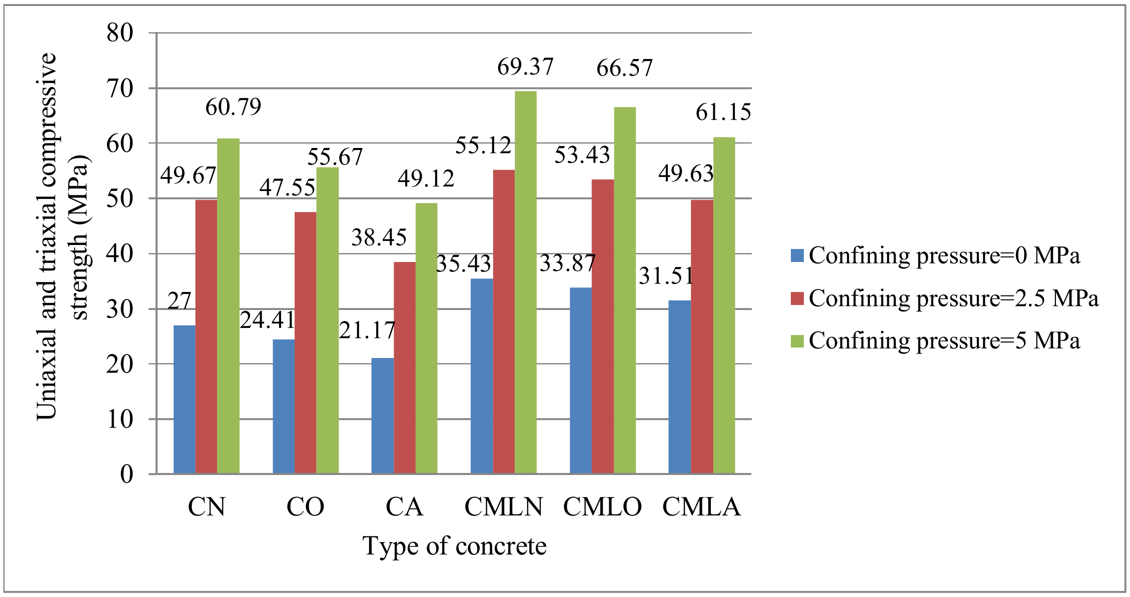

Figure 14. Uniaxial and triaxial compressive strength of concrete specimens at $\sigma_3 = 0$ MPa, $\sigma_3 = 2.5$ MPa, and $\sigma_3 = 5$ MPa.

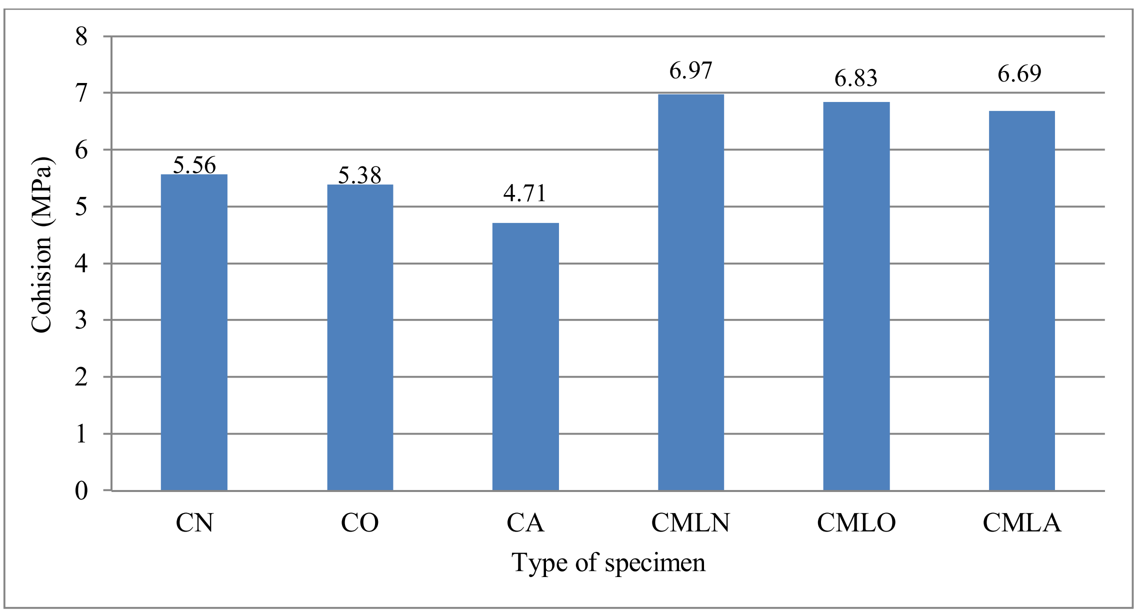

Figure 15. Cohesion of concrete specimens.

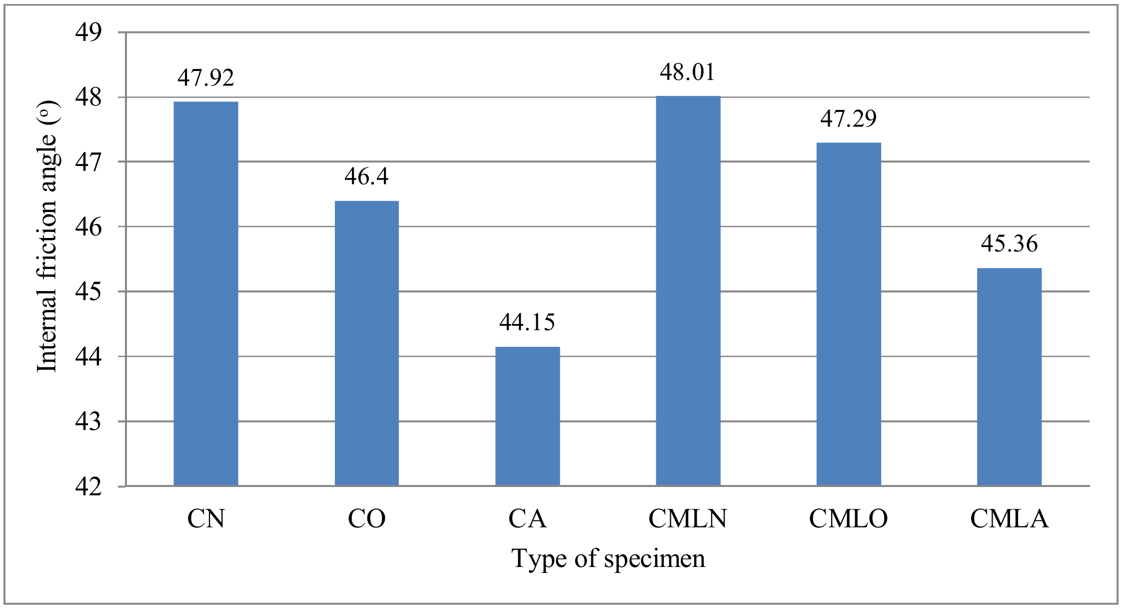

Figure 16. Internal friction angle of concrete specimens.

As seen, the cohesion and internal friction angles of CMLA were 4.01% and 5.52% lower than CMLN, respectively.

The cohesion and internal friction angle of the CA specimen fell by 15.29% and 7.87%, respectively, as compared to the CN specimen.

Generally speaking, adding micro-silica and limestone to concrete improves its properties compared to concrete, which contains no micro-silica and limestone powder.

The pozzolanic activity of micro-silica is mostly responsible for the improvement of the Brazilian tensile strength, uniaxial and triaxial compressive strength, cohesion, and internal friction angles of concrete specimens. As shown in Eqs. (8) and (9), in the presence of water, the micro-silica actively reacts with Ca(OH)2 liberated during cement hydration (pozzolanic reaction) and produces additional calcium silicate hydrate (CSH) [15].

Hydration reaction:	C_2S or $C_3S + H_2O$	$\longrightarrow$	Primary CSH + $Ca(OH)_2$	(8)
Pozzolanic reaction:	$Ca(OH)_2 + (SiO_2) + (H_2O)$	$\longrightarrow$	Secondary CSH	(9)

Since CSH is a major strength-contributing compound, the additional CSH increases the Brazilian tensile strength, uniaxial and triaxial compressive strength, and cohesion and internal friction angles of the specimens. Furthermore, the extra CSH reduces the porosity by filling capillary pores, resulting in the increased strength of concrete specimens.

5. Conclusions

In this work, the physical and mechanical properties of the concrete specimens were examined. The samples were divided into six groups (CN, CO, CA, CMLN, CMLO, and CMLA). The key findings could be summarized as follow:

- In comparison to CMLN, the effective porosity and longitudinal wave velocity in CMLA increased and decreased by 4.83% and 1.58%, respectively. The effective porosity and longitudinal wave velocity in CA increased and decreased by 8.45% and 2.57%, respectively, as compared to CN.
- In comparison to CMLN, the dry unit weight and water absorption of CMLA decreased and increased by 0.63% and 7.12%, respectively. The dry unit weight and water absorption of CA decreased and increased by 1.06% and 15.97%, respectively, as compared to CN.
- In comparison to CMLN and CN, the Brazilian tensile strength of CMLA and CA decreased by 6.45% and 12.03%, respectively. The uniaxial compressive strength of CMLA and CA

decreased by 11.06% and 21.59%, respectively, as compared to CMLN and CN.

- In comparison to CMLN and CN, the cohesion of CMLA and CA decreased by 4.01% and 15.29%, respectively. The internal friction angles of CMLA and CA decreased by 5.52% and 7.87%, respectively, as compared to CMLN and CN.

Along with the consuming mine wastes and tailings, adding micro-silica and limestone powder is essential from an environmental and economic standpoint. Furthermore, by adding micro-silica and limestone powder, the properties of the concrete are significantly improved, and the deterioration of concrete caused by acid rain is reduced.

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اثر باران اسیدی روی خواص فیزیکی و مکانیکی بتن حاوی میکروسیلیس و پودر سنگ آهک

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چکیده:

اهمیت بتن امروزه در تمامی صنایع و فعالیت های معدنی و عمرانی بر همگان آشکار است و از این رو یکی از پر مصرف ترین مصالح موجود در دنیا می‌باشد. خیلی از پدیده های طبیعی و غیر طبیعی می‌توانند بر ویژگی های فیزیکی و مکانیکی بتن تاثیرگذار باشند، به نحوی که منجر به بسیاری از آسیب ها و خسارات جبران ناپذیر شود. یکی از پدیده های طبیعی و اجتناب ناپذیر علی الخصوص در مناطق صنعتی با درصد آلودگی بالا باران اسیدی می‌باشد. در این پژوهش به بررسی تاثیر باران اسیدی بر نمونه بتن هایی که حاوی پودر سنگ آهک و میکروسیلیس هستند پرداخته می‌شود. نمونه ها به شش گروه تقسیم می شوند که شامل بتن بدون میکروسیلیس و پودر سنگ آهک در شرایط بدون باران (با علامت اختصاری CN)، بتن بدون میکروسیلیس و پودر سنگ آهک در شرایط باران معمولی (با علامت اختصاری CO)، بتن بدون میکرو سیلیس و پودر سنگ آهک در شرایط باران اسیدی (با علامت اختصاری CA)، بتن حاوی میکرو سیلیس و پودر سنگ آهک در شرایط بدون باران (با علامت اختصاری CMLN)، بتن حاوی میکرو سیلیس و پودر سنگ آهک در شرایط باران معمولی (با علامت اختصاری CMLO) و بتن حاوی میکرو سیلیس و پودر سنگ آهک در شرایط باران اسیدی (با علامت اختصاری CMLA) می شود. خواص فیزیکی مورد بررسی شامل تخلخل موثر، وزن مخصوص خشک، میزان جذب آب و سرعت امواج طولی و خواص مکانیکی شامل مقاومت کششی برزیلی، مقاومت فشاری تک محوری، سه محوری و چسبندگی و زاویه اصطکاک داخلی می‌شود. نمونه به سه گروه تقسیم می شوند. نمونه های گروه اول تحت شرایط عدم بارش، نمونه های دسته دوم بعد از ۲۰ سیکل بارندگی اسیدی (pH=۲) و نمونه های دسته سوم بعد از ۲۰ سیکل باران معمولی (آب شهری دارای pH=۷) تحت آزمایش قرار گرفتند. هر سیکل آزمایش شامل ۱ ساعت بارندگی و ۱ ساعت عدم بارش می‌شود. نتایج به‌دست‌آمده نشان می‌دهد که افزودن میکروسیلیس و پودر سنگ آهک باعث بهبود خواص آن در مقایسه با بتن بدون میکروسیلیس و پودر سنگ آهک می‌شود به طوری که تخلخل مؤثر، سرعت موج طولی، وزن مخصوص خشک، جذب آب، مقاومت کششی برزیلی، مقاومت فشاری تک محوری، چسبندگی و زاویه اصطکاک داخلی نمونه های CMLA کمتر از نمونه های CA کاهش می یابد.

کلمات کلیدی: باران اسیدی، بتن، میکروسیلیس، پودر سنگ آهک، خواص فیزیکی و مکانیکی.