JOURNAL OF MATERIALS & CONSTRUCTION
Journal of Materials and Construction
ISSN 2734-9438
Website: www. jomc.vn

Designing reinforced concrete structures in bridge, port, railway construction: Solutions to improve the quality of the protective concrete cover

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KEYWORDS

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

ABSTRACT

This study presents an experimental investigation into the development of concrete suitable for structural components used in coastal environments. Due to the aggressive conditions in marine settings—such as high salinity, moisture, and temperature fluctuations—concrete durability is a critical concern. 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

Within the next fifty years, reinforced concrete may become one of the greatest burdens on humanity. This is the alarming warning raised by German scientists following a series of bridge collapses—most recently, the failure of the Carola Bridge in Dresden in the early hours of September 11, 2024 [1]. As a vital transportation artery in Eastern Germany, the sudden collapse of the bridge shocked the public and authorities alike. According to preliminary assessments by German officials, chloride-induced corrosion originating from de-icing agents such as NaCl, KCl, $MgCl_2$, and $CaCl_2$ may have been one of the underlying causes of this tragic event.

The degradation of reinforced concrete poses a serious threat not only to transportation infrastructure but also to residential buildings. In Germany, it is estimated that one out of every ten houses requires urgent renovation. The primary cause of reinforcement corrosion is the ingress of water and oxygen, which penetrate through pores and microcracks in the protective concrete cover. Over time, this process gradually compromises the internal structural integrity of the concrete elements.

Therefore, improving the quality of the concrete cover is an urgent necessity. Key solutions include increasing concrete density, controlling shrinkage cracks, and preventing deterioration mechanisms such as chloride ingress, carbonation, sulfate attack, and alkali–silica reactions. These measures aim to extend the service life of structures and ensure structural safety over time.

Concrete and reinforced concrete elements used in industrial, civil, residential, hydraulic, and especially bridge, port, railway structures are all subject to aggressive environmental attacks. The durability and service life of these structures depend largely on the ability of both concrete and reinforcing steel to resist harsh environmental impacts, including corrosion, chemical ingress, and climate-induced degradation.

Figure 1 above illustrates the typical sequence of reinforcement corrosion in concrete exposed to aggressive environments. The process progresses through several stages: (a) no visible signs of corrosion, (b) initial rust formation on the reinforcing steel, (c) cracking of the concrete cover due to expansive corrosion products, (d) progressive crack development that accelerates chloride and moisture ingress, and (e) spalling of the concrete cover, which severely compromises structural integrity.

This visual evidence highlights the importance of improving concrete durability through optimized mix designs and the incorporation of supplementary cementitious materials (SCMs) to delay or mitigate these degradation stages.

Based on the depth of concrete degradation caused by corrosion, aggressive environments are classified into three levels: mild, moderate, and severe. This classification is detailed in Table 1 [2].

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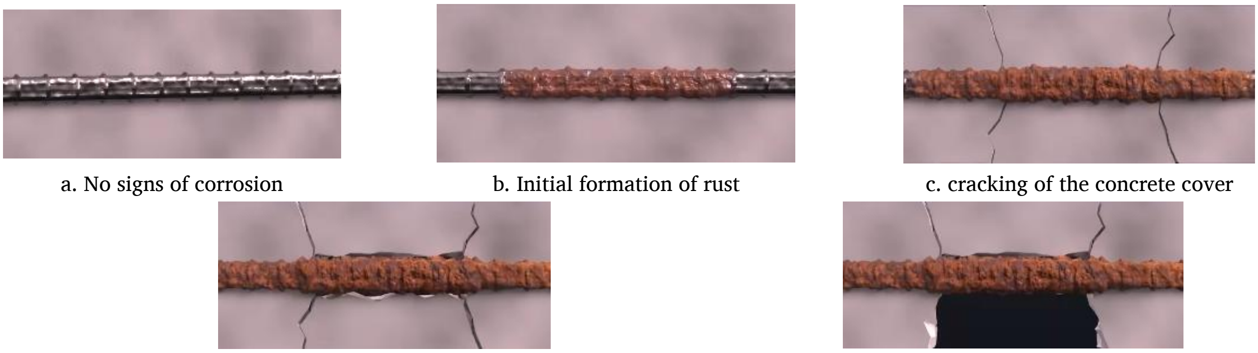
Received 06/08/2025, Revised 20/08/2025, Accepted 21/08/2025
Link DOI: https://doi.org/10.54772/jomc.v15i02.1073



a. No signs of corrosion b. Initial formation of rust c. cracking of the concrete cover

d. Progressive crack development e. Spalling of the concrete cover

Figure 1. Progressive corrosion mechanism in reinforced concrete.

Table 1. The depth of concrete degradation (cm) over 50 years of service life.

Degree of Aggression of the Environment	Structure	
	Reinforced concrete	Concrete
Non-aggressive	1	2
Weak aggression	1 ÷ 2	2 ÷ 4
Moderate aggression	2 ÷ 4	4 ÷ 6
Severe aggression	> 4	> 6

Looking at Table 1, it is clear that the required concrete cover thickness ranges from 4 to 6 cm for coastal bridge and port structures. However, it is important to note that this is only one aspect of the issue. The quality of the concrete is the key factor, playing a crucial role in creating a strong "shield" that prevents the infiltration of the harsh marine environment and protects the internal reinforcement. This understanding has driven the increased focus on improving concrete quality since the 1980s, paving the way for the development of durability-based design approaches, which were pioneered by Europe and the United States.

To reduce the porosity of cement-based materials and limit the movement of gases, liquids, and ions in solution, concrete quality must be enhanced through appropriate measures. The most common method is to reduce the water content while incorporating superplasticizers. Therefore, for concrete used in reinforced concrete structures exposed to harsh environments, maintaining a low water-to-binder ratio (W/B) is a critical requirement to improve durability and extend the service life of the structure [3, 4].

According to TCVN [5, 6], the maximum water-to-binder ratio (W/B) is specified as 0.45-0.40, with a characteristic compressive strength on cube specimens of 45 MPa. The European Standard [7] specifies a maximum W/B ratio of 0.45, with a minimum characteristic compressive strength of C35/45 MPa. Meanwhile, the Canadian Standard [8] sets the maximum W/B ratio between 0.37 and 0.40, with a chloride penetration of less than 1500 Culong after 56 days.

For the purpose of steel protection, ordinary Portland cement concrete has a high alkalinity, with a pH greater than 12.5, which helps maintain the "passivation" layer that protects the reinforcement. However, there are several factors that reduce the protective function of this concrete layer, including: (1) chemical, physical, and mechanical corrosion mechanisms; (2) chloride ion penetration into the reinforcement; (3) carbonation process; (4) differences in electrode potentials of metals in the reinforcement components.

The rate of corrosion propagation significantly affects the durability of the structure; therefore, controlling the resistivity of the concrete before cracks appear is an important factor. The material components of concrete are directly related to the corrosion of steel reinforcement, including Portland cement, supplementary binders, aggregates, mixing water, and other additives. The proper selection and mixing of these materials will contribute to enhancing corrosion resistance and extending the service life of the structure.

Effective corrosion mitigation measures typically include: improving the quality and increasing the thickness of the concrete cover; minimizing the appearance of cracks on the concrete surface (with a maximum crack width between 0.4mm and 0.52mm); and increasing the resistivity of the concrete to prevent the ingress of corrosion-causing agents.

The concrete construction process involves several factors such as: workmanship, reinforcement spacing, concrete curing, formwork, structural design, general layout of the structure, drainage work, and, especially, attention to exposure-prone structural elements.

Additionally, special measures can be employed to protect the reinforcement, such as epoxy-coated reinforcement, corrosion-resistant steel, waterproof membranes, concrete coatings, and cathodic protection. However, these methods are typically costly and are only applied in special cases as required.

Thus, the issue of reinforcement corrosion in concrete is primarily related to the quality and effectiveness of the concrete cover. This study presents the current state of corrosion protection for reinforcement in concrete in Vietnam, while also analyzing and comparing standards from experienced countries such as Europe, Japan, Canada, and the United States. Based on this, the study proposes a suitable solution for the design and fabrication of concrete to enhance the quality of the reinforcement cover and provides guidelines for its application in Vietnam.

2. Current situation of corrosion protection regulations in existing vietnamese standards for bridge, port and railway construction

Corrosion of reinforced concrete (RC) is a common phenomenon and a major cause of structural damage, significantly reducing the lifespan of bridges, port and railway structures built in coastal areas. The current corrosion and deterioration of RC structures are severe and reaching alarming levels. The rate of corrosion, which leads to structural damage, is occurring at a rapid pace. Currently, while some structures have a lifespan of over 30-40 years, many others have suffered corrosion and significant damage after only 20-25 years of use. In some cases, certain structures have been severely damaged after just 10-15 years (Figure 2) [3, 4].

The damage caused by reinforced concrete corrosion is significant and serious, with the cost of repairs and remediation of corrosion potentially accounting for 30-70% of the total investment in the construction of the project. Therefore, it is essential to promptly implement technical solutions for corrosion protection to ensure the quality and lifespan of the structures.

Figure 2. Corrosion of reinforced concrete in a Marine Environment after 20 years of Construction.

a) b)

Figure 3. a) The railway bridge pier (Đuống Bridge – Hanoi) has deteriorated 15 years after its repair;
b) The reinforced concrete sleepers have deteriorated.

The Figure 3 provides real-world evidence of premature deterioration in reinforced concrete structures under Vietnam’s harsh environmental conditions. The observed damage—ranging from cracking and spalling to reinforcement exposure—demonstrates the limitations of conventional Portland cement concrete when used in aggressive environments. These cases emphasize the urgent need for improved concrete durability through the incorporation of supplementary cementitious materials (SCMs) and optimized mix designs, as proposed in this study.

The issue of corrosion protection and safeguarding reinforced concrete structures built in Vietnam's coastal areas is addressed in the country's technical standards, including:

Design Standard TCVN 4116-2023, Hydraulic concrete and reinforced concrete structures, applicable to hydraulic works in general. The corrosion protection content in this standard is indirectly mentioned, focusing on regulations regarding the water resistance of concrete, crack limits, and the thickness of the protective layer.

Vietnamese Standard TCVN 9346:2012 [5], Concrete and Reinforced Concrete Structures, which directly addresses corrosion protection in marine environments. This standard provides detailed regulations on corrosion protection, including issues related to materials, concrete strength, protective concrete layer thickness, minimum cement content, crack limits, and construction requirements.

Table 2. Design lifespan regulations in some current global standards.

N°	Standard	Design Lifespan	Note
1	TCVN 11823:2017	100 year	W/C ≤0,45
2	TCVN 11820-1-2025	100 year	W/C ≤0,45
3	TCVN 12250:2018	30 - 100 year	-
4	TCVN 11820-1-2025	50 - 100 year	W/C ≤0,4
5	BS 6349:2016	50 - 100 year	W/C ≤0,45
6	OCDI 2002& 2009	50 - 100 year	Japan
7	CSA-A23.3-19	75 - 100 year	Canada
8	DB37_T 4466-2021	50 - 100 year	China
9	AASHTO LRFD	75 - 100 year	US

Vietnamese Standard TCVN [2], Concrete and reinforced concrete structures - general requirements for durability design and service life in aggressive environments addresses regulations regarding the water-to-cement ratio (W/C), concrete strength class, chloride ion content limits, minimum thickness of the concrete cover to reinforcement, and the minimum amount of cement per cubic meter of concrete for reinforced concrete structures working in aggressive environments with a service life of 50 and 100 years.

This standard introduces a few changes compared to the EN 206 standard [7], with a 0.05 reduction in the maximum W/C ratio and a 20 kg increase in the minimum cement content. Table 3 presents the minimum design requirements for corrosion protection in marine environments with a 50-year service life [6], covering reinforced concrete structures in different water environments. These requirements include concrete strength, water ingress resistance, concrete cover thickness, minimum cement content, and crack width limit. These requirements are divided into specific zones: submerged, tidal, above water, onshore (0-1 km from the water edge), and nearshore (1-30 km from the water edge), with different standards for outdoor, indoor, seawater, and brackish river water environments. Strengthening the concrete cover and selecting suitable materials will help improve the durability and service life of the structures, especially in harsh environments like seawater or brackish water.

The Standard Concrete quality requirements in aggressive environments [5] specifies comprehensive requirements for concrete used in aggressive environments, with a particular focus on exposure to chloride ions prevalent in marine settings. It categorizes environmental exposure into four levels, ranging from non-corrosive to chloride-induced corrosive conditions. The core technical parameters include the maximum permissible water-to-binder ratio, designated durability class, minimum compressive strength, and required cement content. These criteria are established to enhance the durability and extend the service life of reinforced concrete structures subjected to harsh coastal and marine environments.

The Table 4 highlights the significant difference in performance requirements between ordinary environments (X0) and chloride-rich marine environments (XS1–XS3). While current Vietnamese standards (TCVN 9035:2011) specify minimum strength, durability class, and binder composition, they do not explicitly address long-term durability aspects such as chloride penetration resistance, carbonation, or the role of supplementary cementitious materials (SCMs). This underscores the necessity of further research—such as the present study—to optimize mix designs incorporating fly ash, GGBFS, and other SCMs for enhanced durability in marine infrastructure.

The current Vietnamese national standard for Road bridge design, TCVN 11823:2017, includes provisions for protecting reinforced concrete structures in marine environments. It recommends using epoxy-coated or galvanized reinforcement, or incorporating specific admixtures, along with a minimum concrete cover of 75 mm (Clause 12.3, Part 5). However, these regulations remain relatively general and lack detailed guidance on corrosion-resistant design strategies or clear methodologies to ensure long-term durability of reinforcement exposed to harsh marine conditions.

In contrast, the TCVN 11820:2023 standard for maritime port structures demonstrates a more advanced and comprehensive approach. It not only specifies detailed structural durability and corrosion protection requirements, but also introduces a performance-based design method and provides maintenance documentation such as the Corrosion protection handbook (OCDI 2020)—a technical resource aimed at ensuring the longevity and resilience of port infrastructure in aggressive coastal environments.

3. International Standards on Rebar Corrosion in Reinforced Concrete for Bridge and Harbor Construction

In addition to the quality of concrete, the minimum thickness of the concrete cover protecting the reinforcement is a crucial factor that requires careful consideration. Theoretically, in more corrosive environments, increasing the thickness of the protective layer can help maintain the durability of the structure. However, this thickness cannot be increased indefinitely due to mechanical and economic constraints. In practice, an overly thick concrete cover in reinforced concrete structures may not effectively prevent corrosion as expected. In some cases, the use of an excessively thick protective layer can even result in cracking due to tensile stresses acting on the structure.

The European Standard [7] provides specific regulations regarding the limit of cement content, the water-to-binder ratio, ultra-fine mineral admixtures, and requirements for the thickness of the concrete cover protecting the reinforcement to ensure the durability of reinforced concrete structures. Additionally, this standard offers recommendations for selecting limit values for the composition and properties of concrete depending on various environmental conditions. Notably, the minimum concrete cover thickness for structures located in tidal zones is specified as 60mm.

The UK Standard [9] stipulates requirements for the thickness of the concrete cover to ensure the long-term durability of reinforced concrete structures. Table 5 of this standard outlines the necessary concrete cover thickness based on factors such as the type of environment, the type of structure, and the durability requirements of the project.

Table 3. Design requirements for corrosion protection of structures in marine environments with a 50-Year service life.

Nº	Design Requirements	Structures in the zones												
		Submerged zone		Tidal zone		Above water zone			Shoreline (0-1 km from the water's edge)			Nearshore (1-30 km from the water's edge)		
1	Compressive Strength, MPa	30	40	40	50	30	40	50	25	30	40	25	30	40
2	Water Penetration Resistance, atm	8	10	10	12	8	10	12	6	8	10	6	8	10
3	Thickness of Concrete Cover, mm													
	Outdoor structures	-	-	-	-	-	-	-	50	40	30	40	30	25
	Indoor structures	-	-	-	-	-	-	-	40	30	25	30	25	20
	Seawater	50	40	70	60	60	50	40						
	Brackish Water	40	30	60	50	50	40	30						
4	Minimum Cement Content, kg/m^3	350		400		350			350			350		
5	Crack Width Limit, mm													
	Outdoor structures	≤ 0,1		≤ 0,05		≤ 0,1			0,1			≤ 0,1		
	Indoor structures	-		-		≤0,1			≤ 0,15			≤ 0,15		

Table 4. Concrete quality requirements for aggressive environmental exposure.

Criteria	Corrosive Environment			
	Non-Corrosive	Due to Chloride ions from marine sources		
	X0	XS1 (Marine atmospheric zone)	XS2 (Submerged zone)	XS3 (Tidal and splash zone)
Maximum water-to-binder ratio	--	0,45	0,40	0,40
Minimum durability class	B15	B35	B45	B45
Minimum compressive strength (MPa)*	20	45	60	60
Minimum cement content (kg/m^3)	--	320	340	360
*selection according to TCVN 9035:2011				

Table 5. Nominal thickness of concrete cover for reinforcement to meet durability requirements.

Exposure Conditions	Nominal Concrete Cover Thickness (mm)				
Mild	25	20	20(1)	20(1)	20(1)
Normal		35	30	25	20
Severe			40	30	25
Very Severe					50
Maximum Water/Cement ratio	0,65	0,6	0,55	0,5	0,45
Minimum Cement Content ($kg.m^3$)	275	300	325	350	400
Minimum Concrete Strength Class	C30	C35	C40	C45	C50

1) The thickness of the concrete cover can be reduced to 15mm when the maximum nominal aggregate size does not exceed 15mm.

Note 1: This table refers to normal aggregates with a nominal size of 20mm.

Note 2: Using sulfate-resistant cement must comply with BS 4027. If used in reinforced concrete structures under very severe conditions, the cover thickness must be increased by an additional 10mm.

Note 3: The thickness of the concrete cover must not be less than the nominal values corresponding to the relevant environmental category, plus the value of the cover thickness lost due to wear and tear.

The American standard, ACI 318-19, Chapter 19, "Concrete: design and durability requirements," and Chapter 26, which covers materials and concrete mixtures, are the main sections that address the use of alternative cements and aggregates. The water-to-cementitious material ratio (W/C) and the design strength of concrete based on environmental exposure conditions are provided in Table 6.

Table 6. Maximum W/C Ratio and Design Strength in Special Environments - ACI 318.

Environmental Conditions	Maximum W/C Ratio	Minimum Design Strength MPa
Exposure to water	0,5	25
Exposure to seawater	0,45	30
Freeze-thaw cycles	0,45	30

The thickness of the concrete cover for reinforcing steel is specified in various concrete standards in Europe [7], Norway [10], and particularly in Japan [11]. In these standards, when using regular or ribbed prestressing steel, the steel must be protected by a concrete layer with a thickness of 75mm or 100mm, respectively.

Furthermore, the limit on the water-to-cement ratio (W/C) is also strictly regulated. According to European standards [6], the maximum permissible W/C ratio is 0.45. However, in TCVN [2], this limit is reduced to 0.4. In Norway, the National Public Roads Administration (NPRA) set the maximum W/C ratio for new coastal bridge constructions at 0.4 since 1988 [10]. By 1996, this limit was further reduced to 0.38 to improve the durability of concrete in harsh environments.

In response to the environmental effects that reduce the durability of reinforced concrete structures, researchers have focused on ensuring concrete durability since the early 1980s. Today, many advanced countries' bridge port, and railway design standards, including those from Europe, the UK, Norway, and Japan, provide specific guidelines to protect reinforced concrete structures in highly aggressive environments.

4. Solutions for improving the quality of concrete cover bridge and harbor construction

Cement concrete is a material that is difficult to achieve uniformity due to its properties being influenced by numerous factors, including the composition of aggregates, cement, binder, water, additives, and production technology. To prevent steel reinforcement corrosion, several measures can be applied, such as keeping the concrete dry or wet, cathodic protection, polymer coatings, or using polymer membranes on steel bars or stainless steel. However, in practice, completely eliminating corrosion is not feasible; it can only be minimized, thereby extending the structure's lifespan. While many solutions have been implemented, they are not always universally applicable. Therefore, enhancing the quality of the concrete cover is an effective approach to mitigating reinforcement corrosion.

Ordinary cement concrete has a relatively high porosity, ranging from 10 % to 15 %, and it can be even higher if the construction technology does not meet quality standards. The impermeability (including gas, water, and chloride ion permeability) of concrete depends on factors such as input materials, compaction and curing processes, microcracks, and moisture conditions. The strength and permeability of concrete are closely related to capillary pores. Studies have shown that when properly cured, concrete with supplementary binders like ground granulated blast-furnace slag (GGBS), fly ash, and natural pozzolana helps reduce the pore system, disrupt interconnected pores, and form discontinuous pores [13]. GGBS has the ability to protect against chloride corrosion due to its capacity to absorb free chlorine [14]. The chloride ion permeability rate of concrete using GGBS, ranging from 0 % to 60 %, can increase by up to 20 %.

Silica fume (SF), meta-kaolinite (MK), and rice husk ash are also considered materials that improve the chloride ion permeability of concrete. These materials help achieve a chloride ion permeability of less than 1000 Coulombs. Fly ash (FA) has been widely used in studies and incorporated into standards for producing high-performance concrete (HPC), such as in the ACI 211.4 guidelines. Fly ash is not only effective in reducing hydration heat and limiting microcracks but also significantly improves the impermeability of cement concrete.

The issue of steel reinforcement corrosion is related to the carbonation of concrete, where CO2 in the air diffuses into the pores of concrete, similar to the diffusion mechanism of chloride ions. Studies on the phenomenon of alkali loss of pozzolans through the pH of concrete [15], as well as the measurement of porosity and the distribution of capillary pores using mercury intrusion porosimetry (MIP), show that carbonation increases the porosity of cement paste. Some studies indicate that carbonation depth increases when using silica fume [16], a PC-FA-MK binder mix, and suggest that it is possible to reduce carbonation depth. Meanwhile, mixes of PC-MK, PC-GGBS, and PC-GGBS-MK with 10 % GGBS and 10 % MK can resist chloride ion infiltration and reduce carbonation depth. The PC-GGBS-MK mix has also been used [17], and the results showed it was beneficial for chloride ion resistance and reducing carbonation depth; however, replacing 65% of GGBS led to a higher level of carbonation compared to 50 % GGBS.

According to the recent summary report by RILEM TC 281-CCC [18], when the content of Portlandite decreases in CKD systems containing SCMs (supplementary cementitious materials), the carbonation process occurs rapidly, especially in the CO2 bonding phases such as C-S-H when using SF and C-A-S-H when using GGBS, FA, MK, and other Al-containing SCMs. The carbonation of these hydrates plays a crucial role in the carbonation shrinkage process (due to polymerization), particularly at low Ca/Si ratios in C(-A)-S-H, causing the roughening of the pore structure and reducing mechanical strength. Furthermore, as carbonation occurs, the porosity of the cement paste increases as the SCM replacement ratio increases (von Greve-Dierfeld et al., 2020).

Many studies have combined the use of SCMs to simultaneously improve chloride ion permeability and reduce carbonation depth. The study [19] showed that the depth of chloride ion penetration in concrete without crack-resistant binders from 0-0.4 mm could reach 24 mm-35 mm with an N/C ratio of 0.4, whereas with N/C ratios of 0.5 and 0.6, this depth was ≥ 40 mm. For concrete using GGBS, the penetration depth ranged from 15-33 mm, while for FA, it ranged from 14-27 mm. In CO2 environments, the use of SCMs such as GGBS and FA significantly helps reduce carbonation.

Corrosion in reinforced concrete structures, particularly in infrastructure such as bridges, airports, and nuclear power plants, is a serious issue. Many studies have focused on reducing chloride ion ingress into the protective concrete layer. Research has also indicated that using two- or three-component binders in appropriate ratios can reduce chloride ion ingress, reduce carbonation depth, and lower the water absorption capacity of concrete, thereby improving durability. Survey results emphasize the importance of enhancing the quality of the protective concrete layer to extend the lifespan of reinforced concrete structures in bridge, port and railway construction.

The survey results on two- and three-component binder systems, presented in **Figure** 4, reveals a clear correlation between the water-to-cement (W/C) ratio and the chloride ion penetrability of concrete. Concrete mixtures containing only Portland Cement (PC) or Portland Composite Blended Cement (PCB), represented by black dots, generally exhibit significantly higher charge passed values, many of which exceed the 1500 Coulomb threshold set by CSA A23.1:19, indicating a higher risk of chloride-induced corrosion of reinforcing steel. The red line at 1500 Coulombs represents the threshold defined by the CSA A23.1:19 standard [8] to classify concrete as having good chloride ion penetration resistance. Concrete mixtures exceeding this threshold are associated with a higher risk of reinforcement corrosion due to increased chloride ingress.

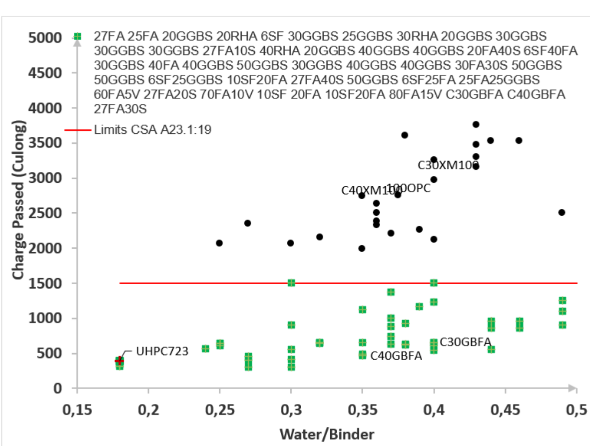


Figure 4. Statistical data on the electrical charge passed through concrete mixtures used.

In contrast, concrete mixtures incorporating supplementary cementitious materials (SCMs), such as fly ash (FA), ground granulated blast-furnace slag (GGBS), silica fume (SF), rice husk ash (RHA), and metakaolin (MK), show a marked improvement in chloride resistance. Most of these SCM-enhanced mixtures remain well below the 1500 Coulomb limit, demonstrating enhanced durability performance. Particularly, ternary blended systems (e.g., PC-GGBS-MK, PC-FA-SF) tend to yield the best results, with several formulations achieving chloride ion permeability under 1000 Coulombs.

The ultrahigh-performance concrete sample UHPC723 using at least 700 kg of cemen stands out with an exceptionally low chloride penetration value, confirming the superior durability characteristics of UHPC.

Overall, the data strongly supports the use of SCMs and optimized mix designs to enhance the quality of the concrete cover layer, thereby increasing the durability and service life of reinforced concrete structures exposed to chloride-laden environments, such as bridges and marine infrastructures.

5. Experiment and experimental results of reinforcing steel corrosion

This section presents the experimental results obtained to establish the correlation between the composition of concrete mixtures, particularly the use of active admixtures, and the degree of reinforcing steel corrosion when exposed to a simulated aggressive environment.

5.1. Experimental test

The experiment was conducted on various concrete mixtures with designed compressive strengths from 30 MPa to 40 MPa, encompassing control specimens utilizing 100 % Ordinary Portland cement and concrete specimens incorporating a blend of mineral admixtures comprising Ground Granulated Blast-Furnace Slag (GGBFS) and Fly Ash (FA) with a total content of up to 50 % of the binder.

The objective of this comparison was to evaluate the influence of GGBFS and FA incorporation on the corrosion resistance of concrete within the study's experimental environment.

Figure 5 illustrates the specimen preparation process in the laboratory of the University of Transport and Communications. The concrete mixtures were proportioned according to the designed mix compositions and mixed in a laboratory concrete mixer (Figure 5a). Fresh concrete was cast into cylindrical molds in two layers with proper compaction to minimize voids and ensure uniformity. After casting, the specimens were covered with plastic sheets for 24 hours to prevent moisture loss. Subsequently, the specimens were demolded and cured in water at 20 ± 2 °C for 28 days (Figure 5b). After curing, they were exposed to the test conditions for corrosion monitoring.

For the corrosion experiments, cylindrical concrete specimens with standard dimensions of approximately 100 mm in diameter and 200 mm in height were prepared. Each specimen had a single reinforcing steel bar embedded centrally, aligned along the longitudinal axis of the cylinder. The reinforcing steel bar had a nominal diameter of 10 mm and a length sufficient to protrude from both ends of the concrete specimen. These protruding ends facilitated electrical connection to monitoring equipment for corrosion assessment. The concrete was cast using various mix proportions and subjected to standard curing conditions prior to the commencement of the corrosion tests.

The corrosion resistance of reinforcing steel in concrete was evaluated according to the NT-Build 356 standard. A 5V direct current (DC) power source was used to accelerate corrosion, as shown in Figure 6.

a. Concrete mixer b. Test specimens

Figure 5. Specimen preparation in a laboratory.

a. Test specimens immersed in NaCl solution b. Measuring the current flowing through the test specimen

Figure 6. Reinforced concrete corrosion Test.

5.2. Experimental results

The current intensity (mA) was measured to evaluate the corrosion level of the reinforcing steel within the concrete specimens.

Concurrently, throughout the experimental period, the concrete specimens were visually inspected to assess the rust formation on the reinforcing steel and the occurrence of cracking on the concrete surface as Figure 7. This aimed to determine the impact of the corrosion process on the structural integrity of the specimens.

The Figure 8 below shows the current intensity data continuously recorded from December 16, 2023, to January 19, 2024. The variation in current intensity reflects the rate and extent of corrosion over time of the different concrete mixtures 100-OPC, C30GBFA, C30XM100, and C40GBFA, C40XM100.

Figure 7. Steel corrosion causes concrete cracking.

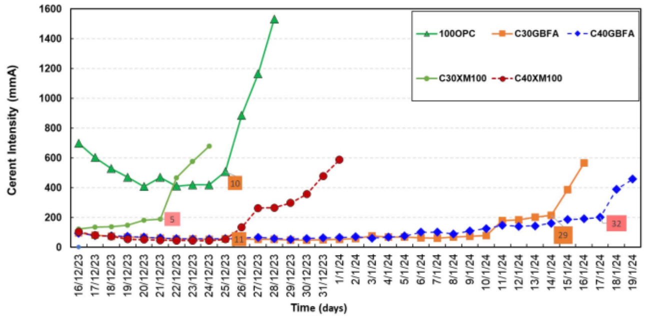


Figure 8. Corrosion results of reinforcing steel in concrete.

The 100-OPC mixture, using 100 % Portland cement, with a designed strength of 35 MPa. C30GBFA and C30XM100: respectively using GGBFS and FA, and using only 100 % Portland cement, with a designed strength of 30 MPa. C40GBFA and C40XM100: respectively using GGBFS and FA, and using only 100 % Portland cement, with a designed strength of 40 MPa.

The experimental results for each concrete type were recorded over time. The experiment was terminated upon complete cracking of the concrete specimen.

The C40GBFA mixture (blue line, diamond markers) and the C30GBFA mixture (light green line, circle markers) exhibited the best corrosion resistance, with current intensities reaching approximately 420 mA and 600 mA, respectively, at the end of the experiment on January 19, 2024.

The 100-OPC, C30XM100, and C40XM100 mixtures, which did not incorporate GGBFS and FA, exhibited a significant increase in current intensity, and the specimens experienced complete cracking at very early stages, ranging from December 24, 2023, to January 1, 2024. This indicates that these samples were the most severely affected by corrosion among the tested mixtures.

Therefore, improving the quality of the concrete cover has become an urgent necessity. Potential solutions include enhancing the density of the concrete, controlling shrinkage-induced cracking, and preventing chloride ingress. In addition, attention should also be paid to other durability aspects such as limiting carbonation, mitigating sulfate attack, and improving freeze–thaw resistance, even though the latter is not directly addressed in this study.

From a practical perspective, the developed concrete not only shows improved durability against carbonation and sulfate attack but also offers cost-effectiveness due to the partial replacement of cement with locally available supplementary materials. This makes it applicable in marine and transportation infrastructure such as railway and bridge components. These findings suggest that current durability-related standards could incorporate performance-based criteria to better reflect the advantages of such sustainable mixtures

Conclusion

Design and maintenance standards for transportation structures such as bridges, ports, and railways in Vietnam have not specified detailed requirements for the quality of the concrete cover protecting the reinforcement. This may compromise the concrete's ability to protect the embedded steel. Currently, concrete design mainly focuses on achieving the required strength and cover thickness, but does not adequately take into account the long-term durability of the concrete.

Improving concrete quality by enhancing its strength and incorporating supplementary cementitious materials is a fundamental and long-term solution for developing construction projects and ensuring structural durability.

Binary and ternary systems — including GGBS, FA, GGBS-MK, GGBS-FA, GGBS-RHA, GGBS-SF, and FA-SF — are recommended as potential options that should be studied and optimized in terms of mix proportions for the concrete cover layer, especially for structures located in marine environments.

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