JOURNAL OF MATERIALS & CONSTRUCTION

Journal of Materials and Construction
ISSN 2734-9438
Website: www. jomc.vn

Experimental study on the development of concrete for use in coastal structural components

Thai Minh Quan[1*], Nguyen Thanh Sang[2]

[1*]Faculty of Construction Engineering, University of Transport and Communications

KEYWORDS

Coastal concrete
Fly ash
Ground-granulated blast-furnace slag
Chloride resistance
Durability

ABSTRACT

In this paper, an experimental study was performed on the concrete used in structural members for coastal areas. Because the reaction conditions are severe in marine environments of high salinity, humidity, and temperature change, the durability of concrete is a pivotal subject. The research focuses on optimizing concrete mix designs by incorporating supplementary cementitious materials—specifically 10% fly ash and 30–40% ground granulated blast-furnace slag (GGBFS) to enhance the mechanical performance and durability of the concrete. A series of laboratory tests were conducted, including compressive strength, chloride ion penetration, to evaluate the behavior of the proposed concrete mixtures. The results indicate that certain combinations of supplementary cementitious materials (SCMs) and admixtures significantly improve resistance to chloride ingress and corrosion, making them suitable candidates for use in coastal structural components. These concrete mixtures achieved a minimum compressive strength of 30 MPa at 28 days and demonstrated excellent durability with charge passed values below 1000 Coulombs, indicating low chloride ion penetrability. These findings contribute to the development of more durable and sustainable concrete structures in marine environments.

1. Introduction

Viet Nam has many advantages compared with other countries, especially in terms of its geographical location and natural conditions, with a coastline of more than 3,000 km. Amid strong economic growth in coastal cities, the demand for residential buildings, hotels, and high-rise office structures has been rapidly increasing in recent years. Thanks to its outstanding advantages over other materials, reinforced concrete remains the primary material used for load-bearing structures in construction.

Corrosion due to chloride ions is emerging as a major threat to the load-bearing capacity and lifespan of reinforced concrete (RC) structures in marine environments, and recent studies have shed light on this mechanism of action [1-3]. The 7-year long real-world experiment by Xu et al. [4] observed the accumulation of chloride ions in specific regions of RC beams, causing steel corrosion with the formation of characteristic corrosion products.

The research by Li et al. [5] clearly demonstrated that cracks in concrete provide ideal conditions for chloride ions to "attack" the reinforcing steel, accelerating this destructive process. The stark difference in corrosion rate between carbon steel in cracked concrete and stainless steel (which maintained its passive layer) was proven in a salt-containing environment. More seriously, the numerical model by Sun et al. [6-8] revealed that the combined effect of chloride and sulfate ions in marine environments can create a negative "resonance" effect, increasing the corrosion rate and leading to the rapid degradation of offshore RC structures. These research findings not only warn about the importance of preventing chloride ion ingress but also emphasize the necessity of effective crack management in RC. These are key factors in ensuring the safety, usability, and extended lifespan of concrete structures in challenging marine environments.

a. Steel corrosion b. Concrete cracking and spalling

Figure 1. Reinforced concrete piles corroded in marine environments (Center in Vietnam).

The corrosion resistance requirements for reinforced concrete structures in marine environments are specified in the Vietnamese national standard TCVN 9346:2012 – “Concrete and Reinforced Concrete Structures – Requirements for Corrosion Protection in Marine Environments.” This standard outlines detailed provisions for design, material selection, and construction methods to ensure the durability and long-term performance of concrete and reinforced concrete

*Corresponding author: minhquan.thai@utc.edu.vn
Received 12/04/2025, explanation 28/04/2025, accepted 05/05/2025
Link DOI: https://doi.org/10.54772/jomc.v15i01.906

structures under aggressive marine conditions. The ultimate goal is to achieve a service life of up to 100 years, meeting the demands for safety, cost-efficiency, and sustainability in coastal infrastructure development.

In addition to protective measures for reinforced concrete against corrosion, the research and application of concrete types with high resistance to marine environments-such as those incorporating mineral admixtures like fly ash and ground granulated blast-furnace slag (GGBFS)-have been receiving significant attention. Studies have shown that structures using these types of concrete exhibit excellent durability in marine conditions, contributing to an extended service life of the construction.

The use of mineral admixtures, particularly fly ash and ground granulated blast-furnace slag (GGBFS), has been shown to significantly enhance the performance of concrete in marine environments. These materials refine the pore structure of the cement paste and accelerate the hydration process, thereby improving the bonding and cohesion between particles. As a result, the concrete matrix becomes denser and more uniform, effectively reducing the presence of large capillary pores. This leads to greater resistance against aggressive agents such as chloride ions, acids, and alkalis, which are common in coastal conditions, and ultimately contributes to the extended service life of concrete structures. Furthermore, domestic research has confirmed that the inclusion of fly ash and GGBFS not only improves mechanical properties and long-term durability, but also reduces slump loss, prolongs setting time, and enhances impermeability-key characteristics for ensuring structural integrity in harsh marine environments. [9–13].

In this study, fly ash was combined with ground granulated blast-furnace slag to partially replace cement in producing concrete with low chloride ion permeability and enhanced salt resistance. The aim of designing concrete mixtures with enhanced chloride ion resistance and low permeability is closely aligned with sustainable construction goals. This approach leverages the abundant availability of local materials, reduces construction costs, and contributes to environmental protection. To fully harness this potential, it is essential to conduct in-depth studies on mix design optimization, material interaction mechanisms, and techno-economic evaluations-paving the way for the widespread application of such materials in Vietnam's transportation infrastructure.

2. Research Methodology

This study focuses on evaluating the effectiveness of incorporating fly ash and ground granulated blast-furnace slag (GGBFS) into concrete mixtures intended for use in coastal structures. The experimental program was designed to assess the chloride ion permeability and salt resistance of the concrete, aiming to determine an optimal mix that balances performance and sustainability.

2.1. Theoretical basis

Chloride-induced corrosion is one of the most severe forms of deterioration affecting reinforced concrete structures in marine environments. Chloride ions penetrate the concrete cover and depassivate the steel reinforcement, leading to rust formation, cracking, and eventual structural failure. The use of supplementary cementitious materials (SCMs), particularly fly ash and ground granulated blast-furnace slag (GGBFS), has been shown to significantly improve the resistance of concrete to chloride ingress.

Fly ash, a by-product of coal combustion in thermal power plants, and GGBFS, derived from the steel manufacturing industry, react with calcium hydroxide during the cement hydration process to form additional calcium silicate hydrate (C-S-H) gel. The pozzolanic reaction is a key mechanism contributing to the enhanced durability and sustainability of modern concrete. When fly ash GGBFS are incorporated into concrete mixtures, they react with calcium hydroxide [$Ca(OH)_2$], a by-product of Portland cement hydration, in the presence of water. These materials contain reactive forms of silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), which undergo a secondary reaction with $Ca(OH)_2$ to form additional calcium silicate hydrate (C-S-H) and, in some cases, calcium aluminate hydrate (C-A-H). The overall reaction can be simplified as:

$$SiO_2 \text{ (from fly ash and slag)} + Ca(OH)_2 + H_2O => \text{C-S-H (gel)} \quad (1)$$

This gel refines the pore structure, reduces permeability, and enhances the overall durability of concrete. Furthermore, the pozzolanic reaction reduces the content of $Ca(OH)_2$, a phase vulnerable to leaching in aggressive environments, particularly marine conditions. The improved microstructural integrity also enhances resistance to chloride ion (Cl^-) penetration, which is critical for the long-term performance of reinforced concrete structures exposed to corrosive agents. As a result, the rate of chloride ion diffusion into the concrete matrix is greatly reduced, which delays the onset of steel corrosion. Numerous studies have confirmed that concrete containing high-quality fly ash and GGBFS exhibits lower chloride diffusion coefficients and reduced corrosion rates of reinforcing steel compared to ordinary Portland cement concrete [10-12]. This makes them particularly suitable for applications in coastal infrastructure, where long-term durability is critical.

2.2. Materials

The binder materials used for the preparation of concrete specimens consisted of grade-40 Portland cement (PC), in accordance with TCVN 2682:2020. The mixing water was domestic water, meeting the requirements of TCVN 4506:2012 — the standard for water used in concrete and mortar. A Polycarboxylate-based superplasticizer (ĐQ-HP2) was employed to significantly reduce water content and promote early strength development in the concrete.

The fly ash used in this study is Class F fly ash from the Nghi Son Thermal Power Plant. It meets the technical requirements specified in TCVN 10302 and ASTM C618. The chemical composition of Nghi Son fly ash is presented in Table 1.

a. Cement PC40 b. ĐQ-HP2 superplasticizer

Figure 2. Cement and superplasticizer.

The total content of the three oxides SiO_2 + Al_2O_3 + Fe_2O_3 is 78.99 %, which is greater than or equal to the 70 % minimum requirement; thus, the Nghi Son thermal power plant fly ash is classified as Class F with high pozzolanic activity according to ASTM C618. The low total content of CaO and MgO indicates that the fly ash is acidic, making it suitable for pozzolanic reactions with $Ca(OH)_2$ in concrete. All other indicators meet the technical requirements of ASTM C618.

Blast furnace slag is used in concrete at 30–45 % by the weight of the binder. The chemical composition of ground granulated blast-furnace slag (GGBFS) S95 from Hoa Phat used in this study is presented in Table 2.

The above composition shows that the total content of CaO + SiO_2 + Al_2O_3 is 79.59 %, which is greater than or equal to the 70 % requirement, thereby satisfying Clause 5.2 of TCVN 11586:2016 regarding the requirements for slag used as a mineral additive in cement. Additionally, the MgO content is below 10 %, ensuring no harmful expansion in concrete. The low SO_3 content (0,56 %) helps reduce the risk of steel reinforcement corrosion, and the very low total content of Na_2O and K_2O minimizes the risk of alkali–aggregate reactions. The basicity index of the slag, calculated from the given composition, is 1,76, which meets the requirements of TCVN 4315:2024. This indicates high pozzolanic reactivity, allowing the slag to react effectively with free lime ($Ca(OH)_2$) during the hydration process.

Table 1. Chemical composition of Nghi Son cement.

Indicator	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	LOI
Content (%)	20,3	3,51	5,05	62,81	3,02	2,00	0,039	0,772	1,83	20,3

Table 2. Chemical composition of Nghi Son fly ash.

Indicator	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	LOI
Content (%)	46,6	6,22	26,1	2	1,91	1	4,3	0,13	0,3	6,8

Table 2. Chemical composition of GGBFS.

Indicator	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3
Content, %	31,35	31,5	16,74	3,7	7,44	0,83	0,01	0,56

a. GGBFS b. Fly ash

Figure 3. Ground granulated blast furnace slag (GGBFS) S95 and fly ash.

The fine aggregates employed in this study comprise 50 % crushed sand sourced from Thanh Hoa and 50 % natural river sand. The particle size distribution along with selected physical and mechanical properties of the fine aggregates are presented in the accompanying Figure 4.

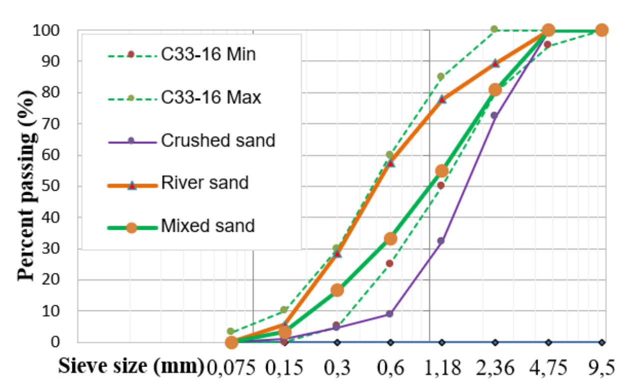


Figure 4. The particle size distribution curve of the fine aggregates.

Mixed sand, a 50:50 blend of crushed and river sand, lies well within the C33 grading envelope and shows a balanced gradation. Its curve runs between those of the individual components, suggesting that blending can help achieve a more favorable particle distribution. The results indicate that mixed sand meets the ASTM C33 gradation requirements, offering a compromise between the flowability of river sand and the mechanical stability of crushed sand. This makes it a suitable candidate for concrete production where both workability and strength are critical.

The particle size distribution of the coarse aggregate was determined through a sieve analysis in accordance with ASTM C136. The obtained gradation curve is shown in Figure 4, alongside the upper and lower specification limits defined by ASTM C33 for aggregates with a nominal maximum size of 19 mm.

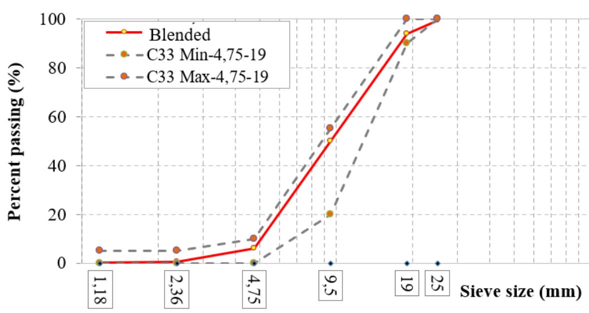


Figure 5. The particle size distribution curve of the coarse aggregates.

The red curve represents the actual gradation of the blended coarse aggregates. The aggregate gradation falls entirely within the ASTM C33 specification limits (dashed lines), indicating conformance to the standard. The particle size distribution demonstrates a smooth and continuous gradation from 4.75 mm to 19 mm, with minimal fine particles retained on sieves smaller than 4.75 mm. This is consistent with the gradation requirements for structural concrete.

2.3. Mix design of salt-resistant concrete for reinforced concrete piles

Based on the physical-mechanical properties and particle composition of crushed sand, river sand, stone, along with binders such as cement, finely ground blast furnace slag, and fly ash, the mix design has been formulated with appropriate proportions, as detailed in Table 3. The designations are as follows:

- C30X30T10 - C30X40T10: Concrete with a strength class of C30, using 30 % - 35 % - 40 % blast furnace slag and 10 % fly ash to replace cement.

- C30XM100: Concrete with a strength class of C30, using 100 % cement with no mineral admixtures.

Table 3. Mix proportions of concrete mixtures.

Mixture	Cement	Fly Ash	GGBFS	Water	Crushed Sand	River Sand	Gravel 5 x20	Admixtures
C30X30T10	251	42	126	158	369	369	1106	4,20
C30X35T10	230	42	147	171	368	368	1106	4,30
C30X40T10	210	42	168	176	367	367	1106	4,35
C30XM100	419	0	0	171	0	763	1106	5,50

The concrete mixtures C30X30T10, C30X35T10, C30X40T10, and C30XM100 have distinct compositions. Total binder content (419-420 kg) remains consistent, but C30XM100 stands out by excluding fly ash and GGBFS, focusing on cement and crushed sand. The water/cement ratio increases from 0.38 to 0.41.

3. Research Results and Discussion

3.1. Experimental Results

3.1.1. Evaluation of Compressive Strength

The Figure 6 below illustrates the compressive strength (MPa) and strength development ratios (R3/R28, R7/R28) of four concrete mixtures-C30X30T10, C30X35T10, C30X40T10, and C30XM100-at 3 days, 7 days, 28 days, and 90 days.

The C30XM100 concrete mixture, without fly ash or GGBFS, demonstrates the highest early strength. This can be attributed to its faster hydration rate compared to mixtures containing fly ash and GGBFS, as evidenced by the lower R3/R28 ratios.

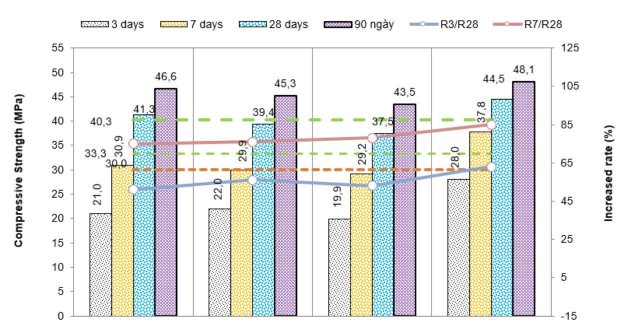


Figure 6. Compressive strength test results.

At 28 days, the C30X40T10 mixture (with the highest GGBFS content) achieves the highest strength (43.5 MPa), proving GGBFS's positive impact on strength development at this stage. Although C30XM100 still exhibits slightly higher strength (44.1 MPa), this can likely be linked to its high cement content and low water/cement ratio (0.41).

However, the C30X30T10 and C30X35T10 mixtures show a significant improvement in strength from 28 to 90 days (increasing by

15.6 % and 14.9 %, respectively), highlighting the advantage of pozzolanic reactions from fly ash and GGBFS in forming additional C-S-H.

In summary, incorporating fly ash and GGBFS in concrete not only reduces the required cement quantity, saving costs, but also enhances the sustainability and durability of the structure. Consequently, the C30X30T10 and C30X35T10 mixtures are suitable choices for common applications where a balance between strength and long-term performance is desired.

3.1.2. Evaluation of Splitting Tensile Strength

The graph in figure 7 allows for a comparison of the splitting tensile strength of different concrete mixtures over time, from early to later stages, while also providing information on their strength development rate. The mixtures with varying compositions, especially the content of the mineral admixture Fly ash and GGBFS show distinct differences in splitting tensile strength over time.

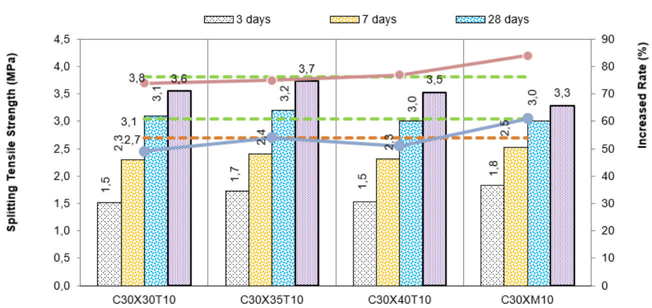


Figure 7. Splitting tensile strength test results.

Similar to the compressive strength results, the C30X40T10 mix (highest GGBFS content) achieved the highest splitting tensile strength, highlighting the significant role of GGBFS in enhancing strength at 90 days. The pozzolanic reaction of GGBFS produces additional hydration products, increasing the density and strength of the concrete.

The C30XM100 mix (without any additives) exhibited higher strength than the mixes with lower GGBFS content (C30X30T10), but lower strength than those with higher GGBFS content (C30X35T10, C30X40T10). This indicates that while cement plays a crucial role in early strength development, mineral admixtures can contribute to achieving higher strength at later ages.

3.2. Results of chloride ion penetration test

The chloride ion penetration test in concrete (RCPT – Rapid Chloride Penetration Test) is conducted according to ASTM C1202 to evaluate the concrete's resistance to chloride ion ingress. In this test in the figure 8, a cylindrical concrete specimen is placed between two cells containing 3 % NaCl solution and 0.3N NaOH solution. A constant voltage of 60V is applied for 6 hours, driving chloride ions through the specimen. The total charge passed, measured in Coulombs, is recorded and used to classify the level of chloride ion penetrability: the lower the charge, the better the resistance.

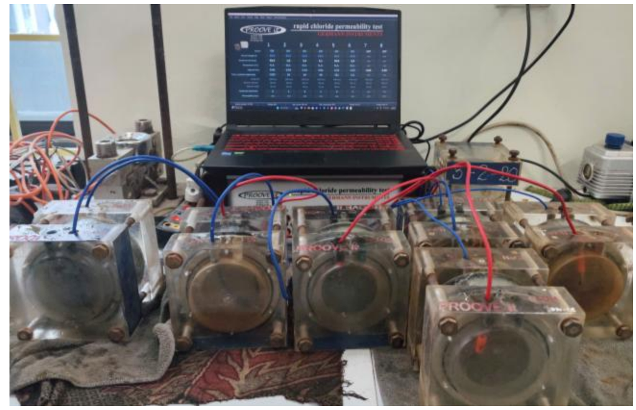


Figure 8. Chloride ion penetration test.

The bar chart in the Figure 9 below illustrates the charge passed Q (in Coulombs) after 28 days for four different concrete mixtures: C30X30T10, C30X35T10, C30X40T10, and C30XM100. The left vertical axis represents the value of Q, while the horizontal axis indicates the types of concrete mixtures. Additionally, the chart includes horizontal lines that indicate standard levels of chloride ion penetrability, categorized as very high, high, moderate, and low.

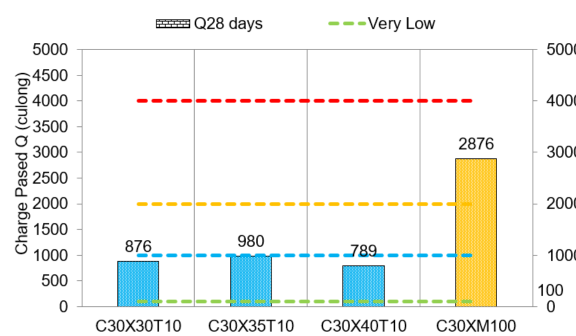


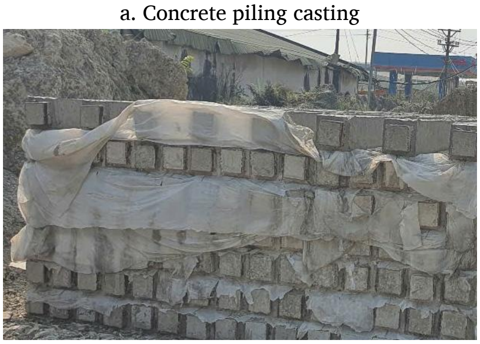
Figure 9. Chloride ion permeability test results.

Concrete samples containing mineral admixtures (C30X30T10, C30X35T10, C30X40T10) exhibited significantly better resistance to chloride ion penetration compared to the sample without admixtures (C30XM100). An increase in GGBFS content (from C30X30T10 to C30X40T10) tended to reduce the charge passed, indicating improved chloride ion resistance. Among the tested samples, C30X40T10 (with the highest GGBFS content) demonstrated the best resistance. The C30XM100 sample (containing only cement) showed the poorest performance, with chloride ion penetrability falling within the moderate to high range according to standards. This highlights the important role of mineral admixtures in reducing chloride ion permeability in concrete. This result reflects the durability of concrete, especially in aggressive environments such as marine or salt-exposed conditions.

3.3. Application of salt-resistant concrete in coastal structure construction

Salt-resistant concrete that designed in the upper section is used for manufacturing reinforced concrete piles in residential buildings and bridge structures located in coastal areas, where exposure to aggressive environments is common. In practice, concrete piles can be either square or circular, depending on design requirements and construction conditions. Square piles are commonly used in residential and onshore projects due to their ease of construction and good connection with foundation structures, see the figure 10. Meanwhile, circular piles-especially prestressed spun piles-are often applied in bridge works or offshore structures thanks to their superior load-bearing capacity and enhanced durability in harsh environments. Therefore, the concrete used must ensure both high strength and strong resistance to chloride-induced corrosion to guarantee the long-term durability of the structure.

a. Concrete piling casting



b. Salt-resistant concrete piles

Figure 10. Reinforced Concrete Piles for Coastal and Marine Construction Projects (center in Vietnam).

Besides pile structure, in practice, the proposed concrete mixtures have been effectively applied in structural elements such as reinforced beams, slabs, and bridge decks, where durability and long-term performance are essential. Their improved sustainability and cost-efficiency also make them suitable for use in retaining walls and precast components.

The effectiveness of this type of concrete is also demonstrated in terms of economic and environmental aspects, as shown in Figures 11 and 12 below. The Figure 11 illustrates a combination chart with columns and a line, comparing material cost (VND/1m^3 of concrete) represented by columns and cost reduction percentage (%) represented by a line between four concrete mixtures: C30X30T10, C30X35T10, C30X40T10, and C30XM100.

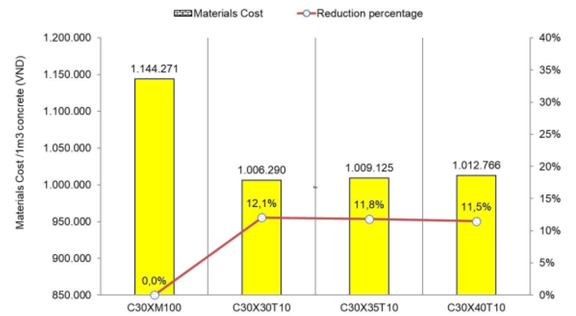


Figure 11. Materials cost of mix concrete design.

The reference mix (C30XM100), which uses 100 % cement, has the highest cost, whereas the mixes incorporating fly ash and slag (C30X30T10, C30X35T10, C30X40T10) demonstrate cost savings ranging from 11.5 % to 12.1 %. These results clearly demonstrate the economic benefits of using industrial by-products in concrete.

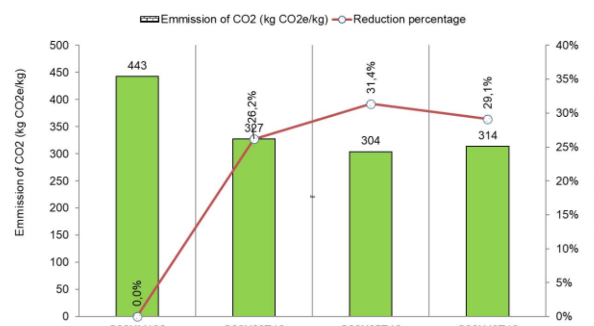


Figure 12. Emisssion reduction of mix concrete design.

This chart in Figure 12 above clearly illustrates the benefits of using mineral admixtures in concrete, which helps reduce emissions compared to traditional concrete that only uses cement. Concrete mixtures containing mineral admixtures (C30X30T10, C30X35T10, C30X40T10) show a significantly higher emission reduction rate compared to the C30XM100 mixture (without admixtures). The figure above shows the CO_2 emissions (green bars) and the emission reduction percentage (red line) per kilogram of concrete for different mix designs. The reference mix (C30XM100) emits 443 kg CO_2e/kg. With partial replacement of cement by fly ash and slag, the emissions are significantly reduced: C30X30T10: 318 kg CO_2e/kg (28.2 % reduction), C30X35T10: 304 kg CO_2e/kg (31.4 % reduction), C30X40T10: 314 kg CO_2e/kg (29.1 % reduction). This demonstrates that the use of fly ash and/or GGBFS helps reduce the amount of cement required, thereby lowering CO_2 emissions associated with cement production. The C30X35T10 and C30X40T10 mixture stands out with a good balance between economic efficiency and environmental benefits.

The two figures clearly illustrate the dual benefits-economic and environmental-of partially replacing cement with fly ash and slag in concrete. The material cost was reduced by 11.5 % to 12.1 %, while CO_2 emissions decreased significantly, reaching up to 31.4 % reduction in the C30X35T10 mix. This demonstrates that using fly ash and slag is not only a technically viable solution but also a practical contribution to sustainability goals in the construction industry. The synergy of cost efficiency and environmental performance strengthens the case for broader implementation in real-world applications.

4. Conclusions

The concrete mixtures presented in this study are designed to optimize both strength and durability, particularly in aggressive environments such as marine conditions. These mixtures include C30X30T10, C30X35T10, and C30X40T10, which are made with a combination of Ordinary Portland Cement (OPC), fly ash, and Ground Granulated Blast Furnace Slag (GGBFS). Specifically, these mixtures contain 30 % to 40 % GGBFS and 10 % fly ash as partial replacements for cement. The C30XM100 mixture, on the other hand, is composed solely of cement, without the addition of any mineral admixtures.

Incorporating mineral admixtures such as fly ash and GGBFS into concrete significantly enhances both its performance and sustainability. The mixtures containing mineral admixtures (C30X30T10, C30X35T10, and C30X40T10) show improved long-term strength and resistance to chloride ion penetration, with the highest performance observed in the C30X40T10 mixture. The C30X40T10 mixture, with the highest content of GGBFS (40 %) and 10 % fly ash, reached the highest strength of 43,5 MPa at 28 days. Notably, the C30X40T10 mix achieved a charge passed value of just 789 Coulombs, which is at the level required for durable concrete. These benefits are due to the pozzolanic reactions that contribute to strength development over time, making these mixtures ideal for applications where durability and environmental sustainability are prioritized. On the other hand, the C30XM100 mixture, containing only cement, shows better early strength but lacks the durability benefits provided by mineral admixtures.

The addition of fly ash and GGBFS also plays a crucial role in reducing the environmental impact of concrete production. The C30X35T10 and C30X40T10 mixture, in particular, achieves a good balance between cost efficiency and emission reduction. The findings clearly demonstrate that mineral admixtures not only help reduce CO2 emissions by minimizing the amount of cement required but also lower material costs without compromising on performance.

In coastal and maritime structures, which may be often in the presence of aggressive environments, mineral admixed concrete mixtures have greater resistance to chloride induced corrosion, thereby leading to the durability of structures such as reinforced concrete piles, used for residential homes and bridges. Therefore, the use of fly ash and GGBFS in concrete mixes is an effective and environmental friendly approach.

References

[1]. Zheng Li, et al., "Asymmetric deterioration of reinforced concrete marine piles subjected to nonuniformly localized corrosion: Experimental study", *Case Studies in Construction Materials*, Volume 20, 2024, https://doi.org/10.1016/j.cscm.2024.e03145.

[2]. Masoume Hoseinzade, Mohammadmahdi Esfahani, Fatemeh Arbab, Milad Shakiba, Mohammad Yekrangnia, "Residual flexural capacity of pre-cracked RC beams exposed to chloride penetration at the sea surface temperature," Construction and Building Materials, Volume 343, 2022, https://doi.org/10.1016/j.conbuildmat.2022.128126.

[3]. Yuan, W.; Li, X.; Pang, X.; Tian, C.; Li, Z.; Zhou, P.; Wang, Y. Cyclic Behavior of Rectangular Bridge Piers Subjected to the Coupling Effects of Chloride Corrosion and Bidirectional Loading. Buildings 2023, 13, 425. https://doi.org/10.3390/buildings13020425

[4]. Xu, Y., Wang, J., Zhang, S., & Zhou, J. (2023). Long-term chloride penetration and corrosion of RC beams exposed to marine environment: Experimental observations and modeling. Construction and Building Materials, 397, 131963. https://doi.org/10.1016/j.conbuildmat.2023.131963

[5]. Li, Q., Li, H., Zhang, Y., Zhang, T., & Wang, X. (2022). Chloride-induced corrosion behaviors of carbon and stainless-steel reinforcements in cracked concrete. Structural Concrete, 24(1), 236–251. https://doi.org/10.1002/suco.202200296

[6]. Sun, Z., Zhang, X., Yu, Z., & Wu, Y. (2022). Degradation of concrete in marine environment under coupled chloride and sulfate attack: A numerical and experimental study. Construction and Building Materials, 341, 127946. https://doi.org/10.1016/j.conbuildmat.2022.127946

[7]. Nguyen, H. T., Nguyen, V. T., & Pham, D. Q. (2021). Durability of road concrete incorporating ground granulated blast-furnace slag (GGBFS) under chloride-induced corrosion. Advances in Civil Engineering, 2021, 8851005. https://doi.org/10.1155/2021/8851005

[8]. Tan, L., Yu, R., & Shui, Z. (2021). Microstructural evolution and phase development of blended cement mortars exposed to chloride and sulfate attack. Materials, 14(16), 4430. https://doi.org/10.3390/ma14164430

[9]. Yuichiro Kawabata, et al., "The long-term suppression effects of fly ash and slag on the expansion of heat-cured mortar due to delayed ettringite formation," *Construction and Building Materials*, Volume 310, 2021, https://doi.org/10.1016/j.conbuildmat.2021.125235.

[10]. Ho Van Quan, The effect of the binder on porosity and chloride diffusion decay coefficient of hpc. *Transport and Communications Science Journal*, Vol 71, Issue 9 (12/2020), 1120-1129. https://doi.org/10.47869/tcsj.71.9.10.

[11]. Sundar Rathnarajan, et al., Carbonation model for concretes with fly ash, slag, and limestone calcined clay - using accelerated and five - year natural exposure data, *Cement and Concrete Composites*, Volume 126, 2022. https://doi.org/10.1016/j.cemconcomp.2021.104329.

[12]. Nguyễn Công Thắng, Nguyễn Văn Tuấn, Phạm Hữu Hanh, Nguyễn Trọng Lâm, "Nghiên cứu chế tạo Bê tông chất lượng siêu cao sử dụng hỗn hợp phụ gia khoáng Silica Fume và Tro bay sẵn có ở Việt Nam". *Tạp chí Khoa học Công nghệ Xây dựng* số 2, tr.24-31, 2013.

[13]. Boğa, A. R., Topçu, İ. B. "*Influence of fly ash on corrosion resis-tance and chloride ion permeability of concrete*", *Construction and Building Materials*, 31, pp. 258–264, 2012. https://doi.org/10.1016/j.conbuildmat.2011.12.106.