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Durability of Steel-Reinforced Concrete Structures Under Effect of Climatic Temporality and Aggressive Agents (CO_2, SO_2) in Boca del Rio, Veracruz

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Abstract: The development of sustainable infrastructure is essential to address the challenges of climate change and reduce CO_2 emissions. The use of alternative materials, such as agro-industrial ashes and silica fume, emerges as a promising option to enhance the durability of concrete and diminish its environmental impact. These materials can partially replace conventional cement, contributing to the construction of more sustainable infrastructure without compromising performance, even under adverse environmental conditions. In this study, we present an analysis of the use of sugarcane bagasse ash (SBA) and silica fume (SF) as a 15% cement replacement. The behavior of these materials was investigated under coastal conditions, analyzing climatic variables and degrading gases such as CO_2, CH_4, and N_2O. Electrochemical techniques were employed to measure corrosion rate and potential, in addition to conducting carbonation and compressive strength tests. The mixtures with a 15% addition of SBA and SF showed improvements compared to conventional mixes. SBA reduced the corrosion rate by 25% and increased compressive strength by 12% after 150 days, while SF enhanced carbonation resistance by 20% and compressive strength by 25%. The incorporation of SBA and SF provides significant durability in coastal environments, contributing to the sustainability of infrastructure exposed to adverse weather conditions.

Keywords: infrastructure; alternative materials; corrosion; sugarcane bagasse ash; silica fume

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1. Introduction

Historically, infrastructure has been essential for human development, providing systems that drive both social well-being and economic growth. These systems range from the supply of potable water and wastewater management to the enhancement of connectivity, even in tourist and marginalized areas [1–3]. Traditionally, the concept of infrastructure encompasses all human activities that promote human capital and are fundamental in social sectors (education, health, culture, and finance) and economic sectors (energy, water supply, sewage, and transportation) [4]. However, conventional infrastructure construction has generated significant environmental impacts due to the extraction of materials and greenhouse gas emissions, particularly attributable to concrete. This material is responsible for approximately 8% to 9% of global anthropogenic greenhouse gas emissions [5].

In response to these environmental impacts, much research has focused on developing sustainable alternatives that reduce dependence on nonrenewable raw materials and lower the carbon footprint of concrete. Among the most studied options are fly ash [6–8] and silica fume derived from industrial processes [9,10], materials known for their high pozzolanic activity and their capacity to improve the strength and durability of concrete. Additionally, in recent years, the use of agro-industrial waste has been explored, such as biomass ash from bamboo leaves, palm trees, elephant grass, rice husks, olive waste, wheat straw, corn cobs, and sugar cane [5]. These materials can be used as a partial replacement for aggregates or as supplementary cementing additions, contributing to a reduction in cement content in concrete and, consequently, a decrease in carbon emissions associated with its production.

Given the concern over environmental contamination risk stemming from the accumulation of agro-industrial waste, its utilization through sustainable technologies can convert these wastes into valuable resources [11]. The implementation of sugarcane bagasse ash (SBA) and silica fume (SF) has proven to be an effective option for enhancing the quality of both the natural environments and built infrastructure. Agro-industrial wastes have a high potential for utilization due to their varied chemical composition [12,13], and multiple possibilities for their reuse as partial substitutes for hydraulic cement have been observed, positively impacting the strength and durability of concrete.

Of particular interest is SF, which stands out for its high pozzolanic activity and elevated silica content. This allows it to significantly improve the strength and durability of concrete, especially in reinforced concrete applications, where its structure of fine particles with sharp edges increases its reactivity with the hydration products of Portland cement, promoting a greater concentration of solids, enhancing mechanical properties, and reducing porosity in the concrete matrix [14,15]. These properties are beneficial for concrete in aggressive environments, where greater corrosion resistance is required.

Recent studies have incorporated SBA and SF into concrete mixes, demonstrating significant improvements in durability and compressive strength. For example, Abdalla et al. (2022) [16] observed that a 10% replacement SBA offered the highest strength compared to mixes with 20%, 30%, 40%, and 50%, as well as the control mix. Furthermore, this proportion showed better performance under high-temperature conditions. Similarly, Landa-Ruiz et al. (2021) [17] found that mixes with additions of 10% to 20% SBA and SF achieved up to 90% greater strength compared to control mixes. In addition to these findings, Farrant et al. (2022) [18] emphasized that using ash in proportions below 30% not only improves compressive strength but also increases permeability, a critical property for preventing sulfate attack in aggressive environments.

Although research demonstrates the benefits of using SBA and SF as cement substitutes in simple and reinforced concrete, further investigation is needed regarding their performance in aggressive environments, such as coastal zones. These regions present unique degradation conditions due to the presence of chlorides and sulfates, which pose particular challenges to the durability of concrete. For instance, Landa-Ruiz et al. (2021) [19] evaluated reinforced concretes with additions of 10% SBA and SF exposed to a magnesium sulfate ($MgSO_4$) solution, demonstrating their resistance under these conditions. Likewise, Neto et al. (2021) [20] investigated the influence of the additions on chloride permeability, while Wu et al. (2022) [21] demonstrated the potential of SBA to enhance concrete durability against sulfuric acid (H_2SO_4) attacks. These studies represent significant progress toward the development of resilient infrastructures; however, it is necessary to broaden research toward other degrading agents present in coastal environments and areas facing greater environmental impacts.

Climate change intensifies the risks to these infrastructures, particularly in coastal urban areas, where effects such as increased energy demand for building cooling, health problems in vulnerable populations (such as the elderly and low-income individuals), and reduced availability of water for consumption and hydroelectric power generation are anticipated [22,23]. Additionally, the displacement of vulnerable infrastructure due to extreme environmental conditions contributes to forced migration, further compromising the stability and resilience of affected areas. Coastal protection infrastructures, such as breakwaters and freshwater reserves in wetlands and aquifers, face critical risks due to saline intrusion (see Figure 1). The durability and sustainability of these infrastructures, both current and future, largely depend on their geographic location and the specific environmental vulnerability of each area.

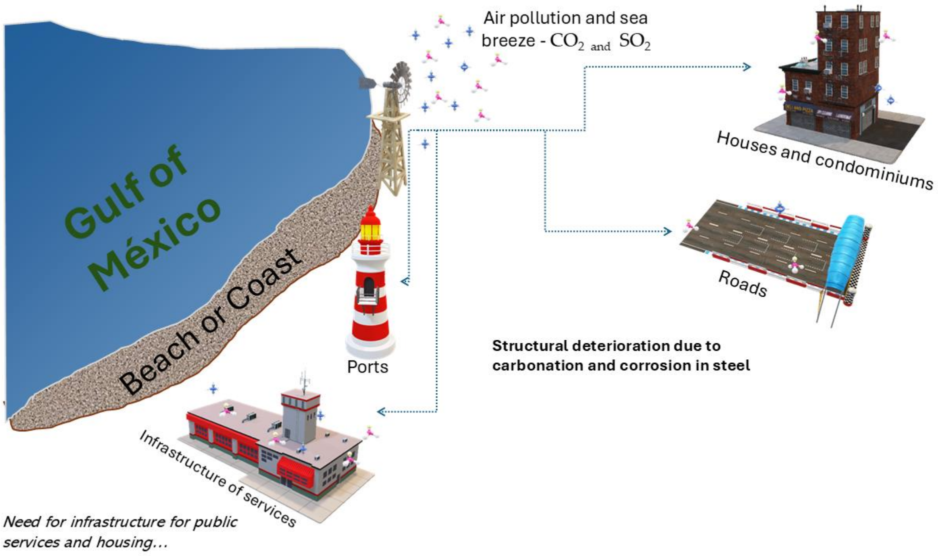

Figure 1. Effect of coastal environment on reinforced concrete infrastructure for community needs.

Therefore, this research evaluates performance in terms of corrosion, carbonation, and compressive strength in concrete mixtures modified with SBA and SF. Two types of mixtures were designed as follows: one with 15% SBA and another with 15% SF as substitutes for Portland Composite Cement (CPC 30R). For the corrosion test, carbon steel reinforcements bar AISI 1018 were subjected to a curing period of 28 days and a hardening period of 302 days in an environment of corrosive gases, including CO_2, CH_4, and N_2O; these gases contribute to the chloride-induced deterioration process, as illustrated in Figure 2.

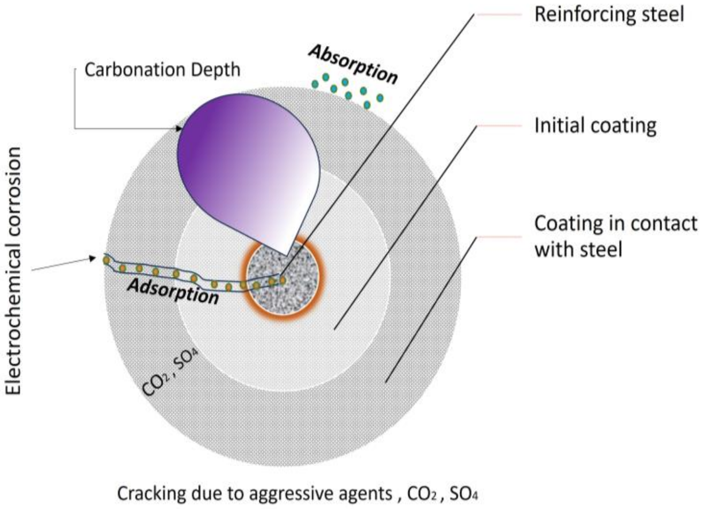

Figure 2. Deterioration process of chloride corrosion in steel and CO_2 carbonation in reinforced concrete structures.

2. Materials and Methods

The project begins with the specimen preparation phase, which includes mold fabrication, material characterization, mixture preparation, and specimen curing. The second phase involves placing the specimens in the exposure area, in this case, Boca del Río, Veracruz, Mexico (Figure 2). The third phase of the project has a series of deterioration techniques, including electrochemical corrosion techniques (corrosion potential and rate), carbonation depth (by the phenolphthalein method at 1% in alcohol) [24], and mechanical tests (compressive strength). The fourth phase contemplated taking a climatic series from this study area, which includes the following: precipitation, relative humidity, wind speed, wind direction, and temperature.

The manufacture of concrete specimens was carried out in accordance with NMX-C-159-ONNCCE-2004 at the facilities of the Instituto Tecnológico Superior de Misantla. Mixtures were designed according to the ACI 211.1 standard [25]. In addition, the characteristics of the mixture of gravel, sand, and cement were determined, as well as the treatment or processing of the residues to be used, such as sugarcane bagasse ash and silica fume. A water-cement ratio (w/c) of 0.56 was used. The cement employed was ordinary Portland cement resistant to sulfates (OPC), the gravel used was 19 mm silica, and the sand was river sand. The silica fume was ELKEM brand, while the sugarcane bagasse ash was extracted from a sugar mill in Mahuixtlán, Veracruz. The slump was 10 cm, and the specimens were cured for 28 days in potable water at room temperature (24 °C). Likewise, two types of specimens were used: plain concrete specimens of 15 × 15 × 30 cm and reinforced specimens of the same dimensions, but with four bars of 9.5 mm with concrete coverings of 15, 20, and 30 mm; 2 per covering [26]. Subsequently, the curing of the concrete specimens was performed using water at ambient temperature of 24 °C, as mentioned in the NMX-C-148 ONNCCE standard.

The incorporation of high amounts of silica fume (10 and 15%) in high-performance concrete mixes (w/cm ratio of 0.35) tends to require high dosages of superplasticizers. The high demand for superplasticizers is attributed to the very fine particle size of the silica fume, which causes part of the superplasticizer to be absorbed on its surface. In this type of mixture, silica fume increases the compressive strength by 21% compared to the control at 28 days of age. However, the development of strength in mixtures with silica fume is insignificant after 90 days [27].

Sugarcane bagasse ash was used as agro-industrial waste. This ash is the byproduct of the combustion of sugarcane bagasse, which results from the grinding of sugarcane for sugar production in the sugar mills of the country at elevated temperatures ranging from 700 °C to 900 °C. The sugarcane bagasse ash (SBA) residue is collected both from the bottom of the boiler and as fly ash. This material is considered pozzolanic by some researchers due to its high concentration of SiO_2 [28]. Among its outstanding characteristics are ultrafine particles, which are obtained through grinding processes. Applications of SBA include obtaining glass-ceramic materials, as adsorbent material for chromium (III) ion removal, as bedding material for broiler chickens, and as an additive to Portland cement, among other uses [29].

Regarding the reinforcing steel of the concrete specimens (beams), the steel bars were protected with epoxy material at the ends, leaving 30 cm^2 of free steel, in order to force the interaction with the aggressive agents through the lateral face of the concrete specimens. Six plain concrete specimens and six reinforced concrete specimens (three for each w/c ratio) were placed in the exposure stations [30].

Placement of Concrete Specimens

The concrete specimens were placed on the roof of the faculty of Civil Engineering at the Universidad Veracruzana, Boca del Río campus, Mexico, with the following UTM projection coordinates: Zone 14 Q 803,326.31 m east, 2,121,715.45 m north (Figure 3). The specimens were placed at strategic points in the two study areas. Figure 4 shows the placement of the mentioned study specimens. It was decided to place them on a rooftop to ensure as homogeneous exposure as possible, since at ground level, neighboring buildings, vegetation, or other external factors could negatively affect the results of the research. In contrast, placing them on the roof allows the weathering factors to be more representative of real-world conditions. This arrangement ensures that the cylinders are impacted uniformly from all directions, making full use of the specimen area.

Figure 3. Exposure zone for concrete specimens.

Figure 4. Arrangement of concrete specimens for experimentation.

3. Results and Discussions

The project exposure days were defined based on the current information from the meteorological and pollutant stations in the state of Veracruz. It has been recommended that at least 100 days of exposure be observed to notice any corrosion progress, although this is contingent upon the compressive strength of the initial design (see Table 1). This information will be utilized for the publication of a scientific article; thus, it is presented in a formal and technical language to meet the standards for approval in a scientific journal.

Table 1. Assessment of the duration of exposure to environmental conditions.

Study	Materials Used	Type of Exposure	Duration of Exposure	Key Results	Conclusions
Ahmad et al. (2022) [31]	Silica Fume	Exposure to weather	90 days	Improvement in compressive strength and durability	Silica fume enhances durability in aggressive environments.
Alvarenga et al. (2024) [32]	Bagasse Ash	Cycles of moisture and dryness	120 days	Reduction in cracking and improved mechanical performance	Bagasse Ash contributes to the stability of concrete.
Singh et al. (2024) [33]	Silica Fume and Bagasse Ash	Exposure under extreme climate conditions	180 days	Increased resistance to chloride attack	Combined mixtures optimize concrete properties.
Andrade et al. (2020) [20]	Bagasse Ash	Exposure to water and sun	300 days	Low permeability and reduced water absorption	Bagasse ash enhances water resistance.
Yavuz et al. (2024) [34]	Silica Fume	Exposure to freezing cycles	60 days	Superior freeze and thaw resistance	Recommended for cold climates, increases concrete lifespan.
Harilal et al. (2023) [35]	Silica Fume and Bagasse Ash	Exposure to coastal environments	90 days	Protection against corrosion in saline environments	Suitable for coastal areas, improves durability.

3.1. Potential (Ecorr) and Corrosion Rate (Icorr)

Corrosion rate measurements were taken for approximately 302 days. The standardization used to determine corrosion potentials and rates was carried out according to the UNE-EN ISO 16773-2:2017 [36]. These measurements were carried out on three types of mixtures: silica fume, sugarcane bagasse ash, and conventional mixture, each with a different type of steel (AISI 1018 and galvanized rebar). The results show that the AISI 1018 steel in the conventional mixture presents a higher corrosion rate, while the galvanized steel in the mixture with silica fume shows a lower corrosion rate. However, the differences in the values are not significant since they are all in the zone of negligible values, as shown in Figure 5.

The zones in the steel-related specimens show that no significant de-passivation has occurred, as they fall within the negligible range according to the pre-established corrosion potentials, as shown in Figure 6. However, the corrosion rate indicates that AISI 1018 carbon steels tend to behave uniformly in conventional mixtures. In the case of mixtures with sugarcane bagasse ash, the rates are closer to negligible corrosion values. Considering the exposure time, it is likely that this mixture will experience negligible to low-level corrosion in the coming years, based on the observed trend. Furthermore, mixtures with sugarcane bagasse ash show favorable performance in combination with galvanized steel, so a 15% cement substitution could offer a significant cost benefit. It is also important to analyze the adhesion of chloride particles to the steel, as this is highly dependent on the winds in the area. Therefore, it is recommended to install weather stations or specific measuring devices to monitor the intensity and movements of air mass.

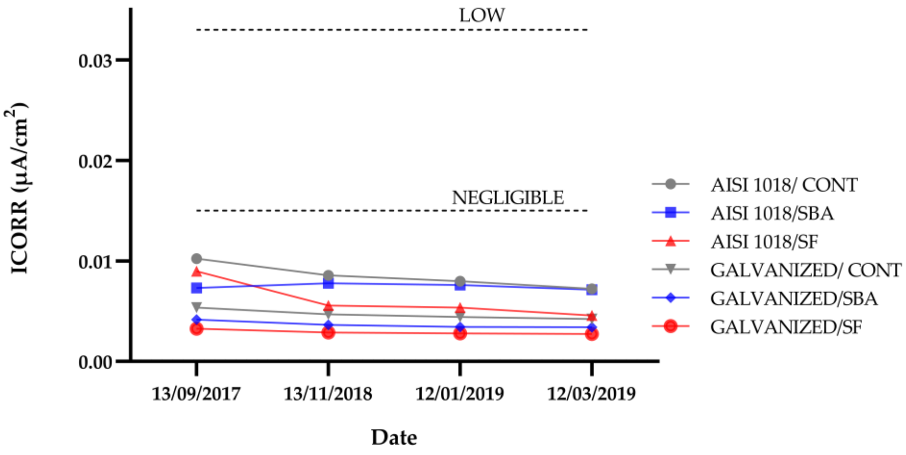

Figure 5. Corrosion potential in AISI 1018 and galvanized steel bars in control mixtures, with 15% replacement of Portland cement by silica fume and 15% replacement of Portland cement by sugarcane bagasse ash.

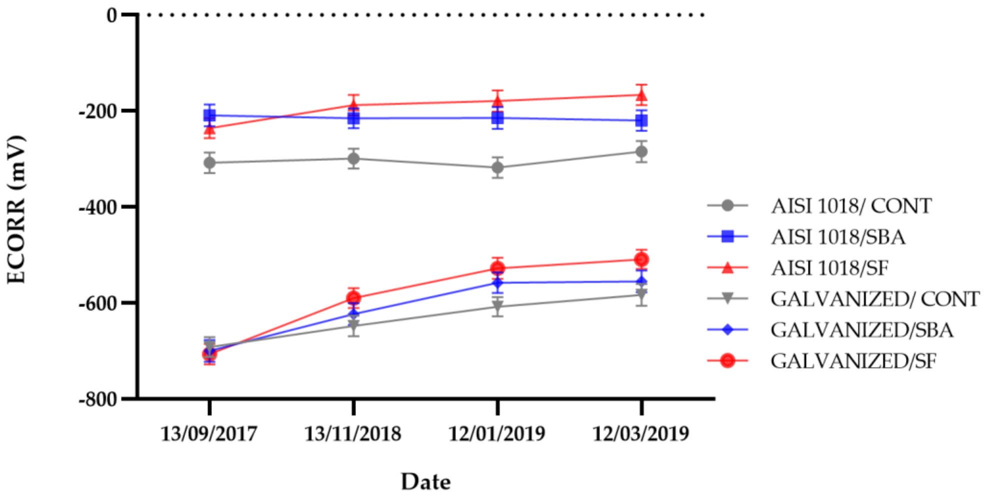

Figure 6. Corrosion rate in AISI 1018 and galvanized steel bars in control mixtures, with 15% replacement of Portland cement by silica fume and 15% replacement of Portland cement by sugarcane bagasse ash.

So far, much of the infrastructure near the beach in Boca del Río and Veracruz is surrounded by seawalls and infrastructure such as hotels, shopping malls, and some government buildings. Each of these structures is built with steel-reinforced concrete, highlighting the importance of the corrosion results and the evaluation of the mixtures used.

3.2. Carbonation Depth

The behavior of the sugarcane bagasse ash mixture has been consistent with the research expectations, and when compared with previous studies carried out by other authors [37,38], a progressive increase in the carbonation depth was observed. However, this increase has not been uniform, due to the varying climatic conditions that contribute to carbonation and structure deterioration throughout the exposure period. This has resulted in variations in the bimonthly results compared to the expected average.

In this research, as shown in Figure 7, during the first months of exposure, the specimens exhibited a slight resistance to carbonation, with only a few millimeters of carbonation depth. By the end of the period, the carbonation depth reached 12 mm. This suggests that the mix could be suitable for this context, since, according to the construction regulations for the Federal District and the durability manual for concrete structures in Mexico, the minimum coverings recommended for reinforcing steel in aggressive environments, such as urban–marine areas, are 5 cm.

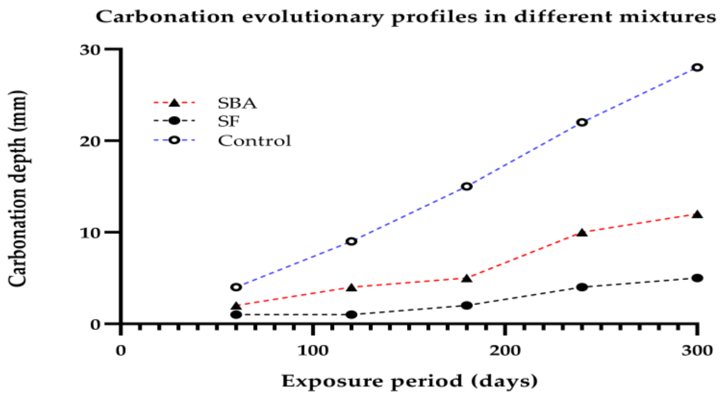

Figure 7. Evolutionary profiles of carbonation in different mixtures.

The mixture with silica fume demonstrated the best performance in this study, consistently showing a tendency to surpass other mixtures in carbonation depth evaluation from the first months of exposure. During the initial four months, there were barely any recorded changes, but over time, the deterioration became evident, although less pronounced than in the control specimens.

The climatic conditions, particularly during the February–March and April–May bimesters of 2019, favored a slight increase in carbonation depth, attributable to humidity and CO_2 emissions that facilitate the penetration of particles into the pores of the specimens.

The control specimen, made with conventional concrete, exhibited greater deterioration compared to the experimental mixtures, reaching critical levels of carbonation that severely affected the top portion of the specimens. It is estimated that the reinforcing steel would not be compromised, provided that a minimum cover of 5 cm is maintained according to prevailing regulations. Failure to adhere to this requirement would considerably increase the risk of deterioration and collapse.

3.3. Correlation Analyses

For a comprehensive analysis of the studied parameter data, we will highlight the graphs that integrate climatic conditions with levels of SO_2, CO_2, and carbonation. To develop and compare the climatic data of the coastal zone of Veracruz, bimonthly data were obtained, including maximum, minimum, and average annual temperatures, wind speed, humidity, and precipitation.

All this information was gathered from the IPCC and the National Institute of Ecology and Climate Change portals. This situation allows us to interpret the effects on the concrete or the exposure of the specimens. In March, the CO_2 index was elevated, reaching approximately 175 ppm, as shown in Figure 8. Despite this, the amount of sulfates was not high enough to damage the concrete matrix. Given this situation, the hypothesis that temperature is not directly related to CO_2 or SO_2 emissions could be maintained. However, the rates of these gases and salts, which cause corrosion in steel or concrete, tend to be random, as increases in pollutants occur intermittently.

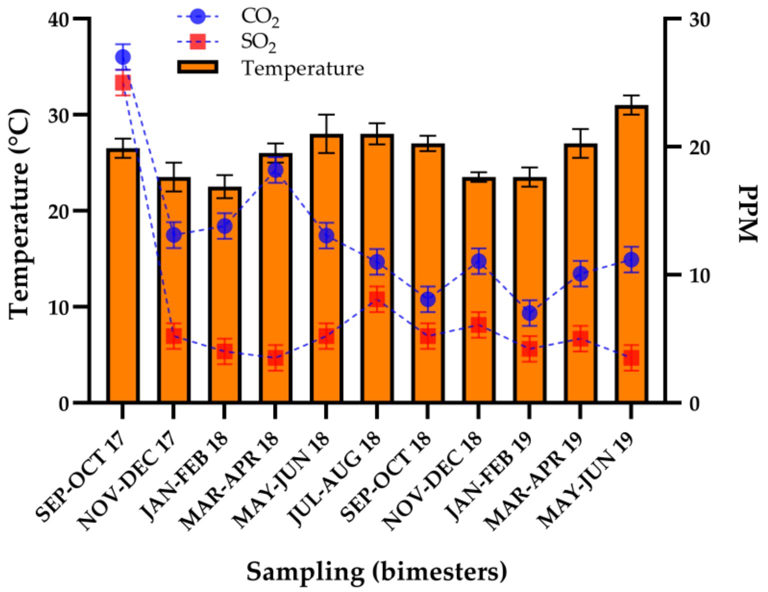

Figure 8. Correlation between temperature, CO_2, and SO_2 from 2017 to 2019 in this study area.

To determine the correlations, the relationship between CO_2 and temperature was first evaluated, starting with a normality test based on the number of data points. The results indicated that there is a normal distribution between the CO_2 and temperature variables. Subsequently, the correlation was performed using the Pearson coefficient, obtaining a value of 0.02214 with a confidence interval of −0.5855 to 0.6139, indicating the absence of correlation. Similarly, the correlation between temperature and SO_2 was evaluated, but since the data set did not follow a normal distribution, the Spearman coefficient was used. The result was 0.07925, with a confidence interval of −0.5608 to 0.660, also indicating no correlation between temperature and SO_2.

Temperature does not greatly influence carbonation, as illustrated in Figure 8. In the first approach, carbonation could be considered a chronological and irreversible degradation process, and the only possible outcome is to mitigate or reduce its effect on the concrete matrix. However, temperature does have a noticeable interaction with precipitation and relative humidity rates.

A correlation was performed again to determine with certainty if these variables are associated. As for temperature in contrast with SBA, the data presented a normal distribution, yielding a Pearson coefficient of −0.4075 with a confidence interval of −0.9834 to 0.91, indicating an inverse correlation of moderate intensity. The correlation between temperature and the mixture with silica fume was also evaluated and exhibited a normal distribution. The Pearson coefficient obtained was −0.4330, with a confidence interval of −0.9844 to 0.9045, indicating once again an inverse correlation of moderate intensity. Finally, the correlation between temperature and the control mixture was analyzed, which also followed a normal distribution with a Pearson coefficient of −0.3859 and a confidence interval of −0.9826 to 0.9143. From this analysis, it is concluded that temperature is not significantly associated with carbonation depth.

Wind speed has a significant influence when it moves at 10 km/h or less since it causes carbon dioxide levels to remain in the environment and can be absorbed by the concrete structures (Figure 9). In addition, wind speed showed a relevant index related to the displacement of chlorides in the environment, which interferes with the carbonation rate. Figure 10 indicates that the bimonthly period with the highest wind speed was March–April 2019, with an average speed of 20 km/h. The period with the lowest wind speed is July–August and September–October, both of 2018, with a speed of 5 km/h. The average wind speed recorded is 12.5 km/h. The periods closest to this average are May–June 2014, March–April and November–December 2015, January–February and September–October 2016, March–April 2017, and January–February 2019, all with an approximate speed of 12 km/h. Considering these data, the March–April period can be defined as the most demanding. This is because it not only records the highest speed but also appears frequently in other years, both in terms of average and maximum speed.

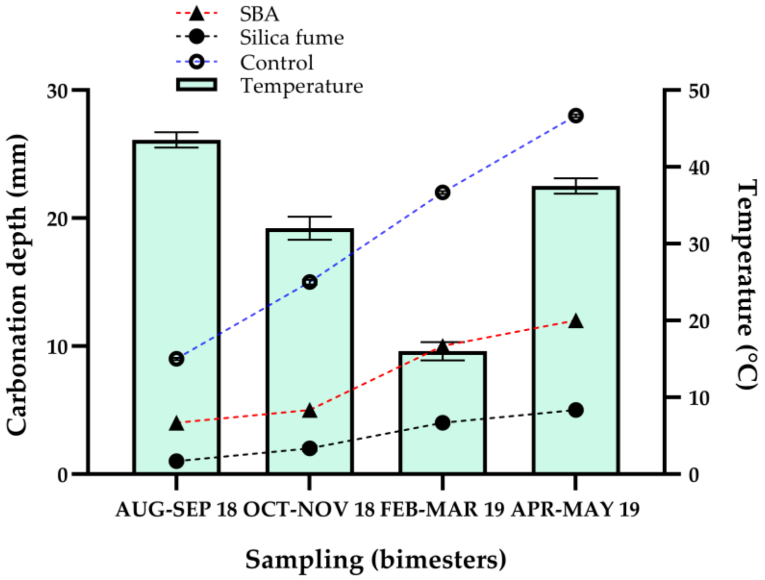

Figure 9. Correlation between SBA, silica fume, carbonation depth, and temperature in this study area during the exposure period.

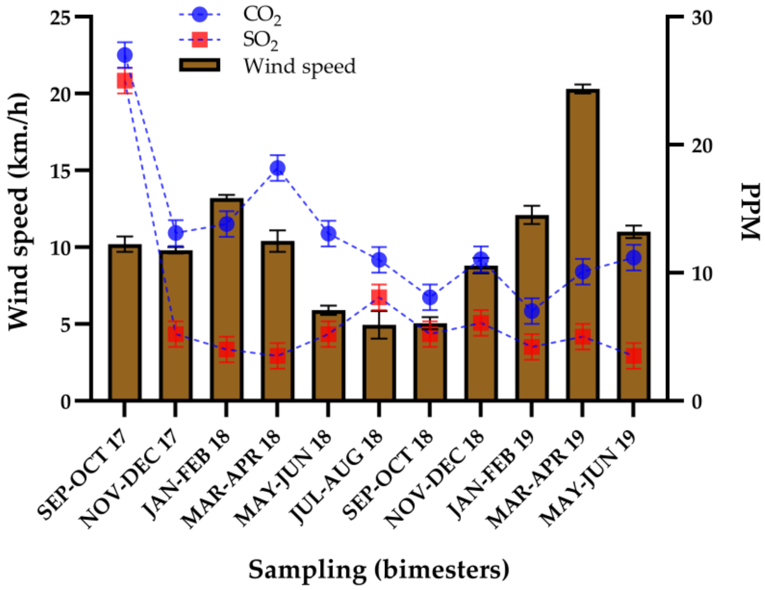

Figure 10. Correlation between wind speed, $CO_{2,}$ and SO_2 content in this study area during the exposure period.

In the correlation analysis between wind speed and CO_2 and SO_2, the data did not follow a normal distribution. The Spearman coefficient values were 0.08182 for CO_2 and −0.6483 for SO_2. This suggests that only wind speed shows an inverse correlation of moderate intensity with SO_2.

Humidity promotes the development of carbonation and the decrease in pH in concrete. In particular, the November–December period had the greatest potential to influence this phenomenon. During the January–April period, it was observed that CO_2 levels interacted more significantly with humidity due to the high levels. However, according to SEDEMA, CO_2 levels decreased considerably, while the amount of SO_2 remained constant, interacting mainly with the wind. As shown in Figure 11, relative humidity is a determining factor, as it indicates how the coastal environment can specifically affect concrete structures. The humidity reached a level of 100%.

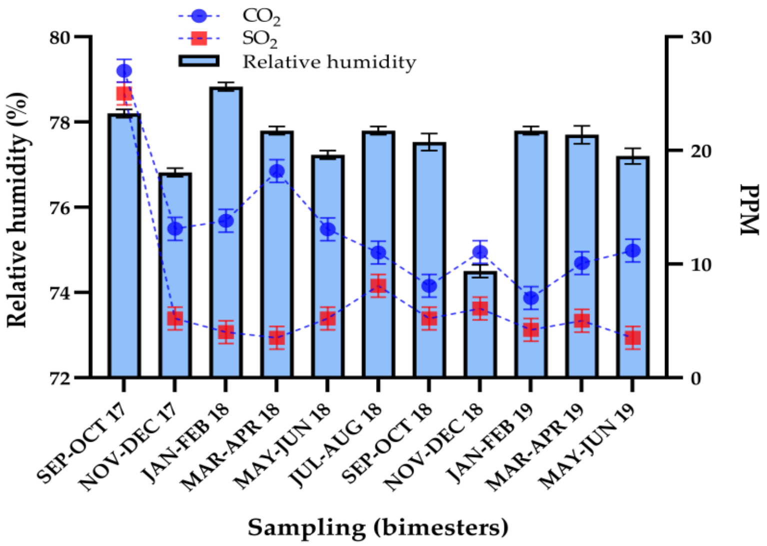

Figure 11. Correlation between relative humidity, CO_2, and SO_2 for the period 2017–2019.

A correlation analysis was conducted between relative humidity with CO_2 and SO_2. As with wind speed, the data did not follow a normal distribution. The Spearman coefficient values were 0.2569 for CO_2 and −0.0789 for SO_2, with confidence intervals of −0.4224 to 0.741 and −0.6598 to 0.5611, respectively. This resulted in a weak and null direct correlation, suggesting no association between relative humidity with CO_2 and SO_2.

Precipitation, combined with humidity, contributes to higher production of chlorides, while wind speed and temperature influence their dispersion. In the data obtained over 5 years, precipitation causes periods of scarcity, where the data are not representative. Precipitation is measured in millimeters. The July–August 2017 period presents the highest precipitation recorded, with 391.28 mm/m^2. In contrast, the period with the lowest precipitation was March–April 2014, with only 1.40 mm/m^2. However, it is notable that the September–October 2014 period shows a precipitation of 387.48 mm/m^2, the second highest amount recorded in the last 5 years, suggesting a radical change in precipitation in only two-month intervals. The mean precipitation was recorded in the May–June 2018 period, with 182.62 mm/m^2. For precipitation, a correlation analysis was also carried out, which showed that the data did not follow a normal distribution. The Spearman coefficient values were 0.2636 for CO_2 and 0.5472 for SO_2. This indicates a weak correlation between precipitation and CO_2 and a moderate correlation with SO_2.

3.4. Sulfur Dioxide (SO_2) and Carbon Dioxide (CO_2) Levels

Other variables considered were the levels of SO_2 and CO_2, gases that contribute to the greenhouse effect and potentiate climate change. According to data from the National Inventory of Greenhouse Gas and Compound Emissions, there are no records available prior to July 2017. Therefore, the work was conducted using data available from that date onwards. It is worth mentioning that, even within the periods with records, there were days in which the levels were 0 or no data were captured. According to Figure 12, the highest levels of both gases were recorded in July, with 25.1 ppm for SO_2 and 27.3 ppm for CO_2. This suggests that in previous months the levels may have also been elevated. Analyzing specifically CO_2, a noticeable change is observed throughout the two and a half years. The highest values were recorded in the bimesters of July–August 2017, January–February, September–October 2018, and May–June 2019, with levels of 27.3, 18.8, 11.11, and 14.5 ppm, respectively.

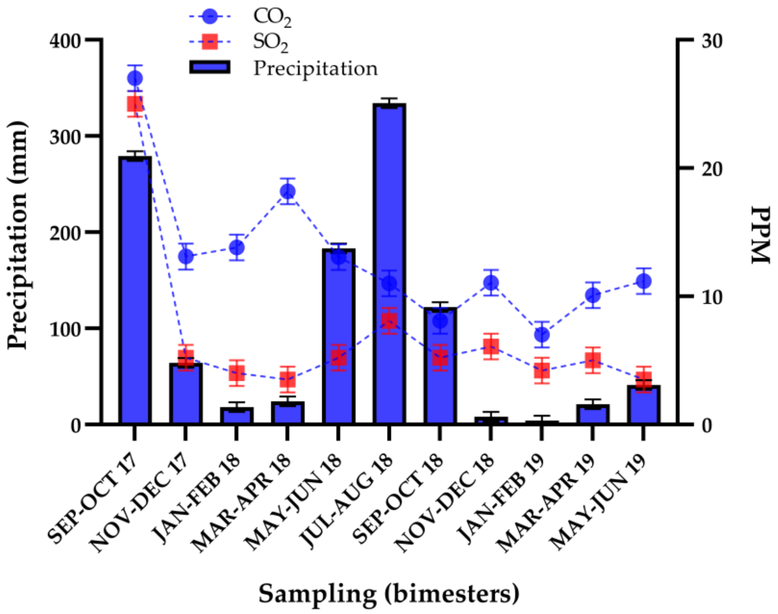

Figure 12. Correlation between precipitation, $CO_{2,}$ and SO_2 for the period 2017–2019.

3.5. Compressive Strength

The compressive strength of the concrete specimens in this study area was evaluated following the NMX-C-083-ONNCCE-2014 standard [39].

Figure 13 shows that compressive strength varies depending on curing and exposure zone. In this case, the mixes with sugarcane bagasse ash complied with the strength condition, with a design of 250 kg/cm^2. However, the mixtures with silica fume show a significant increase in compressive strength as the hardening time advances. From day 150 onwards, there is a noticeable improvement in this strength. The 15% substitution with mixture designs of 150 to 250 kg/cm^2 confirms that the use of waste materials and the reduction in the use of Portland cement are effective. This finding is supported by both previous research and the results obtained in the present study.

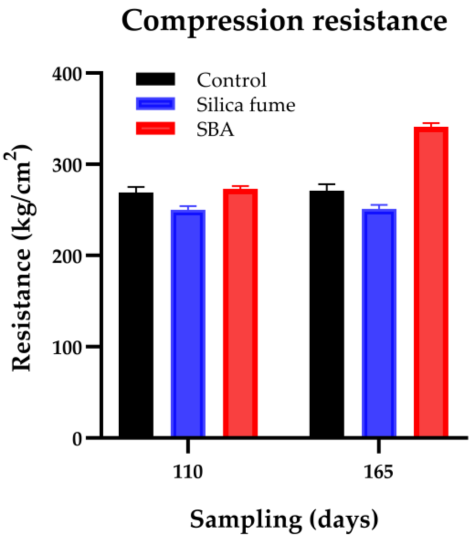

Figure 13. Compressive strength of conventional mixtures (control), Silica Fume (SF) mixture, and sugarcane bagasse ash (SBA) mixture at 110 and 165 days.

In various parts of the world, waste materials of either industrial or agro-industrial origin were utilized, assessing their performance in concrete mixtures at different percentages (see Table 2). The contribution of the current research is significant due to its added value in the performance of the coastal area of Boca del Río, Veracruz, México.

Table 2. Substitution indices for Portland cement worldwide.

Reference	Cement Substitute	Replacement Percentage	Key Results	Region	Year
[40]	Silica Fume	10–30%	Improvement in compressive strength and durability	India	2020
[41]	Bagasse Ash	5–15%	Reduction in cement consumption and CO_2 emissions	Brazil	2023
[42]	Silica Fume	15%	Significant increase in sulfate resistance	China	2021
[43]	Bagasse Ash	20%	Improvements in workability and cost reduction	México	2017
[18]	Silica Fume and Bagasse Ash	10% Silica 10% Ash	Synergy in mechanical properties and durability	South Africa	2022
[44]	Silica Fume	25%	Optimization of mix superior properties	Iraq	2023
[45]	Bagasse Ash	10–20%	Increase in carbonation resistance	Bangladesh	2024
[46]	Silica Fume	20%	Positive effect on concrete sustainability	Croatia	2023

The results underscore the importance of reducing cement use and promoting sustainable development in construction. It is concluded that concrete with 15% silica fume is the most resilient option against climate change and chloride aggression along the coast of Veracruz, while concrete with 15% bagasse ash may present greater economic value. Sustainable concrete production is essential to mitigate global warming, particularly in Veracruz, where climate promotes structural deterioration. The implementation of meteorological stations is recommended to assess the impact of degradation. This approach enables the integration of innovative alternatives in construction, optimizing resources, and reducing costs and risks associated with natural disasters.

4. Conclusions

The following conclusions were drawn from the conducted research:

1. The use of partially sustainable alternatives to Conventional Portland Cement (CPC) using sugarcane bagasse ash (SBA) and silica fume (SF) demonstrates significant potential in the production of high-durability concrete. The incorporation of SBA percentages produced a compressive strength comparable to that of CPC, reaching strength levels of 250 kg/cm^2. However, with the addition of SF, there was up to a 21% increase in strength at 28 days compared to the control samples over the 302-day

duration of the experiment, without compromising the integrity of the structural element and aligned with ecological objectives.

2. Regarding the use of concrete in coastal climatic conditions (Boca del Rio, Veracruz, Mexico), which are exposed to aggressive agents such as CO_2 and SO_2, there is an increase in carbonation depths and corrosion rates. The mixtures utilizing SF exhibited lower depths (not exceeding 12 mm over the 302 days) compared to control mixtures, thus providing effective protection against environmental degradation.
3. The implementation of sustainable alternative materials promotes their use and may inform public policies aimed at reducing the environmental footprint caused by construction activities. Additionally, the utilization of SBA contributes to the economic development of the sugar sector, as the commercialization of this agricultural byproduct generates a sustainable alternative to cement and creates economic opportunities.
4. The performance of concrete modified with alternative cementitious materials, its behavior in the presence of aggressive agents from hostile environments such as coastal zones, and its resistance over time provide valuable information regarding performance, structural reliability, and numerous real-world applications.

This study demonstrates that modified concretes, by reducing the need to extract aggregates from quarries and process them at high temperatures, significantly reduce environmental impact.

In the Veracruz region, and taking as an example one of the numerous local sugar mills, such as “Ingenio de Mahuixtlán” or “La Concepción”, it is recommended to analyze sugarcane wastes, like bagasse, to explore their potential use. This would help justify the pollution generated during the sugar production process, demonstrating that the subproducts, if not reused, could be minimized through finding a second use for them. The use of byproducts such as sugarcane bagasse in the production of sustainable concretes can boost regional development in the area. Experimentation with waste from the Mahuixtlán sugar mill demonstrates the viability of using sugarcane bagasse ash, which can foster community awareness and promote local and regional processing and commercialization of this material. Based on the above, a sugarcane bagasse ash analysis could be carried out at various sugar mills. It is recommended to carry out a characterization of the Moctezuma cement plant in Apazapan, Veracruz, to collect the silica fume generated during the clinker production process.

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