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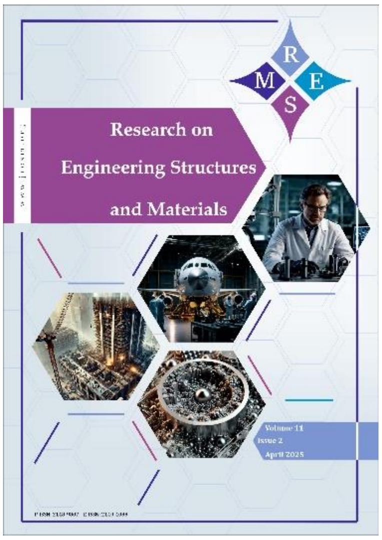

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Review Article

Artificial intelligence-assisted optimization of concrete mixes to enhance the durability of civil engineering structures in marine environments

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Abstract

The durability of concrete is a major concern for civil engineering professionals, a concern that is amplified by the considerable impact of climate change and environmental factors. This issue becomes critical for infrastructure located along maritime and river foreshores. These structures are constantly exposed to a series of aggressive agents, including chemical and mechanical actions, as well as variations in temperature and humidity. Therefore, to maintain the sustainability of these structures, a set of mineral additives and pozzolans is added to the concrete formulation to improve performance and extend the service life of concrete structures. With the emergence of Industry 4.0, the construction sector has undergone a profound transformation through the integration of various digital technologies throughout the entire project life cycle, from design to implementation. These technologies include BIM, modeling, artificial intelligence, automation, 3D printing, and optimization of concrete formulations. This technological shift has enabled significant advancements in material management and the enhancement of concrete durability. Leveraging alternative additives and AI technology, we can develop robust, environmentally friendly concrete that excels in challenging environments, delivering optimal results in terms of cost, time, and performance. The objective of this work is to demonstrate the potential of AI tools in optimizing concrete formulations by identifying the most effective combinations of additives, materials, and dosages to mitigate the effects of environmental aggressions on structures in maritime environments.

1. Introduction

Concrete plays a structuring role in the development of territories. It has been adopted for building needs for decades in the four corners of the world. Indeed, this material has been fully privileged due to its proven quality characteristics, including strength, durability, thermal and acoustic performance. Moreover, it is known for its ability to meet different architectural and structural design needs. It is manifested in the majority of infrastructures: civil engineering structure, industrial or commercial equipment, road infrastructure, public facilities and housing. By its omnipresence, concrete has become a key component of urban modernization and the development of living spaces.

Moreover, although concrete combines key mechanical properties: rigidity, strength and durability, it is not immune to vulnerabilities and failures. Its durability can indeed be compromised when

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exposed to an aggressive environment characterized by chloride sulfate attack as well as thermal variations [1,2]. Seawater with an average salinity of 35 g/l, is dominated by NaCl, and also contains $MgCl_2$, $MgSO_4$, and $CaSO_4$, all of which react chemically with concrete [3]. In the Moroccan context, this phenomenon is very common, as structures built along the Atlantic and Mediterranean coasts are frequently subjected to these physical and chemical aggressions [4]. The consequences include series of cracks, surface dislocations and reinforcement corrosion. $MgCl_2$ dissolves portlandite ($Ca(OH)_2$), forms partially soluble $CaCl_2$, and develops expansive products such as Friedel's salt ($3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O$) which induce cracking and increase porosity. Similarly, $MgSO_4$ produces gypsum ($CaSO_4{\cdot}2H_2O$) and brucite ($Mg(OH)_2$), which weaken the cementitious matrix. [6,7]. These reactions clearly demonstrate the limitations of traditional concrete formulation under marine environmental conditions.

To improve durability by limiting the penetration of aggressive agents and improving the mechanical performance of concrete, various materials and minerals were studied and incorporated into the concrete matrix. This approach indeed involves using additional cementitious materials such as fly ash (20–50% replacement) and silica fume (up to 10%), known for refining the pore structure and reducing permeability [32,33]. Recent advances also focus on nanomaterials such as nano-silica (1.5-2 wt%), nano-TiO and multi-wall carbon nanotubes that densify the microstructure, reduce chloride ion diffusion by up to 38%, and improve the interfacial transition area (ITZ) [21, 22]. Furthermore, the integration of treated loam and dredge products (used up to 20% substitution), PVC polymers and alternative binders such as ultra-fine palm oil ash (UPOFA, about 10% substitution), decreases porosity, enhances the compressive strength by up to 40% and resists sulfate attacks [24, 36, 40]. These approaches not only prolong the lifespan in marine environments, but also contribute to sustainability by integrating waste and reducing dependence on natural resources.

Furthermore, to better identify and optimize these innovative approaches aimed at strengthening concrete formulation, artificial intelligence, and more particularly machine learning, opens promising prospects. This technology based on neural networks and decision trees allows has become increasingly important in the optimization of concrete formulation. Unlike traditional models, AI can handle complex relationships between concrete composition, mechanical properties and environmental conditions, which is essential in aggressive environments with many influencing factors. ML models were used to predict compressive strength with errors less than 5%, optimize mixing designs and evaluate durability against chloride and sulfate attacks. [43, 45].

This work aims to design sustainable concrete for marine and river structures, by consolidating the results of scientific research carried out and optimized by artificial intelligence tools.

2. Aggressive Media and Pathologies of Concrete

2.1. Exposure Conditions and Aggressiveness of Marine Environments

The marine environment is one of the harshest and most aggressive environments for civil infrastructure, due to the combined effects of mechanical actions (such as swell, waves and tidal movements), chemical agents (including dissolved salts like chlorides and sulfates), climatic factors (including temperature fluctuations), and biological influences (such as microbial activity). Three exposure configurations can be distinguished for marine structures: the permanently submerged area which is generally less prone to degradation; the continuously emerged area, where concretes are partially affected by the transported chlorides, and the tidal zone, which is the most aggressive, subjected to alternating cycles of immersion and drying, which further promotes the accumulation and penetration of aggressive agents.

Salinity representing the determining factor which varies from a few g/L to more than 200 g/L, with an average of 35 g/L in the large oceans [3]. In Morocco, it is relatively stable on the Atlantic coast (about 35 g/L), but reaches up to 38-39 g/L on the Mediterranean coast, especially in areas with low water renewal [4, 5].

2.2. Mechanisms of Corrosion and Crack Propagation

Chloride ions, particularly $MgCl_2$, react with calcium hydroxide (portlandite) to form $CaCl_2$, which increases porosity, and also forms expansive salts such as ($3CaO\ Al_2O_3\ CaCl_2\ 10H_2O$), which are responsible for cracking. $MgSO_4$, in turn, causes the formation of secondary gypsum and brucite, which degrade cement hydrates and increase concrete porosity. These chemical reactions promote concrete cracking and reinforcement corrosion [6-8], as observed in several ports, where thickness losses due to chloride attack and carbonation have been reported [2].

Fig. 1. Cut cross-section in 2009 of a 450 mm thick deck slab (cover 40 mm) exposed since the 1930s in the Newcastle Harbour marine atmosphere, showing delamination crack passing through the bottom of the 16 mm diameter bars. R.E. Melchers 2009 [2]

A study on a breakwater crown wall exposed in the marine environment revealed widespread corrosion of the reinforcements, confirmed by the appearance of concretions, internal damage (ultrasound) and strong chlorinated contamination (up to 150 mm deep). [9-11]. Corrosion rates exceeded 0.10μA/cm² in most of the structure, with 90% of values above 0.6μA/cm², which corresponds to a material loss greater than 0.070 mm/year. The calculated corrosion index classified the structure as very degraded, requiring immediate intervention [9-11]. In addition, another study [12] showed that chloride-induced corrosion in reinforced concrete beams subjected to flexural stresses progresses more rapidly in the presence of large deformations. Over a period of five years, five beams were exposed to a saline solution simulating a marine environment without artificial acceleration of corrosion. The results showed that bending cracks facilitated the entry of chlorides and oxygen, thus accelerating corrosion. The first signs appeared within the first 90 days.

Indeed, these beams, all with a width of 0.08 m, have variable heights (from 0.050 m to 0.104 m) in order to generate different levels of deflection in the middle under controlled loads, while maintaining the same initial stress in the reinforcements (210 MPa) [12]. This constant stress was essential for simulating the phenomenon of stress corrosion in conditions close to reality. The concrete used for all the beams had a homogeneous composition, with identical proportions. As a result, the bending cracks that appeared under the effect of the charges favored the penetration of chloride ions and oxygen, which led to an intensification of corrosion, especially in the central area in direct contact with the saline solution. The table below presents the geometric characteristics, reinforcement details and load and deflection parameters of the five beams tested:

Table 1. Characteristics of the tested beams [12]

Beam No.	Height (m)	Reinforcement	Concrete Cover (m)	Applied Load P (N)	Deflection (d) (m)	Slenderness Ratio (L/d)
1	0.050	2 × Ø8 mm (0.008 m) bars	0.025	2800	0.0100	200
2	0.070	2 × Ø8 mm (0.008 m) bars	0.025	1350	0.0067	300
3	0.082	2 × Ø8 mm (0.008 m) bars	0.025	1710	0.0050	400
4	0.094	2 × Ø8 mm (0.008 m) bars	0.025	2020	0.0040	500
5	0.104	2 × Ø8 mm (0.008 m) bars	0.025	2300	0.0033	600

The evolution of cracks was monitored throughout the duration of the test (1800 days), distinguishing between bending and corrosion cracks. The former is due to traction in the tense areas, while the latter result from the internal pressure exerted by the corrosion products. These two types of cracks interact and amplify each other, contributing to the degradation of the beam.

Table 2 below presents the observed linear trends for the total cracking area (sum of bending and corrosion cracks) as well as for the maximum width of the cracks, expressed by equations obtained via least squares method, with their determination coefficient R^2 indicating the quality of the fit. Consequently, this research highlights the crucial importance of crack and sag control to improve the durability of reinforced concrete structures in marine environments [12-14].

Table 2. Evolution of total cracking area and maximum crack width over time (up to 1800 days) [12]

Beam No.	Total Cracking Area (m^2 ×10^{-6}) **x:** Time (in days) & **y:** Cracking area or crack width	R^2	Max Crack Width (m)	R^2
1	y=0.1282x+1.5998	0.97	y=0.0002x+0.1401	0.76
2	y=0.1084x−8.342	0.94	y=0.0001x+0.0475	0.89
3	y=0.0637x−0.9815	0.99	y=0.0002x−0.0018	0.87
4	y=0.0572x−10.697	0.91	y=0.00006x−0.0625	0.63
5	y=0.0574x−9.9234	0.97	y=0.00008x−0.0327	0.79

2.3. Effectiveness of Cementitious Binders and Resistance to Chemical Attacks

Three types of cementitious binders were evaluated in aggressive marine environments:

- OPC: Ordinary Portland cement,
- PBC: Pozzolanic cements, incorporating reactive mineral additions such as fly ash, silica fume or blast furnace slag,
- AAMs: Alkali-activated materials, high silica and alumina waste binders activated by alkaline solutions to generate N-A-S-H or C-A-S-H gels.

The analysis of this evaluation was directed towards their chemical interactions with abundant Cl^-, SO_4^{2-} and CO_2 ions in seawater, as well as their properties in the hardened state such as compressive strength, porosity, water absorption and chloride permeability. The results revealed that [15]:

- The OPC can lose between 15% and 25% of its mechanical strength after six months of exposure, compared to less than 10% for PBC, while AAAMs show stability due to the reduced portlandite content.
- The chloride permeability measured by the rapid migration test is significantly lower in PBC (1000-2000 C) and AAM (<1000 C) compared to that of OPC (>3000 C), reflecting a better resistance to penetration of aggressive agents.

Consequently, the combined marine conditions of wet-dry cycles, as well as high temperatures significantly increase the degradation of concrete, particularly OPC-based concretes [16,17]. Attacks on sulfates and acid aggressions are two major forms of concrete degradation in hostile environments. Sulphates present in soils or in certain industrial wastewater can react with the components of the cementitious matrix, leading to the formation of secondary ettringite. This process generates internal swelling that causes significant cracks to appear within the material [18,19]. In parallel, in industrial and agricultural environments, concrete is frequently exposed to acidic environments (pH < 5). This acidity induces a gradual dissolution of the cementitious paste, compromising the durability of the structure. Sulphuric and nitric acids, as well as some organic leachates, are particularly aggressive, causing significant mass losses and a strong deterioration of the mechanical strength of concrete [20]. Faced with these issues, several research studies have proposed the incorporation of pozzolanic materials such as silica fume or metakaolin. These additions densify the microstructure of the paste, thus reducing its permeability and improving its resistance to chemical attacks [35].

3. Conventional Methods for Improving Concrete Durability

3.1. Nanomaterials: Nano-silica, Nano-TiO_2, Carbon Nanotubes and Graphene

For several decades, engineers, researchers and professionals have been implementing a set of techniques and approaches incorporated into the concrete matrix in order to strengthen its resistance to aggressive environments, thus providing a reference base in the field. The incorporation of nanofillers into concrete represents a significant advance to improve its durability without compromising its initial mechanical strength. Materials such as nano-silica (NS), nano-TiO (NT), multi-wall carbon nanotubes (MWCNTs) and multilayer graphene (MLG) densify the internal microstructure of concrete, reduce water absorption and limit chloride ion transport. Indeed, the incorporation of 1.5% by weight of nanosilica reduces the diffusion coefficient of chloride ions from 18.6 × 10^{-12} m^2/s (for the control concrete at 28 days) to 13.62 × 10^{-12} m^2/s at 84 days, representing a reduction of 26.8% [23].

These nanofillers also promote the formation of more compact C-S-H gels, modify the morphology of hydration products and improve cohesion between aggregates and the cementitious matrix by refining the interfacial transition zone (ITZ). For CO_2 emissions, the values increase from 463 kg/m³ (for traditional high-strength concrete with a compressive strength of 88 MPa) to 360 kg/m³ (for concrete with NS and 49 MPa), representing a reduction of 22.2% [22,23]. Similarly, the production cost decreases from USD 83/m³ (88 MPa) to USD 60/m³ (49 MPa with NS), which corresponds to a cost reduction of 27.8%. In terms of sustainability, the integration of nano-silica increases the durability indicator (kSB) by up to 16.6%, comparing with traditional concrete. Additionally, by combining 2 wt% of NS with 1 wt% of nano-calcium carbonate (NC) in ordinary and high-volume concrete of fly ash (HVFA), the performance is significantly improved. Sorptivity is reduced by 30% and chloride ion penetration is reduced by 38%. Microstructural analysis by MIP and DTA/TGA confirms a decrease in porosity and portlandite (CH), reflecting the higher efficiency of NS compared to NC, especially in 40% F-type HVFA concretes. [21-23]. This figure presents that incorporating 1.5 wt% nanofillers significantly improves the sustainability index of concrete by 11.7%–16.6%, without increasing cement content. It also shows the potential of low-cost, low-carbon, and durable nano-engineered concrete for marine engineering applications [23].

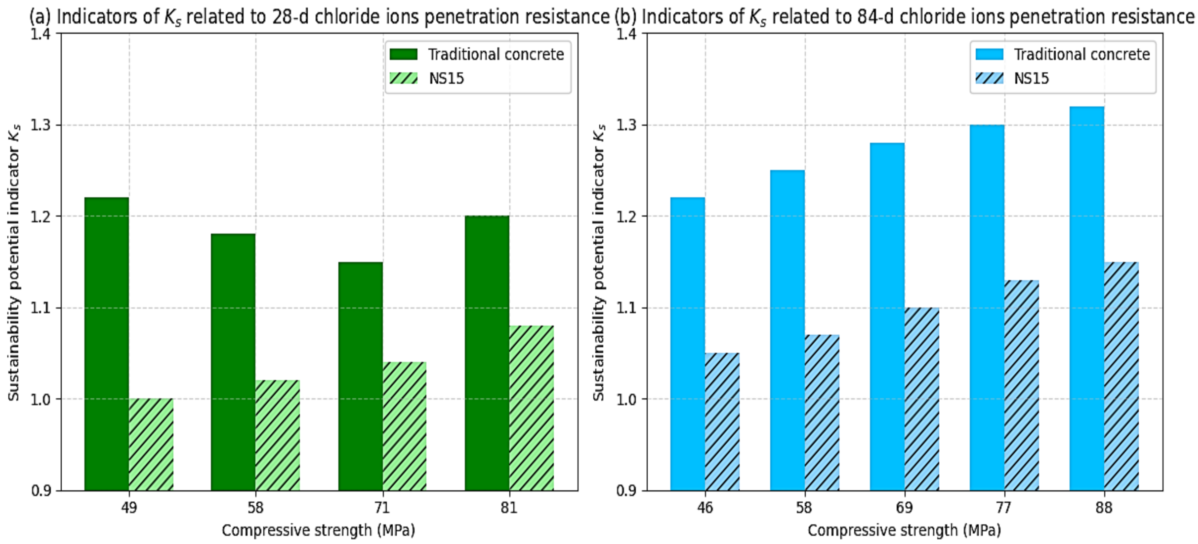

Fig. 2. Indicators of the sustainability potential indicator (kSB) related to 28-d and 84-d chloride ion penetration resistance [23]

3.2. UPOFA: Ultra-Fine Palm Oil Fuel Ash

The incorporation of alternative materials such as ultra-fine palm oil ash (UPOFA) significantly contributes to improving the compacity of concrete and reducing its porosity. 10% cement substitution with UPOFA reaches a compressive strength of 37.95 MPa at 28 days, which represents an increase of about 40% compared to control concrete without addition [24]. This improvement is also accompanied by better corrosion resistance and reduced chloride ion penetration. The RCPT (Rapid Chloride Penetration Test) and HCP (Half-Cell Potential) tests confirmed the good performance in terms of durability, while the high ultrasonic speeds measured by the UPV method (Ultrasonic Pulse Velocity) testify to a homogeneous and densified internal structure. [24], [25], [26].

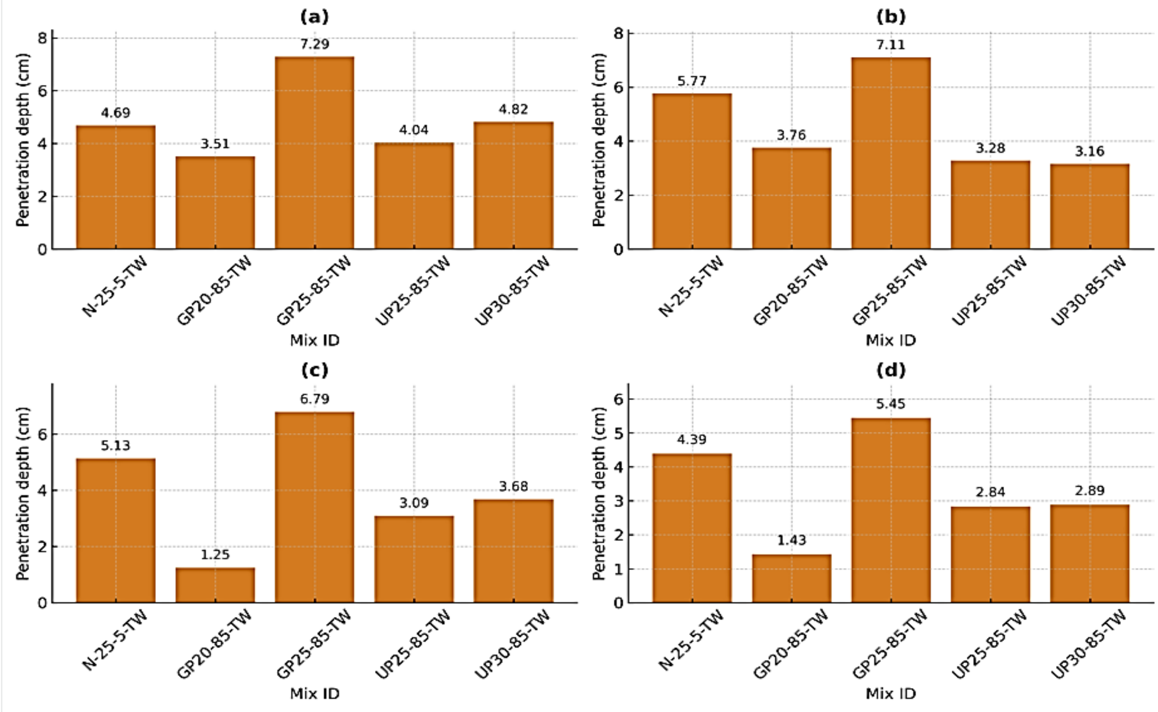

Fig. 3. Chloride-penetration depths of (a) RS-TW, (b) SS-TW, (c) RS-SW, and (d) SS-SW specimens [24]

This figure shows the chloride-penetration depths of the concrete disc specimens at 28 d. Specimens without POFA exhibited the following depths: N-RS-TW (4.69 cm), N-SS-TW (3.76 cm), N-RS-SW (5.13 cm), and N-SS-SW (1.43 cm). The highest penetration depth was observed in GP20-RS-TW, at 7.29 cm. Additionally, the penetration depth of the UPOFA samples tended to improve as the ratio of UPOFA increased. The tests [24] also revealed that a higher amount of UPOFA in cement decreases concrete compressive strength, particularly during the early curing period. Lower compressive strength indicates reduced density in the concrete matrix, primarily due to the presence of pores. Furthermore, concrete mixed with seawater and containing 10 % UPOFA showed a notable reduction in chloride-penetration depth. This improvement may be attributed to mineral admixtures like POFA, which effectively bind unbound chloride ions in seawater, thereby enhancing the concrete's durability [24].

3.3. Mineral Waste Additions: Crushed Glass, Marble, Silica Sand and Syenite Nephelin

The partial substitution of natural sands by mineral waste (syenite nephelin, marble, crushed glass, silica sand) also offers a sustainable solution, with a significant reduction in porosity, better compactness (increased UPV speed), and an improvement in mechanical and chemical properties. Crushed glass, rich in amorphous silica, promotes the formation of additional C-S-H via pouzzolanic reactions, reducing the Ca/Si ratio and increasing resistance to sulphate attacks (low mass loss and swelling at 90 days). Marble and syenite nephelin provide increased resistance to abrasion and shearing thanks to their fine grain size [27-29].

3.4. Fly Ash-Based Systems and Supplementary Cementitious Materials

Lv et al. [30,31] conducted a study on the addition of Crassostrea gigas (giant oyster) as a protective layer in concrete. They concluded that this layer further reduced the depth of neutralization of exposed concretes in the tidal zone. This protection is due to the ability of Crassostrea gigas to form a resistant barrier against chemical aggressions and limit the intrusion of chlorides and other aggressive ions. Simčič et al. [32,33] explored the effects of adding fly ash in concretes exposed to marine environments. Their study showed that partial replacement of cement with 20 to 50% fly ash appreciably reduces chloride penetration. Fly ash contributes to the formation of denser, more corrosion-resistant mineral phases in marine environments, which protects metal reinforcement from premature degradation. Similarly, Zhang et al. [34] observed a palpable reduction in the chloride diffusion coefficient after 600 days of tidal exposure. The results designate that adding fly ash not only reduces chloride penetration, but also increases the durability of concrete exposed to moisture and salinity cycles. However, some research has shown that there are adverse effects of the excessive addition of silica fume (SF) in marine concretes. Indeed, Ganjian et al. [35] found that the incorporation of 7-10% SF, combined with 50% slag, resulted in an increase in water absorption from concretes exposed to the tidal zone and seawater. This could be due to a change in the porous structure of concrete, making the material more susceptible to water absorption and aggressive ion infiltration.

The study [35] has also revealed the impact of the marine environment on the properties of HVFA (High Volume Fly Ash) pastes, where 70% of cement is replaced by fly ash. Due to the low initial resistance of HVFA pastes, additions of 20% metakaolin (MK) and 10-20% quartz (Q-P) were made to compensate for this deficit. The samples were subjected to various hardening conditions in air, water, seawater and wetting/drying cycles, simulating tidal conditions over a period of 270 days. The results were analyzed using X-ray diffraction (XRD), thermogravimetry (TGA/DTG) and scanning electron microscopy (SEM), which allowed to show these mineralogical transformations at the level of the concrete paste.

3.5. Marine Silt and Dredged Sediments as Cement or Sand Substitutes

In the context of ports, silt which is abundant in marine environments and often considered a waste has great potential, particularly because of its fine grain size and its high content of silicates and aluminas. Research [36] has shown that after treatment (washing, drying, alkaline activation), it can be used as a partial substitution (10-20%) of cement or fines, without significant loss in mechanical performance and with reduced porosity. This recovery helps to limit the use of clinker and optimize the management of marine residues in the Moroccan coastal regions. [36]. Given that port and river dredging is essential to maintain the depths of navigation and create new operating basins, its planning and management represent a challenge for professionals given the large quantities of extracted sediments and the prohibitive costs of the operation. Therefore, the recovery and reuse of these materials, especially in the building sector, remains a promising solution.

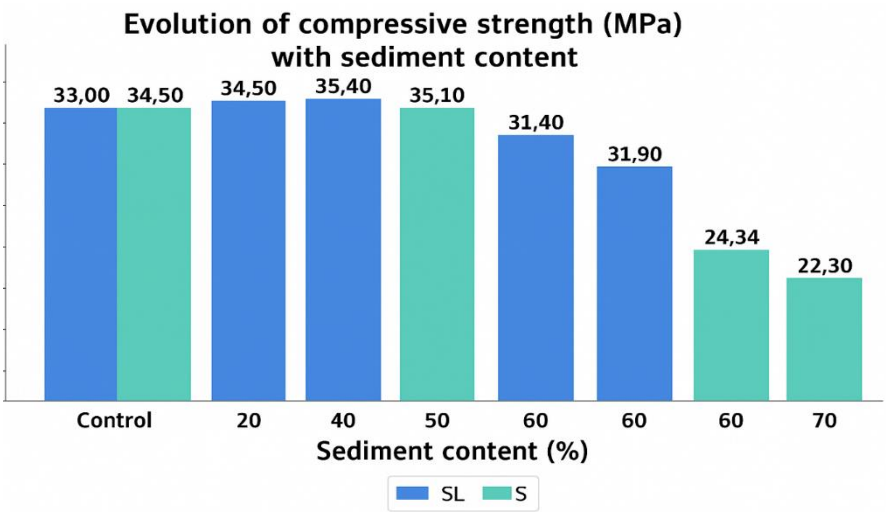

Fig. 4. Effect of Sediment Substitution Rate on the Compressive Strength of Fired Bricks [36].

A study [37] was carried out on the upgrading of sediments from the ports of Tangier and Larache by using them as a partial substitute for sand in cement mortars and in the manufacture of construction materials. The sediments, mainly composed of silt and fine sands, have a water content of 10.8% for those of Tangier and 12.5% for those of Larache. Chemical analyses show a low presence of heavy metals, but hydrocarbons are present in the sediments of Tangier at 0.2%. [36,37]. Results of mortar testing show that incorporation of up to 20% sand replacing sediment does not compromise resistance. with 10% and 20% sediment reached compression strengths of

33 MPa and 30 MPa respectively, meeting the standard for resistance in common applications [37]. In addition, durability tests, including resistance to freeze-thaw cycles, revealed that these mortars showed no degradation after 50 cycles. For the manufacture of construction materials, the addition of sediment has produced the materials with a compressive strength of 10 MPa for those containing 30% sediment and 8 MPa for those containing 70% [37]. These values are higher than the minimum strength required in the material.

The values in Figure 3 show that the Larache sediment allows to make a brick with better mechanical characteristics than those of the control for a rate substitution up to 50%. The 40% substitution rate gives resistance of 35.4 MPa higher than that of the control (7.3% increase) [36]. Thus on the same wavelength and in the context of optimizing clay substitution in the manufacture of terracotta building materials, the results showed that materials containing up to 50% of sediments from Larache have superior mechanical performances to the reference brick, with a compressive strength of 22 MPa, while those from Tangier, with 20% substitution, showed similar results to the control brick (strength of 25 MPa). However, above 60% substitution, the compressive strength drops to 15 MPa, which can be attributed to the increased presence of organic matter in sediments.

In conclusion for this study [36], the valorization of port sediments as building materials has a real interesting potential to reduce the volume of sediment to be disposed of while offering an ecological and economic alternative for the construction industry. This study [37] confirmed that these sediments can be used on a large scale without compromising the performance of the produced materials, paving the way for their use as local resources in construction.

3.6. PVC Grains and Polypropylene Fibers as Concrete-Enhancing Additives

In terms of durability, the study of shrinkage by a coupled experimentation-modeling approach showed that unidirectional drying induced moisture gradients responsible for internal stresses and cracks [39]. Control of relative humidity through internal cure, using PVC grains (partially substituting sand) and polypropylene fibers (partially replacing the binder), allows to modulate deformations and improve durability [38], [40]. PVC improves fluidity and reduces plastic shrinkage, while fibers increase compactness and limit delayed deformation. Poromechanic modeling, integrating moisture, stiffness and shrinkage, allowed to reproduce internal stresses and microcrack areas, confirming the efficiency of the fibers. However, the effect of temperature remains to be investigated, especially in construction conditions [41]. Validation of the model at full scale through durability testing (carbonation, sulphates, freeze-thaw cycles) is essential to confirm the applicability of formulations in aggressive environments [42].

The reinforcement of the concrete matrix by adding additives such as nanofillers, nano-silica, UPOFA (ultra-fine palm oil fuel ash), loam (treated loam), PVC grains and others further densify the microstructure, significantly reduces water absorption and chloride ion penetration and increases resistance to aggressive environments. Corollary, based on the results of the research presented in this chapter [21-42], these additives play an essential role in the longevity of concrete, particularly in maritime and port areas.

4. Contributions of Artificial Intelligence in Concrete Formulation

4.1. Modeling Concrete Complexity with AI in Aggressive Environments

Artificial intelligence (AI), and in particular artificial neural networks (RNAs), decision trees, or regression algorithms, have been increasingly used in the field of concrete formulation. These tools make it possible to model complex relationships between composition, mechanical properties and environmental conditions without requiring strict analytical laws [43].

In an aggressive environment, there are many parameters to consider (type of binder, porosity, resistance to chlorides, carbonation, etc.), which makes traditional models limited. AI provides an effective response to this complexity.

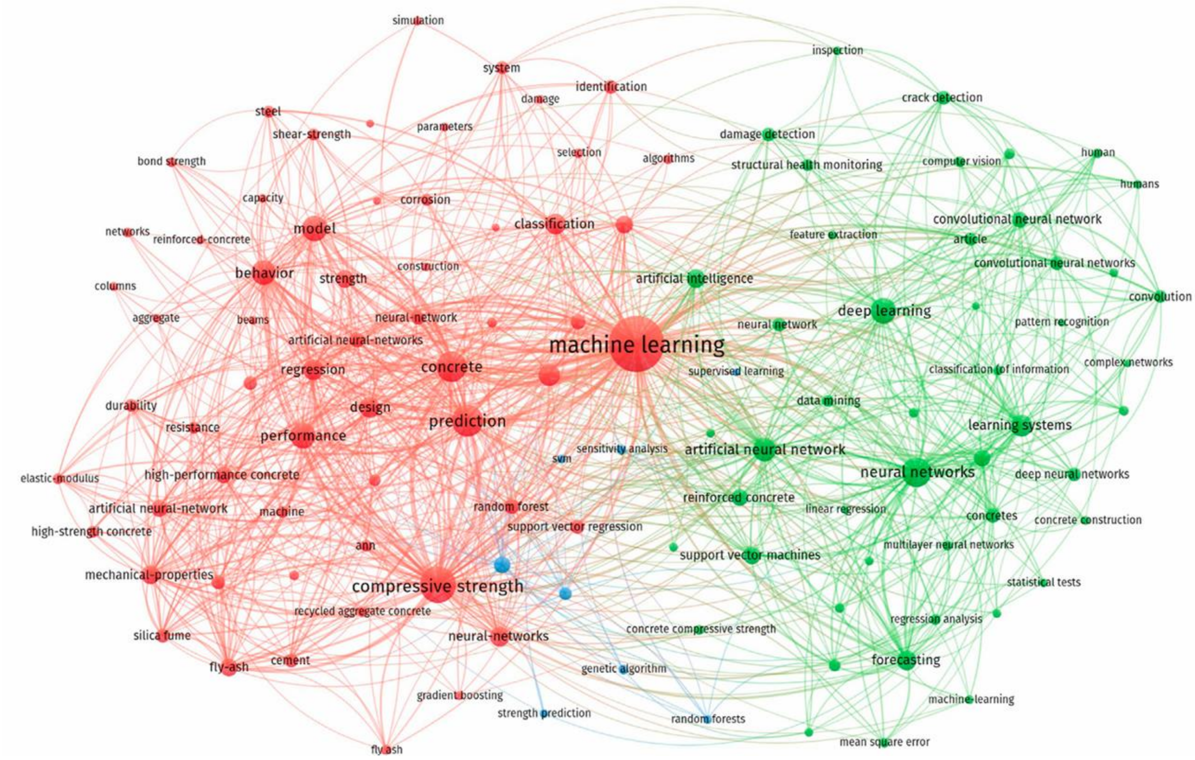

Fig. 5. Application of machine learning in concrete [44]

Figure 5 shows that ML has been used in different parts of concrete technology in different fields of studies. In Morocco [45], some laboratories are starting to develop local databases to integrate these e-learning techniques. Furthermore, the concept of Building 4.0 is directly inspired by Industry 4.0 and encompasses the digitalization of design, manufacturing and quality control processes in the construction sector. In this context, the concrete formulation becomes an integrated step in a global data-driven system. [44,45].

4.2. AI Driven Optimization and Predictive Modeling of Concrete Properties

Several recent studies [46] have used supervised learning models to optimize component dosing, predict marine sustainability or sulfates, and identify 'robust' formulations. For example, a neural network can predict compressive strength at 28 days with an error of less than 5%, based on input data such as E/C ratio, adjuvant content or sand type [46]. Indeed, the use of BIM (Building Information Modeling), combined with IoT sensors (Internet of Things), allows to collect real-time information on the performance in service and to adapt the formulations to the project requirements. All the more so as prototypes of automatic formulation systems based on multicriteria optimization algorithms (e.g. NSGA-II, genetic algorithms) are being tested in several laboratories [44]. They allow to simultaneously take into account mechanical resistance, cost, chemical durability and carbon footprint. [44, 46]

A recent study explored the effectiveness and relevance of machine learning algorithms, to accurately predict and classify concrete compressive strength taking into account formulation parameters and curing time [47]. The use of advanced analytical tools, such as SHAP (Shapley Additive Explanations) values and partial dependency graphs, allowed a detailed examination of the interactions between input variables and their impact on predictions. These results showed the potential of machine learning models to improve formulation optimization, quality assurance and compliance with engineering standards [47, 48]. The SHAP analysis, in particular, has allowed for a better understanding of the contributions of characteristics, both at the global and local scales, which has strengthened the interpretability of the model. In addition, the prediction of the mechanical characteristics of concrete such as its strength of concrete without the need for laboratory tests, undoubtedly allows to accelerate the design process by further reducing costs and time [48].

In this context, the studies conducted in this direction proposes an in-depth review of current applications of artificial intelligence, and more particularly machine learning (ML), in the field of concrete technology. The author highlights the increasing role of EL throughout the concrete life cycle, from raw material characterization to crack detection in in-service structures [44]. ML techniques make it possible to optimize the concrete formulation, predict its properties in fresh or hardened state and evaluate its durability against chemical or physical aggressions. They also offer non-destructive methods for early crack detection, including image analysis and convolutional neural networks. The study in question highlights the advantages of these approaches, including time savings, cost reduction and forecast accuracy [44, 49]. However, the author highlights the persistent challenges related to data quality, algorithm choice and understanding of these tools by civil engineers. In conclusion, the article recommends a better integration of machine learning into concrete engineering practices and university training, to facilitate the transition towards smarter and more sustainable construction [50]. Artificial intelligence (AI) has been used to predict the compressive strength of concrete, an advanced cementitious material known for its outstanding mechanical properties, high durability, very low permeability, as well as its ability to prefabricate and reinforce infrastructure works [50, 51].

In this study, an experimental database of over 200 fiber-reinforced ultra-high-performance concrete (UHSC) formulations was compiled from the scientific literature to predict flexural strength using artificial intelligence tools [52]. This base includes 15 input variables representing the characteristics of the constituent materials of the concrete: the contents of cement, fly ash, slag, silica fume, nano-silica, limestone powder, sand, aggregates, quartz powder, as well as the water contents, superplasticizer, rate of steel fibers, fiber diameter and length, and finally the curing time.

The target variable is the flexural strength, expressed in megapascals (MPa), whose values range from 5.6 to 41.5 MPa. The data was normalized and divided into two sets: 70% for model training and 30% for validation testing, with k-fold cross validation (k=10). The model performances were evaluated using standard statistical indicators: coefficient of determination (R^2), mean absolute error (MAE) and mean square error (RMSE). Among the ensemble techniques tested (Bagging, AdaBoost, Gradient Boosting, Extreme Gradient Boosting), the Bagging model showed the best performance with an R^2 of 0.95, a MAE of 2.05 MPa and a RMSE of 8.26 MPa, indicating very good prediction accuracy [52]. The SHAP analysis revealed that the variables having the most impact on flexural strength are the steel fiber ratio, curing time, superplasticizer amount, water content and active binders (cement, silica fume, quartz). This database thus constitutes a robust foundation for predictive modeling of the mechanical performance of UHSC using artificial intelligence approaches. [52, 53].

Several AI and machine learning models are commonly used in the field of concrete formulation and performance prediction, including: artificial neural networks (RNAs), decision trees, regression algorithms, as well as advanced models such as support vector regression (SVR), random forest, gradient boosting methods, LightGBM, XGBoost, and multi-layer perceptron (MLP). Each model has specific advantages depending on the characteristics of the problem to be solved [50-56]:

- Artificial neural networks (RNAs): particularly effective for modeling complex non-linear relationships between input variables (composition, environmental conditions) and mechanical properties or durability of concrete. Their ability to capture multiple interactions makes them suitable for complex formulations, but they require a large volume of data to avoid overfitting.
- Decision trees and random forest: these models are appreciated for their robustness and ability to manage heterogeneous data, as well as for their relative interpretability compared to neural networks. They are effective in identifying the most influential variables in the formulation and are less sensitive to noise in the data.
- Support Vector Regression (SVR): powerful for regression problems with moderate-sized datasets, SVR offers good generalization and an ability to model non-linear relationships via kernels. It is often used when the data are few but qualitative.

- Gradient Boosting Methods (Gradient Boosting, LightGBM, XGBoost): these ensemble techniques combine several weak models to improve predictive accuracy. They are very efficient in predicting complex properties such as durability or long-term resistance, while providing interpretability tools (e.g. SHAP) that help to understand the contributions of variables.
- Multilayer Perceptron (MLP): a type of simple but powerful neural network, often used for the prediction of mechanical properties when the data structure is not too complex.

In summary, the choice of model depends on the type and quantity of data available, the complexity of the relationships to be modeled, and the importance given to the interpretability of the results. For example, ensemble methods like XGBoost are preferred for their performance and interpretative ability in contexts where precision is crucial. Indeed, among the models tested, XGBoost demonstrated excellent performance with a determination coefficient (R^2) of 0.905 and a mean square error (MSE) of 69.48, thus highlighting its robustness and effectiveness in predicting concrete properties [50-56]. On the other hand, neural networks are better suited to very complex systems, while decision trees facilitate a more intuitive understanding of the factors influencing concrete durability.

4.3. SHAP-Based Interpretability in AI Models for Cementitious Material Performance Prediction

In order to overcome the "black box" nature inherent in many machine learning algorithms especially ensemble methods such as Gradient Boosting or hybrid models of explainable artificial intelligence (XAI) tools like SHAP (Shapley Additive Explanations) have become essential. These tools offer transparency in the model behavior by quantifying the contribution of each input characteristic to a given prediction. SHAP is based on cooperative game theory and assigns each feature an importance value for a particular prediction, in a manner analogous to how Shapley values allocate winnings to players based on their contributions to the total win in a cooperative game. As highlighted by Li et al. [54] in their study on fly ash concrete, the use of SHAP proved effective in identifying the most influential parameters for predicting compressive strength using both simple and hybrid machine learning models. This interpretability is essential not only for validating the robustness of predictive models but also for providing engineering insights that support the optimization of real-world concrete mixture designs. The study confirms that SHAP offers a consistent and mathematically rigorous approach to explaining complex interactions between variables such as fly ash content, water-to-binder ratio, and curing conditions. In particular, the water/binder ratio was found to have a decisive impact: its increase leads to a notable reduction in compressive strength, a finding corroborated by the works of Wang and Yu [56,57]. In another study [55], a SHAP analysis was also performed to interpret the model's predictions regarding flexural strength in ultra-high performance steel fiber reinforced concrete (UHPC). The results highlighted the dominant role of steel fibers, confirming their ability to delay both crack initiation and propagation. A positive contribution of fiber content to strength was observed, but only up to a certain optimal threshold, beyond which excess fiber content leads to saturation or segregation effects, negatively impacting.

Several previous studies have already demonstrated the effectiveness of artificial intelligence (AI) in modeling the mechanical behavior of special concretes, such as those incorporating fly ash or recycled aggregates [58]. The present work is part of this dynamic by highlighting the performance of advanced machine learning (ML) models coupled with an explicable approach (SHAP), not only to accurately predict concrete strength, but also to propose an innovative method, reliable and optimized formulation of mixtures. This method positions itself as an effective alternative to conventional empirical approaches, which are often time-consuming, costly and unreproducible [59-60]. In addition, AI and ML [59-60] contribute to the refinement and efficient optimization of concrete formulation by effectively solving the equation that links material composition, intrinsic properties of the constituents, and environmental conditions, especially under aggressive exposure scenarios: P = f(C, M, E), where:

- P: Target mechanical properties of the final concrete (e.g., compressive or flexural strength)
- C: Concrete composition (e.g., binder content, water-to-cement ratio, additives)

- M: Mechanical and physical characteristics of individual raw materials (e.g., aggregate strength, fiber stiffness, binder reactivity)
- E: Environmental conditions (e.g., curing regime, temperature, chemical exposure)

This formulation reflects the interdependence between the input materials and conditions on the resulting concrete performance. By leveraging machine learning and explainable AI techniques such as SHAP, it becomes possible to model these interactions accurately and improve the formulation process beyond traditional empirical approaches. The integration of AI into construction 4.0 promotes better adaptation of formulations through real-time monitoring systems and the use of massive data.

5. Critical Discussion and Perspectives

The confrontation of data from academic theses, scientific articles and industrial feedback highlights that, despite the considerable advances in concrete technology, several major technological challenges remain. Common formulations struggle to adapt to complex environments such as marine, sulphate or acid environments. In addition to not taking into account the non-linear and dynamic effects related to the simultaneous combination of aggressive factors (temperature, humidity, chloride ions, sulfates, acidity), these formulations often involve rigid manufacturing processes, poorly optimized compositions, and require the addition of mineral additives and high-performance materials, as well as extended validation cycles. These requirements lead to additional costs, increased delays, and complexity of implementation in the field. This is also the case for certain alternatives such as dredging sludge or sediments, which although offering interesting performances on mechanical and environmental levels, pose additional difficulties: lack of performance standards, high characterization costs, high variability of materials, and lack of regulatory framework for their extraction. These barriers reduce the confidence of industrial actors, increase the perception of risk, and slow down their adoption on a large scale.

In this context, AI stands out for its ability to model complex and multivariate relationships, allowing the optimization of concrete formulation and anticipating its behavior in the medium and long term. Its effectiveness, however, depends on the existence of complete, structured and accessible databases. in addition, AI allows for the intelligent exploitation of local resources, by learning the properties of regional materials to precisely adjust dosages and formulate concretes adapted to specific constraints. This synergy between territorial valorization and advanced modeling gives birth to a new generation of concrete, more sustainable, resilient and adapted to aggressive contexts. To achieve these advances, targeted efforts are needed: development of appropriate international standards, creation of open data repositories, training of professionals in AI tools, and strengthening collaboration between engineers, materials researchers, data scientists and policy makers.

6.Conclusion

In conclusion, this study highlights the importance of an integrated approach to design sustainable and effective concretes, especially for structures exposed to aggressive environments such as marine, sulphate or acid environments. By combining the use of alternative materials as additives with AI tools, it becomes possible while optimizing costs and deadlines, to formulate a resistant concrete, ecological and adapted to environmental constraints. The results obtained highlight not only the technical and environmental advantages of these solutions, but also the current limitations in terms of standardization, available data and industrial applicability, which will need to be overcome in future work.

- The integration of alternative materials such as mud, silt, treated sediments, fly ash, ultrafine silica, polymer fibers and nanomaterials (nano-silica, graphene, nanotubes) significantly improve concrete’s resistance to chemical and physical aggressions, while contributing to the reduction of CO emissions and the valorization of local waste; in particular, fly ash allows for a decrease in the heat of hydration and an increase in sustainability in sulphated or extreme environments.

- Conventional formulations remain limited by the rigidity of processes, high costs associated with the use of specialized additives, low adaptability to complex environmental conditions, and the lack of technical standards for non-conventional materials.
- Artificial intelligence tools, such as neural networks, SHAP and supervised learning algorithms, have made it possible to reliably predict the long-term performance of concrete and design optimized formulations based on exposure conditions.
- The AI approach allows a fine customization of compositions according to geological, climatic and functional constraints, by integrating multicriteria criteria such as resistance to compression, durability against sulfates or even energy footprint.
- The integration of the Construction 4.0 approach, based on advanced digital modeling and process digitalization, opens new perspectives for the design of smart, resilient and resource-efficient infrastructures.
- Despite the advances presented, several locks still need to be lifted: lack of standardization for alternative materials, absence of open databases, lack of training of actors in AI, and scarcity of large-scale experimental validations.
- The originality of this work lies in the synergy proposed between the exploitation of local resources, the valorization of waste, and the application of artificial intelligence to the formulation of sustainable concrete, an approach still little developed in the literature.
- Future perspectives should be oriented towards a more advanced multicriteria analysis (technical, economic, environmental), the development of structured data repositories, accelerated protocols for sustainability tests, and guidelines for normative integration on an industrial scale.

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