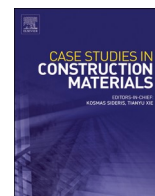




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Potential of fly ash geopolymer concrete as repairing and retrofitting solutions for marine infrastructure: A review

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ABSTRACT

Corrosion in maritime infrastructure, particularly in reinforced concrete, has emerged as a significant cause for concern due to the presence of chloride ions in seawater. To address this challenge, geopolymer concrete has been proposed as a viable solution for retrofitting and restoring marine structures. This review paper explores the potential application of fly ash geopolymer concrete in marine infrastructure restoration. Fly ash's properties make it ideal for marine infrastructure restoration. Its high levels of amorphous silica and alumina enable geopolymerization, forming a strong binder resistant to chloride corrosion. Its fine, spherical particles enhance concrete workability and density, improving mechanical strength and impermeability. This geopolymer binder offers excellent resistance to corrosion from chloride ions commonly found in seawater, making fly ash geopolymer concrete highly suitable for marine applications. Overall, fly ash's chemical composition and physical traits offer resilience and sustainability in restoring marine infrastructure, ensuring long-term durability against corrosion. This review paper explores the potential application of fly ash geopolymer concrete in marine infrastructure restoration. By examining the primary forms of damage and mechanisms underlying concrete degradation in marine settings, this study highlights the durability and sustainability of geopolymer concrete compared to traditional concrete. Additionally, it discusses current solutions for repairing and retrofitting concrete in marine environments, emphasizing the promising characteristics of geopolymer concrete for integration into such structures. Through this analysis, innovative and environmentally conscious approaches are introduced for addressing corrosion-related challenges in the maritime industry, offering a resilient solution for the construction of enduring marine structures. Finally, recommendations for further research on the application of fly ash geopolymer concrete in marine infrastructure restoration are presented.

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1. Introduction

In the world of construction, concrete has established itself as the most widely used material, owing to its widespread availability and reasonable price which making it the top choice for civil and infrastructure construction, particularly in marine environments. Marine infrastructure is typically comprised of concrete components that act as fundamental constituents in a diverse range of applications, such as docks, bridges, maritime bases, terminals, platforms, submarine pipelines, and similar structures [1–6]. The corrosion-induced deterioration of concrete, stemming from steel reinforcement, is a recurrent issue in marine infrastructure [1,3,5,7–9]. The robustness of strengthened cement structures in oceanic surroundings, which are susceptible to degradation, is a foremost anxiety when it comes to conserving their corporeal and mechanical characteristics [6,10–12]. The principal mechanisms of concrete decay, encompassing chemical, physical, and mechanical processes, are intricately interrelated. The primary factor responsible for chloride corrosion in marine concrete structures and posing a substantial threat to the safety of reinforced concrete in the marine environment is the infiltration of chlorides through capillary action via seawater [13–17].

Chloride ions permeate the concrete via diffusion through the pores, as referenced in sources [4,17,18] and [19]. Upon contact with the steel reinforcement, these ions can instigate corrosion, thereby accelerating the oxidation process, as noted in source [4]. The destruction of the passive film over expansive regions of the reinforcement can be caused by exceedingly elevated levels of chloride, where the resultant areas of corrosion are commonly referred to as pitting corrosion. Similarly, the areas of corrosion that are surrounded by non-corroded zones are known as pits, as discussed in sources [19–21]. Chloride attack occurs in concrete within a marine setting or when de-icing salts are used, resulting in the presence of chloride ions, as mentioned in sources [3] and [22]. Eqs. (1) and (2) illustrate a chemical reaction that involves a non-consumable chloride ion in the first reaction [23,24]. In reinforced concrete, the continuous phase of chloride attack enables chloride ions to remain unreacted and available to participate in subsequent reactions [3, 6,10,12,16,17]. The existence of chloride ions, which is deemed as one of the most detrimental and destructive mechanisms in reinforced concrete, gives rise to a heightened likelihood of causing corrosion.



for hydrolysis



Additionally, it is important to acknowledge that chloride salts possess the potential to incite various other forms of deterioration in concrete such as scaling, spalling, and cracking. As a result, modern research endeavours are actively engaged in the restoration and retrofitting of concrete structures that are durable enough to withstand prolonged exposure to marine environments [6]. The appropriate proportioning of concrete mixtures, improvement of structural design, processing, and maintenance techniques must all be enhanced in order to ensure the longevity of concrete throughout its expected service life. The application of these tactics can efficaciously reduce the penetration of chloride salts into concrete, thus ultimately extending its durability.

Geopolymer concrete has the capacity to be produced utilizing an array of precursor substances, encompassing natural pozzolans, metakaolin, and slag [25]. Each of these aforementioned substances presents its own set of benefits and drawbacks [25,26]. The decision to utilize fly ash as a preliminary substance may be impacted by variables such as its accessibility in the area, cost-efficiency, or adherence to particular execution benchmarks, which bear substantial significance in the maritime sector [2,11], and [27]. Consequently, conducting such examinations would contribute to an enhanced understanding of the adaptability and applicability of geopolymer concrete in diverse marine circumstances. The inclusion of fly ash primarily contributes to the sustainability of the construction sector. It is a byproduct of coal combustion, and researchers can aid in the recycling of industrial waste by incorporating it into geopolymers, thus reducing the environmental impact of concrete production. Furthermore, fly ash is conveniently accessible in various areas, thereby rendering it a pragmatic and economically feasible antecedent for the manufacturing of geopolymers.

In addition, earlier studies have revealed that geopolymer concrete manufactured using fly ash exhibits the ability to withstand corrosion induced by chloride, a major concern in maritime environments [2,11,27]. The performance of the material has been assessed to be at the same level as, if not exceeding, that of traditional concrete, thus validating its choice as a suitable precursor. Fly ash contains high levels of amorphous silica and alumina, which are essential precursors for geopolymerization—a process that forms a strong and durable binder within the concrete matrix [11,27]. This geopolymer binder provides exceptional resistance to corrosion caused by chloride ions that are frequently present in seawater, thereby rendering fly ash geopolymer concrete extremely appropriate for marine applications. Additionally, the fine particle size and spherical shape of fly ash particles contribute to improved workability and packing density of the concrete mixture, resulting in enhanced mechanical properties such as compressive strength and resistance to permeability [2,11,27,70]. Overall, the unique chemical composition and physical characteristics of fly ash make it a resilient and sustainable option for restoring and retrofitting marine infrastructure, offering long-term durability and protection against corrosion and deterioration.

However, it's important to acknowledge certain disadvantages associated with this material. One concern is the potential variability in the properties of fly ash depending on its source and composition, which may affect the consistency and performance of the concrete [11,25–27,53]. Additionally, the geopolymerization process typically requires the use of alkaline activators, such as sodium hydroxide or potassium hydroxide, which can be caustic and require careful handling to ensure worker safety and environmental protection [53,60,69,93,137]. Furthermore, the long-term durability of fly ash geopolymer concrete in marine environments is still being studied, and more research is needed to fully understand its performance over extended periods of exposure to seawater and other marine conditions. Despite these challenges, ongoing advancements in materials science and engineering continue to improve

the reliability and effectiveness of fly ash geopolymer concrete for marine infrastructure applications.

The purpose of this review is to focus on the primary mechanisms that have caused concrete damage in marine environments. A literature review was conducted, which included previous research on repair and retrofitting solutions in marine applications, with a focus on improving reinforced concrete performance [5,23,28]. Furthermore, when designing marine infrastructure concrete structures, it is imperative to take into account the chloride migration coefficient of concrete and accurately estimate the initiation and propagation period for chloride-induced corrosion [29–31]. Geopolymer concrete, despite its potential as a solution for repair and retrofitting, has not seen widespread use in marine applications due to concerns regarding durability and environmental impact. This analysis aims to offer valuable insights into the possibility of utilizing geopolymers as a viable substitute for traditional concrete in marine settings.

2. Damage to concrete structure in a marine environment

In marine environments, concrete structures experience a broad spectrum of harsh conditions, including exposure to saltwater, waves, and marine organisms. These factors can accelerate the deterioration process and significantly reduce their operational lifespan. The aforementioned conditions create more intricate challenges for preserving the quality, original form, and serviceability of the reinforced concrete when compared to structures in alternative environments [4,17,32].

Concrete deterioration can occur through the concrete surface (abrasion, erosion, and cavitations), reinforcement (steel corrosion), aggregate (alkali-aggregate reactions, freezing and thawing), and cement-based matrix (seawater attack, salt crystallisation, carbonation, acid attack, sulphate attack), as documented in [6,20], and [32,33]. Tables 1 and 2 present an abridged exposition of the chemical, physical, and mechanical modalities responsible for the degradation of concrete, as well as the factors responsible for reinforced concrete deterioration in marine environments.

Concrete structures are frequently exposed to a variety of environmental conditions, which present a significant challenge in preserving the durability, quality, and serviceability of reinforced concrete in its original form in the marine environment [4,32]. The degradation of concrete can arise from chemical, physical, or mechanical factors, which are often interconnected. Chemical deterioration processes can result in physical effects such as changes in volume, porosity, and permeability, as well as mechanical impacts such as cracking and loss of strength, leading to concrete deterioration including alkali-aggregate reaction, aggressive soft water leaching, acidic liquid or gaseous attack, bacterial or other biological activity [6,20,32]. Furthermore, physical concrete deterioration can predominantly occur on the concrete surface through abrasion, erosion, and cavitations [33]. Furthermore, the physical deterioration of concrete commonly occurs in both the aggregate (due to freezing and thawing) and the cement-based matrix (caused by shrinkage, thermal movement, and salt crystallization) due to prolonged exposure to the continuous abrasion of gravel and sand carried by seawater [32,33]. The mechanisms of concrete deterioration arise through chemical, physical, and mechanical processes, which are frequently interconnected, for instance, impact, blast or abrasion damage, overloading, displacement (settlement), vibration, earthquake [6,20,32,33].

The degradation of reinforced concrete is impacted by a multitude of factors, including but not limited to carbonation, chloride, as well as stray or electric current [4–6,9]. The corrosion of reinforcement caused by carbonation is widely acknowledged as a major factor in the deterioration of reinforced concrete structures [6]. Corrosion is encouraged when the pH level drops below 10, resulting in the dissolution of the steel's thin surface passivation layer [5–7]. Stray currents, especially when originating from power sources and traversing metal structures, can trigger or hasten corrosion as they flow through unintended elements in an electric circuit [5]. This process is marked by chemical and electrochemical reactions with the surrounding environment. The higher conductivity of seawater relative to freshwater implies that stray current from the primary source is more destructive and poses a greater risk [6–8]. In marine environment, stray currents can stem from various sources, including inadequate electrical systems, welding operations, and boats with different grounding polarities [5,6,9]. Corrosion of steel typically results in progressive deterioration of different reinforced concrete structures and is frequently the main culprit for such damage.

A notable degradation mechanism in reinforced concrete is the ingress of chloride, which contributes to the corrosion of embedded reinforcing steel [28–30]. The principal cause of chloride-induced corrosion in marine concrete structures is the infiltration of chloride ions through capillary action, resulting from exposure to airborne salt spray and/or wetting and drying with seawater [16,35]. Corrosion may manifest upon reaching a chloride ion concentration of 0.2–0.4 percent or beyond, which are conveyed into the concrete via sorption and ionic diffusion [5,16,36]. The chloride ion transportation process within concrete is impacted by the structural characteristics of the concrete, environmental conditions, and the method employed for the introduction of chloride ions into the concrete [12,16,17]. Degradation, such as exposed rebar, spalling, rust staining, and delamination, are all examples of visual deterioration damage [32,37,38] (Fig. 1).

In reinforced concrete structures within marine environments, the occurrence of chloride-induced corrosion is widespread and acknowledged as the leading cause of corrosion in such constructions. The resulting reinforcement corrosion causes cracking, spalling, and a reduction in load-bearing capacity, making it a significant durability issue across the globe. To address this concern, there is a

Table 1
Type of concrete deterioration [6,34].

Chemical	Physical	Mechanical
<ul style="list-style-type: none"> Chloride attack, sulphate attack, acid attack, carbonation 	<ul style="list-style-type: none"> Salt crystallization, abrasion, freeze-thaw cycles, erosion, impact and wear 	<ul style="list-style-type: none"> Overloading, corrosion of reinforced steel, settlement and subsidence, fatigue (waves and tides)

Table 2
Factors of reinforced concrete deterioration in marine environment [6,34].

Carbonation	Stray/Electrical Current	Chloride Presence
<ul style="list-style-type: none"> • Normal ambient carbonation diminishes the passivation of concrete alkalinity, thereby leading to reinforcement corrosion. • Within the concrete pore liquid, calcium hydroxide reacts with carbon dioxide (CO₂) from the atmosphere. • As a consequence of this reaction, a zone is formed with lower pH values, known as the carbonated zone, where pH levels drop below 10. • Steel undergoes passivation in this region, whereas unprotected steel is vulnerable to corrosive damage. 	<ul style="list-style-type: none"> • Upon the installation of galvanised steel reinforcements in the vicinity of embedded steel reinforcement for parapet railings, it was observed that reinforcement corrosion had occurred, manifested as rust staining emanating from cracks. • This phenomenon occurs when metals with dissimilar electro potentials are connected within concrete, leading to corrosion. • Additionally, it is worth noting that stray electrical currents from power supply and transmission networks can also contribute to the corrosion process. 	<ul style="list-style-type: none"> • The infiltration of chloride resulting from the application of de-icing salts on marine infrastructures expedites the corrosion of steel by means of permeation, primarily through the joints situated above the support piers. • Irrespective of the underlying cause, the presence of chlorides augments the corrosion procedure. • When the chloride concentration in the concrete exceeds 0.2–0.4%, the passive oxide protective layer on the steel's surface deteriorates. • Chlorides usually originate from exposure to saltwater in marine environments or the use of de-icing salts.

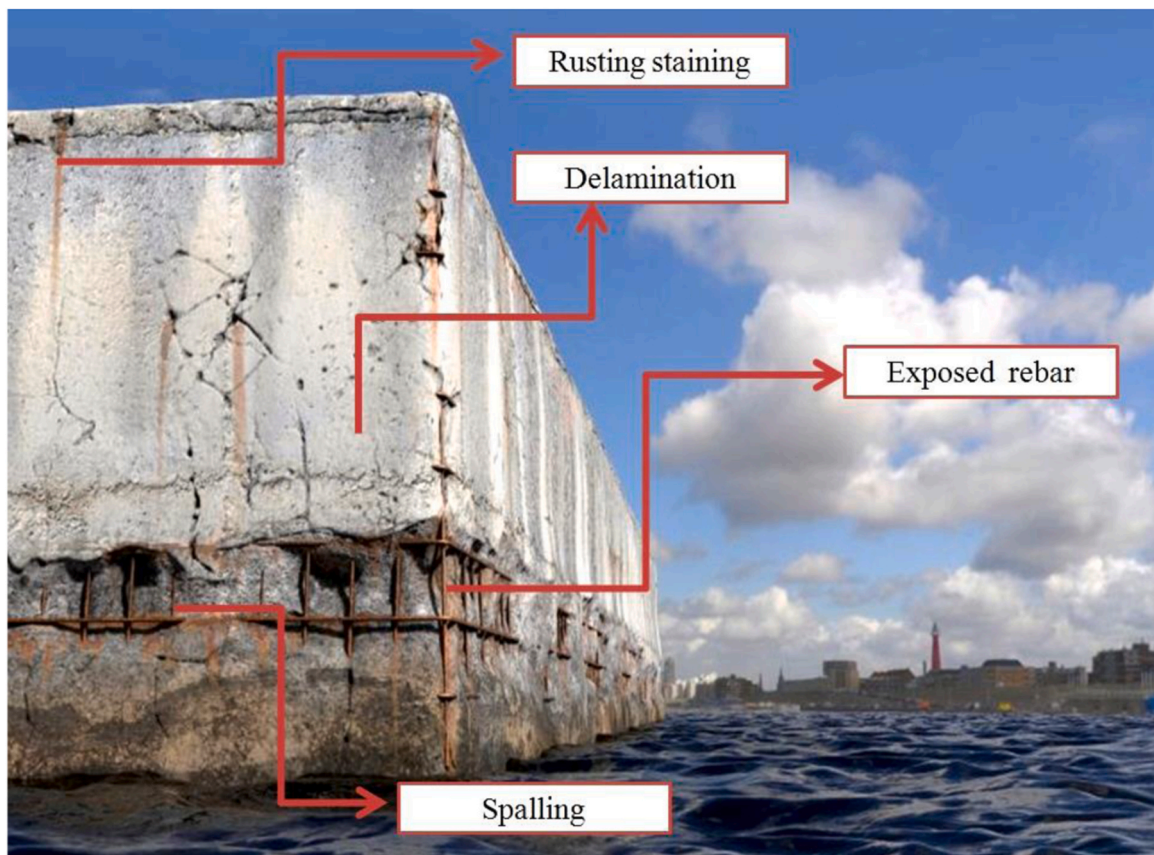


Fig. 1. Example of visual concrete deterioration by reinforcement corrosion in marine environment.

need to comprehend the solutions for concrete repair and retrofitting in marine applications, particularly in safeguarding the reinforcing steel from corrosion.

3. The solution for repair and retrofitting of concrete in marine application

Previous studies have extensively examined methods for restoring and retrofitting reinforced concrete in marine applications to extend its service life [2–6,20]. The focus of these investigations has primarily been on examining the impact of key parameters, including the materials used, compressive strength, concrete cover thickness, and chloride migration coefficient. The main aim of these investigations is to enhance the durability of concrete in marine environments.

Scholars have conducted thorough research on the impact of augmenting concrete cover thickness in impeding diverse harmful

substances that approach the reinforcement and the duration it takes for corrosion to commence. These investigations have closely considered other significant parameters as well [13,29,32,35]. In previous research, the minimum cover thickness has been found to be influenced by factors such as pozzolanic material form, water/cement ratio and replacement level, and exposure conditions [23]. Nevertheless, it is crucial to note that the thickness of the cover must not exceed a limit of 65–75 mm. This is due to the fact that a thick layer of concrete cover bears a high risk of cracking and acts as a barrier to various aggressive agents. This, in turn, lengthens the time for corrosion to initiate [5]. Prior research has indicated that the optimal cover thickness for varying exposure areas should range from 65 to 75 mm. Conversely, in a marine setting, any cover thickness below 40 mm is considered deficient for any exposure circumstance. Similarly, this applies to prior research as well [9,24,35].

In marine applications, the main parameters of the solution indicate that the factor with the most pronounced impact on improving reinforced concrete is its compressive strength [13,39,40]. By increasing the compressive strength, the resistance against chloride ingress is heightened, leading to a longer service life in the end [13,23,36]. Higher compressive strength in marine applications also

Table 3

The summary for corrosion solution in marine application.

No.	Researcher	Materials used	Cover thickness (mm)	Compressive strength (MPa)	Chloride migration coefficient ($\times 10^{-12} \text{ m}^2/\text{s}$)	Year	Country
1	Chindaprasit and Chalee [36]	Class C Fly ash	*	23.4 – 32.2	2.9 – 6.2	2014	Thailand
2	Gao et al., [23]	Cement + admixtures (basalt fiber, silica fume, fly ash)	*	15.8 – 25.5	1.004 – 1.783	2017	China
3	Kim et al., [36]	CEM I, CEM III/A (cement + slag)	*	70 53	1.39 4.21	2018	Scotland
4	Coppola et al., [40]	CEM II/B-V (cement + fly ash) Cement type II, III, IV	*	58 28.4 28.8 25.3	4.21 Cement type III & IV 6 – 16 Cement type II 21	2020	Italy
5	Huang et al., [41]	high sulphate-resistant Portland cement (HSRPC), silica fume (SF) and metakaolin (MK)	*	HSRPC 36 – 44 HSRPC/MK = 0.15 46 – 47 HSRPC/SF = 0.15 38 – 45	HSRPC - 7.07 MK - 2.45 SF - 2.54	2019	China
6	Noort et al., [42]	Cement (type III/B 42,5 N)	*	*	1.2 – 5.0	2016	Norway
7	Zuquan et al., [24]	100% cement 51.1% cement + 31.9% GGBS + 17% fly ash	*	39.4 47.1	1.18 – 1.68 1.3 – 1.78	2018	China
8	Noushini et al., [43]	Australian low fly ashes + ground granulated blast-furnace slag (GGBS)	*	27.4–62.3	Curing at 60 °C 100 Curing at 75 and 90 °C 56 – 61	2020	Australia
9	Naito et al., [44]	Type I cement (CEMI), CEMI + 18% Fly Ash (FA) and Type II cement (CEMII) + 6–20% GGBFS	*	26.0 – 68.0	0.54 – 30.62 Average 9.51	2020	Pennsylvania
10	Velandia et al., [11]	Fly ash Class F + Portland cement (Type III)	*	40 – 80	< 7.0	2018	Columbia
11	Darmawan et al., [37]	Fly ash geopolymer concrete	*	24.78 – 35.09	*	2019	Indonesia
12	Chalee et al., [1]	Portland cement Type I + Ground rice husk–bark ash (GRBA)	*	28.6 – 45.1	2.6 – 3.8	2013	Thailand
13	Zhe Li et al., [13]	Portland cement (Type II) + fly ash (additive)	36 – 52	46 – 56	2.32 – 4.38	2019	China
14	Law et al., [45]	Fly ash (class F)	*	44.4 – 56.9	0.31 – 0.37	2015	Australia
15	Thomas et al., [46]	Portland cement (Type I) + slag	*	(w/c ratio = 0.40) 36.5 – 39.9 (w/c ratio = 0.50) 29.4 – 35.6 (w/c ratio = 0.60) 12.8 – 20.5	(w/c ratio = 0.40) 16.0 – 0.91 (w/c ratio = 0.50) 9.04 – 1.32 (w/c ratio = 0.60) –	2012	Canada

* is not conducted

benefits the durability and bond strength between concrete and steel reinforcement, reducing the initiation time for corrosion and extending the service life of reinforced concrete [5,35,40]. Previous studies have shown that aging, low water/cement ratio, and a decrease in penetration depth all contribute to the reduction of chloride migration coefficient, ultimately mitigating reinforced concrete damage or corrosion initiation [23,36,41].

Furthermore, the endurance of reinforced concrete is considerably impacted by the chloride migration coefficient, which must be reduced to a minimum. Numerous factors play a pivotal role in augmenting the durability of reinforced concrete structures that are exposed to chloride migration coefficient. These include the water-to-cement ratio, type and quantity of cement, binding of chloride ions, materials, and environmental conditions, as cited in [13,21,41], and [42].

Over the past decade, most research studies have aimed to identify effective repair and retrofitting techniques for marine applications, which can enhance the durability of reinforced concrete, as presented in Table 3. To increase the service life of reinforced concrete, it is essential to examine key parameters such as the type of materials used, thickness of concrete cover, compressive strength, and chloride migration coefficient.

The impact of varying concentrations of sodium hydroxide (NaOH) on chloride infiltration, steel degradation, and the compressive strength of fly ash-based geopolymer concrete in a marine environment was studied by Chindaprasirt and Chalee [39] in 2014. Geopolymer concrete with a higher concentration of NaOH showed a decrease in chloride infiltration and steel degradation, while exhibiting improved compressive strength. Meanwhile, in 2017, Gao et al. [23] have found out that different admixture (basalt fibre, silica fume, fly ash) and lower water/cement ratio had significantly reduced the diffusion coefficients ($1.00 - 1.78 \times 10^{-12} \text{ m}^2/\text{s}$) with strength of 15.8–25.5 MPa. Furthermore, the study [39] exclusively focused on the impact of NaOH concentration on chloride permeation and steel corrosion. It also explored the effects of water-cement ratio and admixture type [23]. However, the study did not consider factors such as the thickness of geopolymer concrete, which could influence its durability.

In the subsequent year, Kim et al. [36] carried out an investigation to evaluate the effectiveness of reinforced concrete in marine environment; utilizing three distinct cement types with supplementary cementitious materials (SCMs), such as ground granulate blast slag (GGBS) and fly ash (FA). The chloride diffusion coefficients achieved for CEM I, CEM III/A (a combination of cement and slag), and CEM II/B-V (a combination of cement and fly ash) concrete were $1.39 \times 10^{-12} \text{ m}^2/\text{s}$, $4.21 \times 10^{-12} \text{ m}^2/\text{s}$, and $4.21 \times 10^{-12} \text{ m}^2/\text{s}$, respectively. Although CEM I concrete displayed the greatest resistance, CEM III/A (cement + slag) and CEM II/B-V (cement + fly ash) are still capable of serving as binding agents to hinder chloride ingress, thereby effectively slowing down the process of corrosion. Furthermore, supplementary cementitious materials (SCMs) can obstruct chloride transport by virtue of disconnected pore structures caused by high chloride binding and continuous hydration. In the year 2020, Coppola and colleagues [40] made a report stating that the type of cement used (type II, III, IV) and a lower ratio of water to cement significantly decreased the diffusion of chloride in concrete. Additionally, it was established that it is advisable to avoid using limestone Portland cement (II) in environments that are rich in chloride. Nevertheless, Kim et al. [36] and Coppola et al. [40] neglected to take into account the influence of concrete cover thickness and various process parameters on the identification of defects in the corrosion solution for marine applications.

In 2019, Huang and colleagues investigated the impact of curing temperature and supplementary cementitious materials, specifically metakaolin (MK) and silica fume (SF), on chloride migration in precast concrete designed for marine environments [41]. The compressive strengths attained ranged from 36 to 44 MPa, 46–47 MPa, and 38–45 MPa, while the corresponding chloride coefficients were $7.07 \times 10^{-12} \text{ m}^2/\text{s}$, $2.45 \times 10^{-12} \text{ m}^2/\text{s}$, and $2.54 \times 10^{-12} \text{ m}^2/\text{s}$ for high sulphate-resistant Portland cement (HSRPC), HSRPC/MK = 0.15, and HSRPC/MK = 0.15, respectively. The SF improvement mechanism is based on optimising the pore structure to prevent chloride migration, whereas MK is based on increasing chloride binding capacity. While offering valuable insights into a novel variety of precast concrete that showcases remarkable durability against sulphate and chloride in marine settings, its impact on cover thickness remains unexplored. Additional investigation may be required to examine the impacts of alternative supplementary cementitious materials (SCMs) and to study the extended lifespan of the concrete in marine settings.

Noort et al. conducted a study on the performance of slag cement-based concretes in 2016 using CEM III/B 42.5 N acquired from several cement manufacturers [42]. The study found that as the water/cement ratio, cement content, and effective water content decrease, the resistance to chloride ingress improves ($1.2 - 5.0 \times 10^{-12} \text{ m}^2/\text{s}$). However, a deficiency exists in the current literature regarding the investigation of cover thickness and compressive strength in relation to corrosion solution in marine applications. Additionally, it is imperative to acknowledge that the inquiries were executed on a restricted set of concrete compositions; hence the outcomes may not be universally relevant to all variants of concrete. Furthermore, the research exclusively examines the chloride migration coefficient and resistivity of slag cement-based concretes, thereby omitting any insights into other varieties of cement-based concretes.

In 2018, Zuquan et al. conducted a thorough analysis to determine how fly ash and ground granulated blast furnace slag (GGBS) affect the chloride ion transport and binding capability of concrete when exposed to a maritime environment [24]. The study found that GGBS was more effective than fly ash, resulting in greater resistance to chloride ion penetration in concrete as the corrosion progressed. In terms of the compressive strength, it can be asserted that the impact of GGBS on the chloride migration coefficient is more significant compared to that of slag and fly ash. Moreover, it is recommended that upcoming studies should prioritize understanding the impact of the thickness of the cover. Additionally, the proposed framework has been tested on a limited dataset, and its performance on larger datasets needs to be evaluated.

In the year 2020, a study was performed by Noushini and colleagues to investigate the impact of chloride diffusion on geopolymer concrete based on low-calcium fly ash. The concrete was prepared under various heat curing conditions and its durability was evaluated in a marine environment [43]. The findings of the study revealed that higher heat curing temperatures and longer durations resulted in a decrease in the migration coefficient. The results of the investigation indicate that the chloride diffusion resistance and chloride binding capacity of geopolymer concrete made with fly ash were found to be quite low, with values ranging from 38×10^{-12}

m^2/s to $79 \times 10^{-12} \text{m}^2/\text{s}$. Based on the findings acquired, it can be deduced that geopolymer concrete composed of fly ash possesses a highly desirable suitability for employment in circumstances where any concerns regarding chloride-induced durability are either limited or non-existent. However, the impact of cover thickness has yet to be explored. Additionally, the study only examined the impact of heat curing on the properties of the geopolymer concrete and neglected to explore the consequences of alternative curing techniques. Furthermore, the study did not explore the long-term durability of the geopolymer concrete under different environmental conditions.

In the year of publication, Naito et al. [44] conducted an investigation into three distinct categories of concrete mixtures that were incorporated with Type I cement (CEMI), Type I cement with 18% Fly Ash (FA) replacement, and Type II cement (CEMII) with a replacement of 6–20% GGBFS. Based on the findings, it is clear that the mix design consisting of 82% type I cement and 18% fly ash exhibited the greatest chloride migration coefficients ($0.54 \times 10^{-12} \text{m}^2/\text{s}$), in contrast to the use of Type I cement alone ($30.62 \times 10^{-12} \text{m}^2/\text{s}$). This observation led to the conclusion that as the compressive strength and water/cement ratios of concrete increased the chloride migration values decreased. It is important to acknowledge that the study did not examine the impact of cover thickness. Furthermore, the investigation just assessed the concrete's resistance to chloride migration, neglecting to account for other variables that might potentially impact the longevity of reinforced concrete constructions, including freeze-thaw cycles, alkali-silica reaction, and carbonation.

In 2018, Valandia et al. conducted a report examining the impact of chloride diffusion coefficient over time in Portland cement concrete integrated with fly ash [11]. The research conducted revealed that a chloride diffusion coefficient of $4.00 \times 10^{-12} \text{m}^2/\text{s}$ was associated with a compressive strength of 80 MPa in a mixture without fly ash. Conversely, a similar diffusion coefficient could be achieved in a mixture comprising 50% fly ash and sodium sulphate, resulting in a compressive strength of roughly 40 MPa. The research also indicated that a reduced water/cement ratio led to a reduction in water permeability and diffusion coefficient. Furthermore, it was observed that samples containing varied proportions of fly ash, while having same compressive strength and undergoing the same curing process had different results for chloride penetration and diffusion coefficients. However, the effect on cover thickness was not explored in this investigation.

In a study done by Darmawan et al. (2019), the researchers wanted to investigate the performance of geopolymer concrete specifically in relation to its application for beams [37]. The concrete specimen consisted of fly ash (FA) with high calcium content and underwent a curing process in a maritime environment for duration of 28 days, specifically in a zone where it was exposed to sea splashing. The results of the study indicate that the geopolymer concrete had good compressive strength, with values ranging from 24.78 to 35.09 MPa. Furthermore, the concrete's resistance to the effects of seawater was seen in terms of beam fracture pattern and development. Additional research is required to have a comprehensive understanding of the influence of the maritime environment on geopolymer concrete, specifically in relation to the chloride migration coefficient and cover thickness.

In a study conducted in 2013, Chalee et al. [1] investigated the use of rice husk-bark ash as a potential method for improving the corrosion resistance of reinforcing steel bars in concrete, with a specific focus on maritime environments. They investigated various factors related to chloride diffusion coefficient, chloride binding capacity, compressive strength, and steel corrosion in concrete. By substituting Type I Portland cement with rice husk-bark ash in varying proportions of 0%, 15–35%, and utilising a water/binder ratio of 0.45, the research team achieved a chloride diffusion coefficient ranging from 2.6 to $3.8 \times 10^{-12} \text{m}^2/\text{s}$. Furthermore, this substitution resulted in high compressive strength values ranging from 28.6 to 45.1 MPa, while also minimising the occurrence of embedded steel corrosion. Notably, however, certain significant tests, such as cover thickness, were not subjected to examination. Furthermore, the scope of the investigation was limited to examining the impact of ground rice husk-bark ash alone on the properties of concrete, without taking into account other potential variables that might influence long-term durability of concrete structures exposed to maritime conditions.

In 2019, Zhe et al. conducted a study [13] on two types of high-performance concrete design, namely C40 (land section) and C50 (marine section), by incorporating Portland cement (Type II) and fly ash as an additive to examine the effects on concrete compressive strength, chloride diffusion coefficient, cover thickness, and surface defects. The findings indicated that following a 28-day period of in situ curing, the compressive strengths of the two concrete types examined in the marine and land sections were measured at 56 MPa and 46 MPa, respectively. Additionally, the average cover thicknesses were determined to be 52 mm and 36 mm, while the mean chloride diffusion coefficients have been determined as $2.32 \times 10^{-12} \text{m}^2/\text{s}$ and $4.38 \times 10^{-12} \text{m}^2/\text{s}$. Nevertheless, this study just examines the impact of chloride ingress on reinforced concrete and does not incorporate additional variables that might potentially influence the longevity of concrete buildings in maritime settings.

In 2014, Law and colleagues conducted a study [45] on geopolymer concrete comprising fly ash activated with sodium hydroxide and sodium silicate, with the aim of evaluating its efficacy in preventing chloride induced attack over extended periods in marine environments. The findings of the study revealed that the compressive strength measurements varied between 44.4 and 56.9 MPa. In contrast, the apparent chloride diffusion values exhibited uniformity across all the geopolymer concretes, with a range of $0.31\text{--}0.37 \times 10^{-12} \text{m}^2/\text{s}$. The observed values exhibited similarity to those derived from ordinary Portland and mixed cement concretes. In contrast to ordinary Portland and blended cement concretes, the heat curing process may not cause a long-term drop in the diffusion coefficient of geopolymer concretes. However, it is crucial to prioritise future research efforts towards conducting extended duration tests on geopolymer samples. These tests are necessary to determine the maturity factor of geopolymer concrete in maritime environments, specifically considering the impact of cover thickness. Additionally, based on the information provided, it can be deduced that the research exclusively concentrated on evaluating the essential durability characteristics of geopolymer concrete produced using fly ash that was activated with sodium silicate and sodium hydroxide.

Thomas and Bremner conducted an investigation [46] to examine the penetration of chloride ions in concrete structures that had been subjected to a marine environment for duration of 25 years at Treat Island. Different water/cement ratios (0.40, 0.50, and 0.60)

and varying slag contents (0, 25, 45, and 65% by mass of cementing materials) were utilized to develop various concrete mixtures. According to the results obtained from this investigation, it is recommended that in order to effectively resist chloride penetration and surface scaling caused by freeze-thaw cycles in this extremely hostile setting, the most optimal concrete mixture proportions would involve water/cement ratios of 0.40 or below, together with slag levels ranging from 45% to 65%. The utilization of slag has demonstrated considerable efficacy in mitigating the ingress of chloride ions, as the extent of chloride infiltration diminishes substantially with higher proportions of slag material. However, further investigation into cover thickness should be considered as a crucial parameter in minimizing chloride ingress in marine applications. Additionally, the proposed framework has undergone testing on a restricted dataset, hence necessitating an evaluation of its efficacy on more voluminous datasets.

Based on the conducted review, it is imperative to incorporate certain key aspects such as the materials employed, thickness of concrete cover, compressive strength, and chloride migration coefficient during the design of prospective materials for reinforced concrete structures, as well as during the restoration of existing ones for marine applications. Unfortunately, prior research has failed to consider all of these essential variables in their attempts to determine the optimal method for extending the durability of reinforced concrete in marine environments. Prior research has demonstrated that the usage of a diverse range of materials has greatly enhanced the performance of reinforced concrete, with the ultimate objective of curtailing concrete deterioration and substantially extending its lifespan.

The ensuing step involves conducting studies on geopolymer concrete, which exhibits a considerably greater capacity for employment in marine infrastructure, as opposed to conventional concrete, specifically ordinary Portland cement concrete.

4. Potential of geopolymer concrete in marine infrastructure

The incorporation of Ordinary Portland Cement (OPC) as the principal binding component in the manufacturing of OPC concrete is a widely recognized and established procedure. In recent times, there has been a surge in the production of this cement, resulting in an annual global output of 2.6 billion tonnes with a steady growth rate of 5% [47]. Nevertheless, it is important to acknowledge that Ordinary Portland Cement (OPC) plays a significant role in the release of greenhouse gases, specifically contributing to around 5–8 percent of global carbon dioxide (CO₂) emissions. These emissions have adverse effects on the environment [48,49]. Conversely, geopolymer concrete has emerged as a versatile, durable, cost-effective, and environmentally friendly material that has gained wide acceptance in the construction manufacturing as a viable substitute for OPC concrete [47–50]. Research findings indicate that the utilization of geopolymer concrete exhibits promising prospects in terms of substantial reduction in CO₂ emissions [51–55]. The quest for eco-friendly materials in marine infrastructure is gaining momentum, and it is crucial to reduce the use of OPC, which emits CO₂ without compromising the essential needs of future generations [6,30,37,56,57]. Compared to conventional marine concrete, geopolymer concrete has demonstrated the potential to enhance both environmental and engineering performance [58–61].

Geopolymer has garnered significant attention as a sustainable substitute for OPC on account of its environmentally conscious properties [62–64]. The sustainability of this material is widely recognized in comparison to Ordinary Portland Cement (OPC) owing to its reduced energy demands during the manufacturing process and decreased carbon dioxide (CO₂) emissions [58,65]. Moreover, geopolymer concrete has a smaller carbon footprint in comparison to OPC concretes. This particular form of concrete is commonly produced through the process of alkali activation, wherein industrial waste materials rich in aluminosilicate content, such as fly ash, are utilized [60,61]. Geopolymer concrete has the potential to serve as a feasible substitute for Portland cement concrete due to its outstanding mechanical qualities, which may be achieved through the application of suitable mix design and formulation techniques [52,61].

Recent research has indicated that geopolymer concretes possess the potential to considerably reduce greenhouse gas emissions by up to 70% [66,67]. Furthermore, geopolymer concrete developed from standard Australian materials exhibits a lower rate of greenhouse gas emissions, ranging from 44% to 64% as compared to OPC concrete [65]. Yang et al. [68] conducted further research which demonstrates that geopolymer concrete exhibits the capacity to decrease CO₂ emissions by 55–75% in comparison to ordinary Portland cement (OPC) concrete. Geopolymer concrete is predominantly constituted by fly ash, which exhibits elevated concentrations of silica (Si), alumina (Al), calcium (Ca), and iron (Fe). The dissolution of these constituents in an alkaline solution is a crucial step in the geopolymerization process, leading to the formation of a binder that finds application in the creation of geopolymer concrete. It is imperative to acknowledge that the carbon dioxide content associated with fly ash is significantly lower in comparison to ordinary Portland cement (OPC), as depicted in Table 4 [16,35].

It is evident that by implementing a binder system, one can attain each of the aforementioned benefits. Through the utilization of the key factors outlined below, a well-structured material can potentially be realized. The emergence of geopolymer concretes as

Table 4
Embodied carbon dioxide contents for main materials in concrete [21].

Materials	Embodied carbon dioxide (kgCO ₂ e/t)
OPC (CEM I)	950
Fly Ash	4
Limestone fines	32
Aggregate	5
Reinforcement	427
	-

innovative engineering materials that could constitute a significant component of an environmentally sustainable construction is well-documented [69–72]. Hence, the present moment presents a favourable opportunity to undertake a thorough examination of the control formation in geopolymer concrete design and to scrutinize the fundamental features pertaining to the influential factors that affect the properties of geopolymer concrete.

4.1. Factors influencing geopolymer concrete design

The properties of geopolymer concrete are subject to the influence of several factors that necessitate careful consideration in order to attain an optimal mix design and formulation. These determinants have been extensively studied and reported in academic literature such as [51,53,66,68], and [69]. These factors encompass the solid-to-liquid ratio, the ratio of sodium silicate to sodium hydroxide (NaOH/Na₂SiO₃), the molarity of sodium hydroxide (NaOH), the inclusion of water content in the formulation, as well as the duration and temperature of the curing process. These determinants have been documented in scholarly works such as [55,57,71,73], and [74].

4.1.1. Solid/liquid ratio

The ratio of solid to liquid is a crucial factor in the design of geopolymer concrete, since it significantly influences its workability, strength, and durability [75–78]. Achieving a well-balanced ratio is crucial to ensure optimal particle dispersion, resulting in improved packing density and reduced porosity, thus enhancing compressive strength and resistance to chemical and environmental damage [79–81]. Additionally, the ratio directly affects the geopolymer paste's setting time and viscosity, which, in turn, impacts the casting process and overall workability [11,51]. Inadequate proportion can cause problems such as excessive bleeding or segregation, compromising concrete homogeneity [11,51,53]. Engineers and researchers must carefully study and optimize the solid to liquid ratio, considering specific materials and mix proportions, to achieve the desired properties. Recognizing the ratio's significance is paramount as it directly impacts the performance and quality of geopolymer concrete structures, making it an essential aspect of design considerations [55,57,58,80,81].

4.1.2. Sodium silicate/sodium hydroxide ratio

The relative proportion of sodium silicate to sodium hydroxide is a crucial parameter in the formulation of geopolymer concrete, and its importance cannot be emphasized [55,71,75]. The ratio in question assumes a crucial function within the geopolymerization process, serving as a determining factor for the cohesiveness and subsequent strength enhancement observed in geopolymer concrete [61,76,82–84]. The ratio of sodium silicate to sodium hydroxide exerts a direct influence on the kinetics of the geopolymerization reaction as well as the development and stability of the geopolymer gel [84–86]. An appropriately optimized ratio has the potential to contribute to an increased level of geopolymerization, thus leading to improved mechanical properties and durability of the concrete [51,52,87,88]. In addition, this ratio affects the workability of the geopolymer paste as well as the time it takes for it to set [84,86,88].

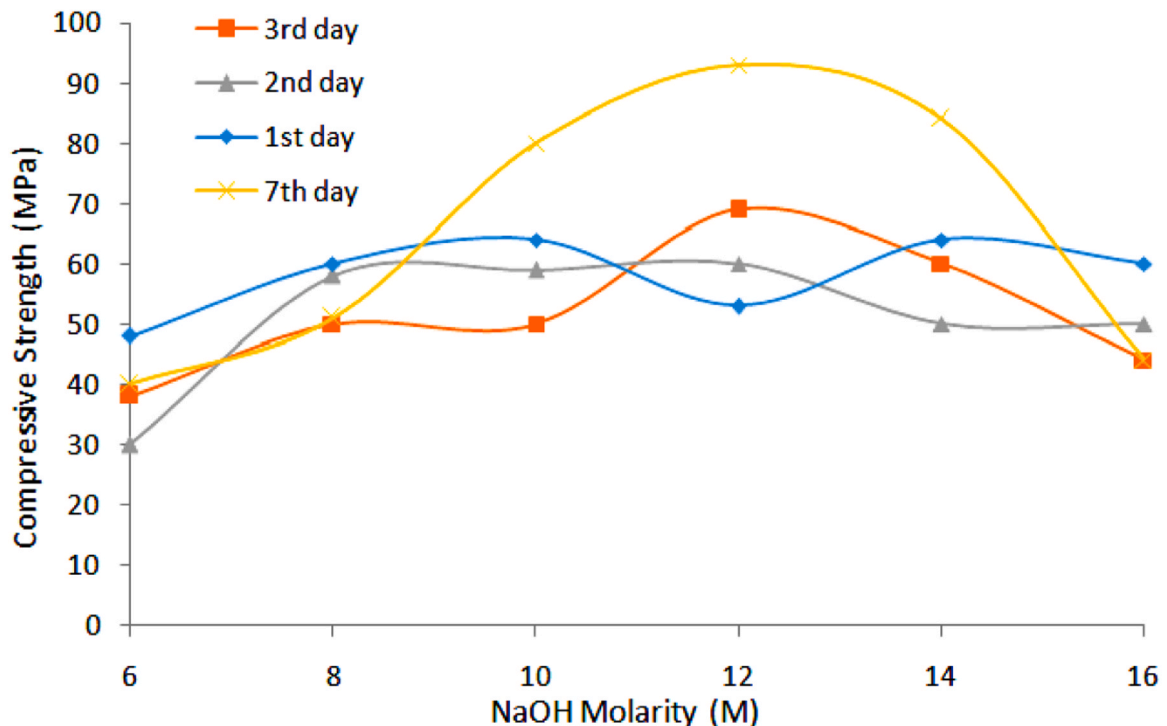


Fig. 2. The compressive strength of various molarity of NaOH [78].

Proper viscosity is ensured by an appropriate ratio, which facilitates better handling and casting of the concrete mixture [88–90]. The appropriate ratio of alkali activator in concrete may vary depending on various aspects, including the specific type of alkali activator used, the properties of the source materials employed, and the desired performance outcomes of the concrete [84–90]. Therefore, it is essential to consider this ratio as a crucial design parameter in geopolymer concrete applications. Thus, the subsequent portion will perform a thorough assessment of the primary factors that have impacted the effectiveness of geopolymer concrete. The parameters encompass the proportions of solid to liquid, the ratio of sodium silicate to sodium hydroxide, and the molarity of sodium hydroxide.

4.1.3. Sodium hydroxide molarity

Several study investigations have demonstrated that the mechanical characteristics of geopolymers are significantly influenced by the content of sodium hydroxide (NaOH) solution [58,80,85], and [89]. The influence of NaOH solution molarity on fly ash-based geopolymers was studied in depth by Rattanasak and Chindaprasirt [90]. A positive correlation was observed between the compressive strength of geopolymers and the molarity of NaOH solutions. Geopolymers exhibited a maximum compressive strength of 65–70 MPa when subjected to solutions with a molarity ranging from 10 M to 15 M. In contrast, a compressive strength of up to 21 MPa was observed for geopolymers treated with a 5 M NaOH solution. This comparison of compressive strengths was utilized to determine the impact of different solution concentrations on the compressive strength of geopolymers.

It is noteworthy to mention that the investigation conducted by Mustafa et al. [78] demonstrated that a concentration of 12 M NaOH resulted in the maximum compressive strength of 94.59 MPa (Fig. 2), which was not evident in other concentrations. This can be attributed to the release of optimum ions, such as Si^{4+} and Al^{3+} from fly ash, which are crucial for geopolymerization. The inclusion of a substantial concentration of hydroxide (OH) ions enhances the process of dissolving silicate and aluminate compounds, thereby facilitating the formation of dissolved species during the geopolymerization reaction. In addition, it should be noted that at this particular concentration, the presence of Na ions serves to maintain charge equilibrium and facilitate the formation of aluminosilicate networks, which act as the binder in the system. This phenomenon has been observed and substantiated by Yip et al. [91]. Therefore, the optimal concentration of NaOH solution for producing the maximum strength fly ash geopolymer is 12 M.

Furthermore, an additional revelation has encompassed the intricate correlation amidst the concentration of sodium hydroxide (NaOH) solution and the compressive potency of fly ash-derived geopolymer concrete. Investigations conducted by Zulkifly et al. (2018) and Pane, Imran, and Budiono (2018) indicate that increased levels of NaOH generally result in enhanced compressive strength. However, the optimal concentration varies based on several factors, such as the specific combination of fly ash and metakaolin, choice of activator, and duration of curing [92,93]. Notably, Zulkifly et al. found that 14 M NaOH was most effective at 7 days, while Pane, Imran, and Budiono discovered that 12 M was ideal at 28 days. Another study conducted by Kumar and Reddy (2023) examines the impact of NaOH molarity on fly ash-based self-compacting geopolymer concrete [94]. Their findings suggest that higher molarities, ranging from 8 M to 16 M, improve the hardened properties and potentially provide superior strength and durability. However, this advantage may affect the fresh properties and influence the workability during the mixing and pouring processes.

These results highlight the importance of taking a detailed approach when choosing the right NaOH concentration. In order to achieve a harmonious coexistence between the desired durable characteristics and the pragmatic demands for recently mixed concrete, it becomes essential to give due consideration to project-specific elements. Ultimately, scholarly sources emphasize that the production of geopolymer concrete is a complex undertaking that is influenced by a multitude of diverse variables, necessitating a meticulous assessment.

4.2. Properties of geopolymer in comparison to OPC concrete

The feasibility of utilizing the geopolymer concrete system as a reinforced concrete structure within a marine environment has been deliberated. Soon, an appraisal of the characteristics of geopolymers, comprising their chemical composition, microstructure, workability (slump), compressive strength, water absorption, and bond strength, will be executed.

Table 5
Chemical composition of fly ash and OPC cement [95,96].

Chemical Composition	Fly Ash (%)	OPC (%)
SiO_2	55.9	19.83
Al_2O_3	28.1	5.29
CaO	3.84	63.85
Fe_2O_3	6.97	3.53
Na_2O	-	0.21
ZrO_2	0.14	-
TiO_2	2.21	-
K_2O	1.55	0.07
V_2O_5	0.09	-
MgO	-	0.52
SO_3	-	2.43

4.2.1. Chemical composition properties

Fly ash is the most widely used primary constituent in geopolymers, and this review will focus on its chemical composition. A comparative analysis between fly ash and OPC has also been conducted. Table 5 displays the chemical composition results. One thing to keep in mind is that the main oxides in fly ash are silica oxide (SiO_2) and alumina oxide (Al_2O_3), while CaO and SiO_2 make up more than 80% of OPC cement. When the concentration of CaO exceeds 5%, there is a greater propensity for the formation of calcium silicate hydrates (C-S-H) compared to sodium aluminosilicate hydrates (N-A-S-H) [95–97]. In contrast, OPC is mostly made up of calcium carbonate (limestone) and silica (Si), which causes a calcinations reaction that, can lead to the rusting process [98].

Chloride permeability is lower in geopolymers than in OPC concrete, mostly because of the dense structure of the gel C-S-H and its cohabitation with a polymer network [99]. Alkaline activation of aluminosilicate precursors (fly ash) yields N-A-S-H gel, while hydration of OPC yields C-S-H gel [95–99]. Compared to typical OPC concrete, geopolymers possess a gel C-S-H with a more condensed and compact structure. This higher density impedes the migration of chloride ions, thereby decreasing their permeability into the geopolymer matrix [97–99]. Consequently, the infiltration of hazardous chlorides, which can give rise to concrete damage and reinforcement corrosion, is significantly minimized. Additionally, the geopolymer matrix's resistance to chloride penetration is improved by the existence of different phases inside it. Geopolymer systems often utilize aluminosilicate precursors and other mineral admixtures to heighten density and reduce permeability. Overall, the decrease in chloride permeability in geopolymers can be attributed to the dense and compact structure of the gel C-S-H and the synergistic effects of coexisting phases inside the geopolymer matrix. Because of these properties, geopolymers are a possible alternative to OPC concrete, especially in areas where chloride-induced corrosion is a concern.

4.2.2. Microstructure properties

Previous research has used Scanning Electron Microscopy (SEM) micrographs to examine and analyse the microstructure of fly ash, Ordinary Portland Cement (OPC), as well as the fracture surface of geopolymer and OPC concrete (Fig. 3) [70,101–103]. Fig. 3(a) depicts spherical solid particles as the dominating particles in fly ash raw materials [70], whereas Fig. 3(b) depicts stone-shaped particles in OPC cement raw materials [101,102]. The fly ash particles have been effectively integrated and interconnected with the matrix material, as shown in Fig. 3(c), and nonporous microstructures are visible [70]. Despite the high alkalinity of the concrete, differential aeration in the wet, chloride-rich air-voids may trigger localised corrosion because the concrete around the steel bars is not properly compacted and is more porous. As a result, corrosion cannot occur at the voids, which are a feature of the permeability and

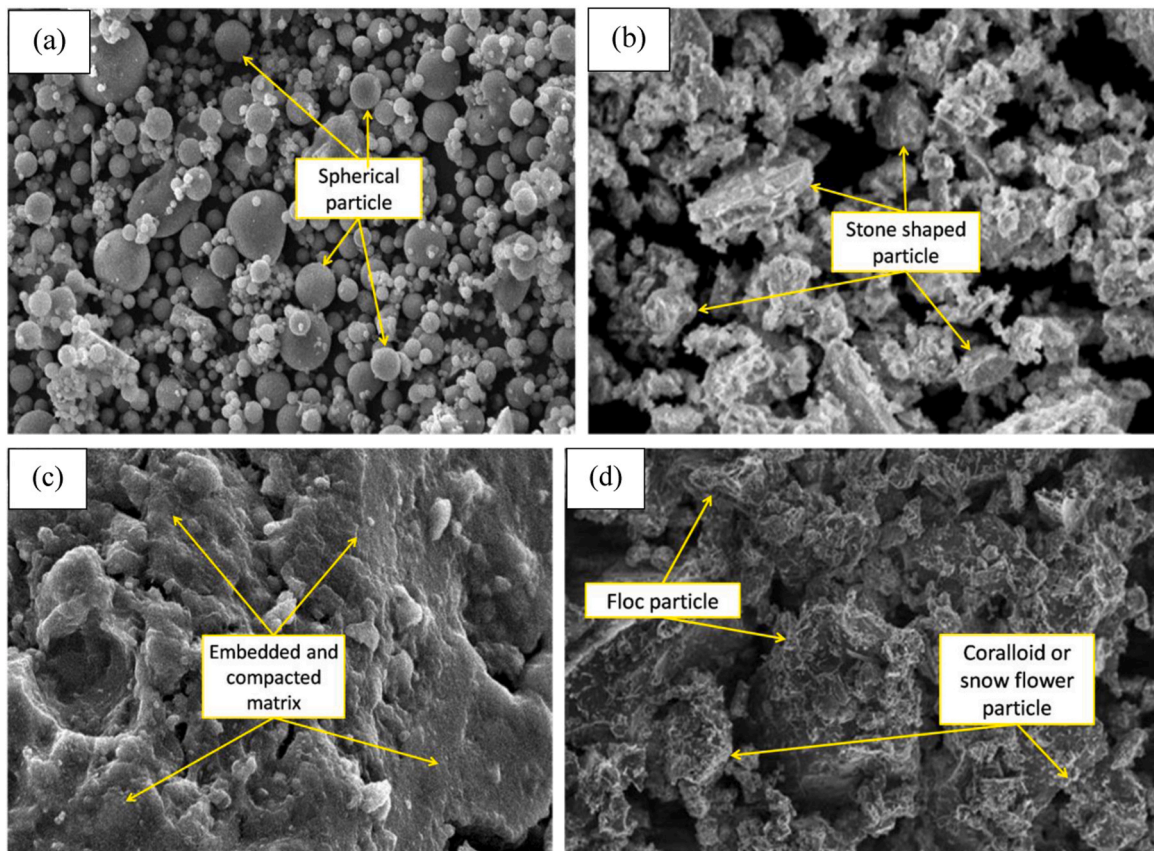


Fig. 3. SEM micrograph of raw materials (a) fly ash, (b) OPC, fractured surface concrete of (c) geopolymer and (d) OPC [70,101,102].

thickness of the concrete cover [3,6,48].

The impermeable microstructure can be ascribed to the extensive dissolution of fly ash particles and the polycondensation of aluminosilicate compounds, along with the noteworthy dissolution of aluminosilicate species before polycondensation, as posited by Hos and Byrne [100]. This leads to a strong bond between these two elements. Meanwhile, coralloid, floc, and snow flower-shaped particles are formed as the C-S-H gel in the OPC concrete matrix goes through its several phases and hardens as demonstrated in Fig. 3(d) [101,102]. In comparison to the geopolymer concrete matrix, the matrix structure in ordinary Portland cement (OPC) has a higher susceptibility to potential corrosion of reinforced bars in maritime environments. This is attributed to the looser nature of the OPC matrix, which contains a greater quantity of voids [37,99]. This looser structure with more voids heightens the risk of seawater penetrating the concrete and causing corrosion of the reinforced bar.

4.2.3. Workability properties

The characteristics of concrete are intricately linked to its ability to be worked [56,61,62]. The slump value, as defined by IS 456–2000 [104], is of utmost importance in concrete workability. When the slump value is less than 25 mm, the concrete is said to possess very low workability, whereas a slump value greater than 150 mm is indicative of very high workability [105]. Conversely, binder, a vital component of concrete that fills and coats the gaps between aggregates, has a significant impact on flow potential [106–108]. Consequently, workability of OPC and geopolymer concrete were evaluated based on various performance parameters, owing to the fact that both concrete types have different binding systems. Table 6 presents a comprehensive overview of recent studies examining the workability performance of Ordinary Portland Cement (OPC) and geopolymer concrete. The findings indicate that geopolymer concrete exhibits superior workability compared to OPC concrete, particularly for concrete with dimensions above 150 mm.

The primary objective of this review is to examine the feasibility properties of geopolymer concrete by the incorporation of fly ash. The incorporation of this modification is believed to enhance the practicality of the material, as evidenced by previous studies [56,61,62], and [112]. In particular, the roundness and fineness of the fly ash have been discovered to have a major effect on its workability, as this morphology decreases tension at the interface between the aggregate and paste, creating a ball-bearing effect that makes it easier for the concrete to flow [56,61,62,113]. Regular Portland cement (OPC) concrete, on the other hand, has high viscosity and cohesiveness, which contribute to its poor workability [115–117]. The phenomenon of slump loss in concrete is associated with both physical and chemical mechanisms, as the augmentation of cement particle density per unit volume of the mixture results in enhanced dispersion [114].

4.2.4. Compressive strength properties

Concrete's compressive strength can be influenced by various factors, including the water-cement ratio, the quality of the raw materials, the ratio of coarse to fine particles, temperature, curing conditions, age, relative humidity, and compaction [97,116]. In a marine environment, the presence of seawater induced by ocean splashing can result in a decline in compressive strength and an acceleration of concrete damage [63,73,74]. In the future, it is crucial to produce cement that possesses both durability and a significant compressive strength in order to address the impact of corrosion on reinforced concrete structures employed in maritime environments [3,16,36]. In contrast, geopolymer concrete, which is more homogeneous, has displayed a robust interface between the concrete matrixes and reinforcing bars [30,40,116]. The hybrid geopolymer materials exhibit (C,N)-A-S-H gels that possess a tortuous characteristic, resulting in a more complex diffusion pattern of chloride ions [16,43,86]. Hence, a limited level of condensation in the geopolymerization procedure will result in the formation of geopolymer concrete with reduced short-term compressive strength [54,55,116].

Rangan [117] provided a detailed analysis of the behavior and effectiveness of fly ash, the main constituent of geopolymer concrete. The study revealed that geopolymer concrete demonstrated a wide range of compressive strengths, spanning from 8 to 100 MPa, and exhibited varying curing durations, ranging from 7 to 28 days. In addition, Rangan [117] detailed how geopolymer concrete can achieve outstanding early strength, with 70% of the final compressive strength achieved in the first 4 h of setting. After 14 days, the strength can be ascertained within the range of 5–51 MPa, exclusively at ambient temperature. As Table 7 illustrates, the compressive strength achieved on day 28 demonstrated minimal variance between both concrete [85,118]. However, increasing the concentration of NaOH in geopolymer concrete has been found to have several beneficial effects. These include an increase in compressive strength, a reduction in chloride penetration and corrosion of embedded steel, and a significantly lower environmental impact. As a result, there is promise for the use of this material in marine applications [40].

Previous research endeavours have directed their attention towards examining six distinct varieties of fly ash, with the resultant quantitative analysis of the compressive strength being presented and visually represented in the form of Fig. 4.

Table 6
Overview of relevant researchers pertaining to the slump value of concrete.

Previous Study	Slump (mm)	Concrete
Kanellopoulos et al. [109]	49	OPC
Olivia & Nikraz[56]	90	OPC
	180–250	Geopolymer
Olivia & Nikraz[110]	230–270	Geopolymer
Olivia, Sarker et al. [111]	230–270	Geopolymer

Table 7
Summary of previous studies on compressive strength of OPC and geopolymer concrete.

Researchers	Compressive Strength, 28 days (MPa)	Types of Concrete
Kanellopoulos et al. [110]	56	OPC
Deboucha et al. [119]	35.42	OPC
Mačiulaitis et al. [120]	27.17–33.32	OPC
Mustafa et al. [76]	31	OPC
	49	geopolymer
Olivia and Nikraz [56]	56.49–60.20	geopolymer
	56.22	OPC
Olivia and Nikraz [110]	25.44–48.06	geopolymer
Chindapasirt and Chalee [40]	23.4–32.2	geopolymer
Law et al. [45]	44.4–56.9	geopolymer

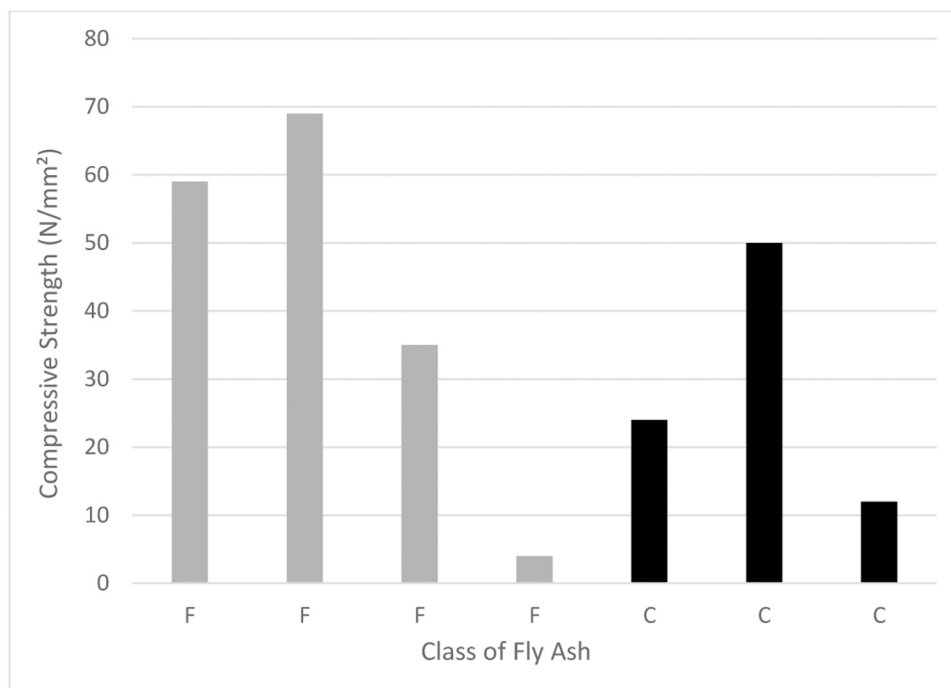


Fig. 4. Compressive strength and porosity analysis of geopolymer concrete [121].

The experimental findings revealed that geopolymer concrete, which was composed of Class C and F fly ashes, had a notable correlation between the highest compressive strength and the presence of Class F fly ash [52,74]. Class F fly ash is characterized by its high aluminosilicate content, which makes it a desirable choice for inorganic polymerization due to its low calcium level [50]. The difference in strength can also be ascribed to other variables, including the substantial presence of calcium in fly ash. This calcium content has the potential to impede the rate of polymerization setting and modify the microstructure. Based on the available evidence,

Table 8
Previous research on water absorption performance by OPC and geopolymer concrete.

Previous Study	Curing (days)	Water Absorption (%)	
		Geopolymer Concrete	OPC Concrete
Luhar and Khandelwal [124]	28	2.76	2.91
Misha et al. [125]	28	2.5	-
Sathia and Santhanam [123]	28	0.8–1.7	0.9–2.1
Olivia et al. [111]	28	3.72–4.58	4.5–4.94
Ganesan et al. [126]	28	2.91	8.1
Mačiulaitis et al. [120]	28	-	7.14–8.25
Olivia and Nikraz [56]	28	3.45–4.33	5.09
Olivia and Nikraz [110]	28 and 91	3.63–4.90	-
Nuaklong et al. [127]	7	5.3–6.5	-

it appears that low calcium (ASTM Class F) [122] fly ash is a more suitable option for geopolymer production compared to high calcium (ASTM Class C) [122,123] fly ash. Furthermore, a study conducted by Olivia and Nikraz [122] revealed that the utilization of fly ash in concrete resulted in enhanced corrosion resistance when compared to ordinary Portland cement (OPC) concrete. Additionally, the researchers found that geopolymer concrete demonstrated a delayed occurrence of the initial crack formation.

4.2.5. Water absorption properties

Concrete's ability to absorb water is a key element in determining its long-term stability in maritime conditions [1–3]. To enhance the durability of the building, a test has been employed to ascertain the concrete's water absorption capacity [6] [18]. Geopolymer concrete, as pointed out by Luhar and Khandelwal [124], has a lower water absorption rate than regular Portland cement (OPC) concrete. This is because geopolymer has less porosity than OPC concrete, which is brought on by fly ash's relative fineness, and has less water absorption as a result. A summary of water absorption performance parameters from earlier studies is shown in Table 8. Numerous studies have shown that in terms of water absorption, geopolymer concrete performs better than OPC concrete.

Based on previous studies, the favourable water absorption performance of geopolymer concrete can assist in diminishing the propensity of reinforcing bars to undergo corrosion when exposed to chlorides, by constricting the penetration of those chlorides into the concrete [40,53,54,57,128]. Water absorption in geopolymer concrete was also studied by Sathia and Santhanam [123], who found that it varied less than in regular concrete as compressive strength increased (refer to Fig. 5). From the determined outcomes depicted in Fig. 6, water absorption levels for the various geopolymer concretes clearly fell below the 3% threshold considered acceptable for high-quality construction materials. The final water absorption findings show that as concrete strength increased, water absorption performance also improved.

4.2.6. Bonding strength properties

Due to the remarkable bond strength that concrete possesses, it is widely used as a construction material in conjunction with steel reinforcement. To provide compatibility and facilitate force transfer between the materials, a solid connection between the reinforcing bars and concrete is required, as explained in sources [29] and [72]. This interplay plays a pivotal role in reinforcing structures and ensuring their optimal performance, as stated in sources [29,72], and [129–131]. In contrast, Sarker [132] came across that reinforced geopolymer concrete demonstrated a higher bond strength (14.32 MPa) than OPC concrete (10.25 MPa) during pull-out experiments. Additionally, Sofi and colleagues [131] acquired nearly indistinguishable bond strength measurements for geopolymer concrete (14.7 MPa). In addition, research conducted by Nuroji and colleagues [130] revealed that geopolymer concrete possesses an average bond strength that is twice as strong as that of OPC concrete. This is demonstrated in Fig. 6.

4.2.7. Shrinkage properties

The effect of shrinkage properties in the context of fly ash geopolymer concrete for marine applications is a diverse and important aspect. Many studies have described the difficulties and potential remedies of shrinkage issues in geopolymer materials. The use of geopolymer coatings to protect marine concrete, as shown by Zhang, Yao, and Wang (2012), has shown encouraging results but faces concerns associated with microcracks caused by shrinkage under normal conditions, emphasizing the need for further investigation to improve durability of materials in marine settings [133]. On the other hand, the inclusion of MgO and other innovative approaches, as

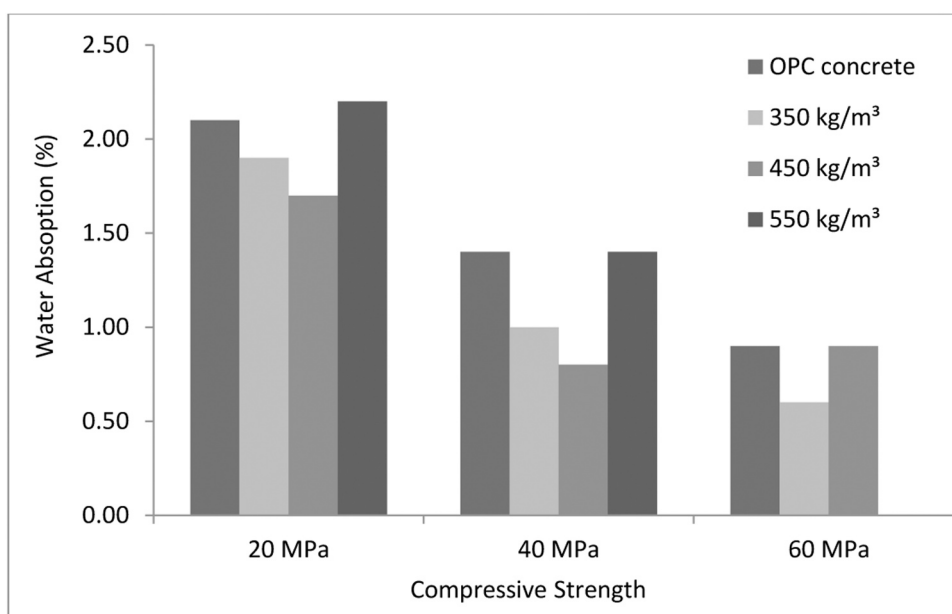


Fig. 5. The results of water absorption with variation content of fly ash with different strength [123].

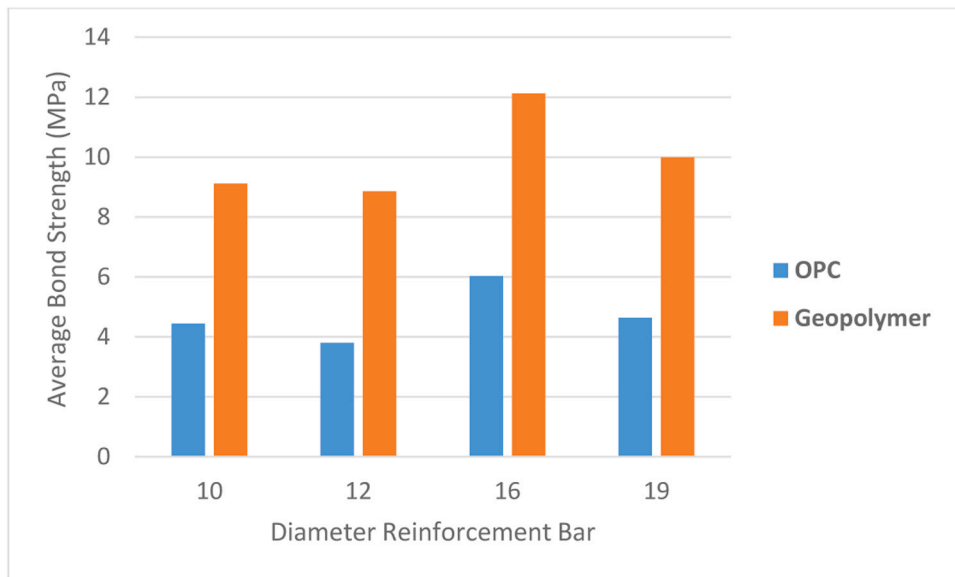


Fig. 6. Comparison of the average bonding strength of OPC concrete and geopolymer concrete [130].

investigated by Yang et al. (2022), exhibit significant potential in reducing shrinkage, making geopolymer concrete a more viable option for engineering applications, including in marine environments [134]. The integration of GGBFS in geopolymer concrete, as shown by Deb, Nath, and Sarker (2015), has also shown promise in shrinkage reduction, adding to the suitability of the material as an alternative to traditional concrete [135]. Additionally, a study conducted by Zhang, Yao, and Zhu (2010) emphasized the need to address shrinkage concerns, which, when effectively reduced using additives such as MgO, can improve the applicability and durability of geopolymer coatings for marine concrete protection [136]. Overall, addressing the challenges associated with shrinkage is important in harnessing the potential of fly ash geopolymer concrete for marine applications.

The aforementioned text examines the drying shrinkage values of OPC concrete specimens and geopolymer concrete mixtures. The drying shrinkage values of the OPC concrete specimens are plotted in Fig. 7, while the shrinkage values of the geopolymer concrete mixture R1.5S20 (sodium silicate/sodium hydroxide (SS/SH) with 20% ground granulated blast furnace slag (GGBS)) are also revealed in the same figure. It cannot be observed from the figure that the OPC concrete exhibited a shrinkage that was 11% higher at 28 days compared to the geopolymer concrete mixture R1.5S20, which possessed a similar compressive strength to that of the OPC concrete. The drying shrinkage value of R1.5S20 at 28 days was found to be 311 microstrain, whereas the value for the OPC concrete specimens was 346 microstrain. Likewise, the respective values at 180 days were 482 and 562 microstrain. Therefore, it can be inferred that the blending of GGBFS with fly ash and the reduction of the SS/SH ratio can diminish the shrinkage of geopolymer concrete to a level that

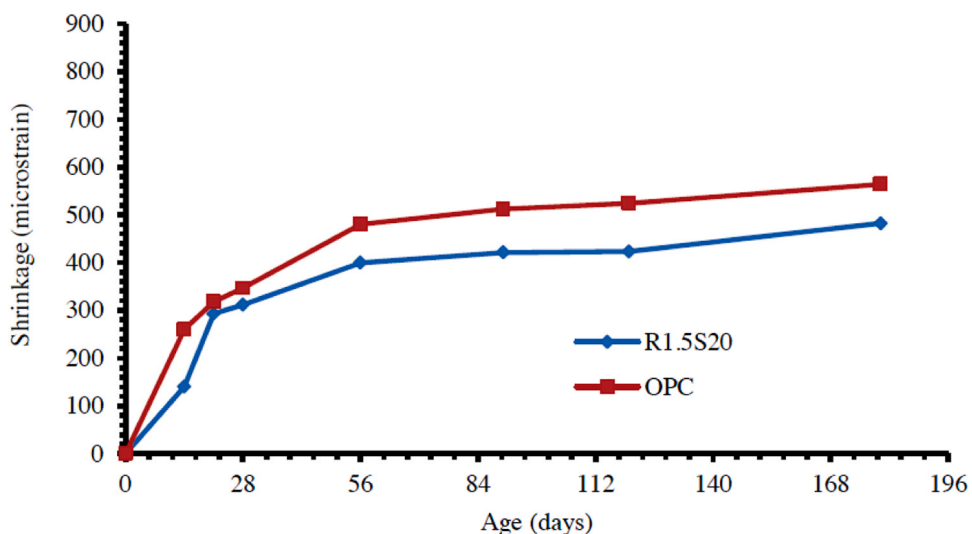


Fig. 7. Properties of drying shrinkage of geopolymer concrete and OPC concrete with similar strength grade [135].

is comparable to that of OPC concrete with similar strength. The lower drying shrinkage of the GGBFS blended fly ash geopolymer concrete can be attributed to the presence of a less interconnected capillary network within the geopolymer matrix. This observation aligns with the findings reported by Ma and Ye [137], which posit that the reduction in the capillary network is a result of the formation of a more compact and less porous geopolymer matrix. The findings of the study indicate that fly ash geopolymer concrete, particularly when combined with GGBFS and a decreased SS/SH ratio, shows a significantly lower drying shrinkage compared to traditional OPC concrete, while still maintaining a similar compressive strength. This discovery offers promise for the use of fly ash geopolymer concrete in marine infrastructure, where reducing shrinkage and improving durability are vital. Drying shrinkage is thought to have decreased due to the creation of a more compact and less permeable geopolymer matrix, resulting in a less linked capillary network. This contradicts prior study, which suggested that fly ash geopolymer concrete has the potential to be a sustainable and cost-effective option for marine application.

5. Summary and future recommendations

The present review highlights a notable challenge encountered in marine infrastructure, specifically the issue of corrosion impacting reinforced concrete. The following findings can be drawn from this review:

- In reviewing the key challenges contributing to structural damage like cracking and spalling in concrete, chloride ingress emerges as a primary concern among carbonation, chloride ingress, and stray/electrical current. Chloride ingress occurs when chloride ions from sources like seawater or de-icing salts infiltrate concrete structures, initiating chloride-induced corrosion of embedded steel reinforcement. This corrosion process results in rust formation on the steel, inducing internal pressure and subsequent cracking and spalling of the surrounding concrete. Ultimately, chloride-induced corrosion undermines the structural integrity of concrete exposed to chloride-rich environments, highlighting its significance as a key problem warranting attention in concrete infrastructure.
- In reviewing critical factors for enhancing the resistance of reinforced concrete in marine environments, concrete cover thickness, compressive strength, and chloride migration coefficient emerge as key considerations. Concrete cover thickness plays a crucial role in providing protection to the embedded steel reinforcement against chloride ingress and other aggressive agents. Higher compressive strength contributes to improved durability and resistance to structural deterioration in marine environments. Additionally, the chloride migration coefficient influences the rate at which chloride ions penetrate the concrete, affecting the likelihood of chloride-induced corrosion. Therefore, optimizing concrete cover thickness, compressive strength, and chloride migration coefficient are critical factors in enhancing the resistance of reinforced concrete structures in marine environments, warranting careful attention in design and construction practices.
- Utilization of geopolymer concrete crafted from fly ash as a sustainable substitute for Ordinary Portland Cement (OPC) concrete, has become apparent that this alternative offers a reduction in CO₂ emissions and decreased chloride permeability. The optimization of geopolymer concrete properties hinges significantly on factors such as the solid-to-liquid ratio, sodium silicate/sodium hydroxide ratio, and sodium hydroxide molarity. Furthermore, the selection of Class F fly ash emerges as advantageous for geopolymer production, demonstrating enhanced corrosion resistance and delayed crack formation in comparison to ordinary Portland cement. These findings highlight the potential of geopolymer concrete, underscoring its environmental benefits and the critical role of specific production parameters in achieving optimal performance.
- Factors influencing its compressive strength encompass the water-cement ratio, raw material quality, temperature, and curing conditions. Geopolymer concrete presents environmental benefits, including reduced CO₂ emissions, lower chloride permeability, and enhanced microstructure properties owing to its dense and compact nature. Moreover, it demonstrates improved workability compared to Ordinary Portland Cement (OPC) concrete, showing superior performance in water absorption and potential resistance to corrosion. Geopolymer concrete exhibits higher bond strength, crucial for the structural integrity of marine constructions, with studies indicating a significant increase compared to OPC concrete. Additionally, when combined with ground granulated blast furnace slag (GGBFS) and a reduced sodium silicate/sodium hydroxide (SS/SH) ratio, geopolymer concrete displays significantly lower drying shrinkage while maintaining comparable compressive strength, attributed to the creation of a more compact and less permeable matrix. These findings underscore the potential of geopolymer concrete as a sustainable and high-performance alternative to OPC concrete in various construction applications.

Geopolymer concrete is a great choice for repairing and retrofitting marine structures because of its exceptional performance in a variety of conditions. Nonetheless, it has not yet been broadly implemented as a solution for repairing and retrofitting reinforced concrete in marine infrastructure. Considering identified gaps in the research, this study proposes several future works as delineated below:

- I. Previous research endeavours have endeavoured to unify novel materials such as fly ash and silica fume with reinforced concrete in order to enhance its properties, ultimately leading to a lengthier lifespan for the concrete. Hence, it is essential to investigate a range of fundamental source materials (such as fly ash, kaolin, slag, etc.) that can be utilized in geopolymer concrete. This exploration must be undertaken with the objective of unveiling a fresh concrete design based on geopolymers, which can serve as an optimal marine infrastructure solution with an ideal solid/liquid ratio and sodium silicate/sodium hydroxide ratio.

- II. The evaluation of a novel geopolymer-derived concrete concept with regards to the thickness of concrete cover, compressive potency, and chloride migration coefficient is imperative prior to its application as a remedial and retrofitting solution for reinforced marine concrete.
- III. Through the process of chloride migration, it becomes feasible to accurately estimate the initiation and propagation of the service life of reinforced concrete based on the exposure condition (XS1, XS2 and XS3). This is an essential study in ensuring the longevity and durability of concrete structures.
- IV. To ascertain the chloride migration coefficient, it is imperative to thoroughly examine various possible standards and methods. This meticulous exploration will culminate in the recognition of the finest available method. Dedication of time and resources to this process is crucial to guarantee the outcome is of the utmost excellence.
- V. Finally, it is of utmost importance that we conduct a comprehensive investigation of the service life analysis, utilizing the results obtained from the most prestigious tests, specifically the non-steady state migration test NT BUILD 492, which is known for its proficiency in chloride migration application. It is crucial that we maximize the service life of our products and provide them with adequate protection from the detrimental effects of corrosion in marine applications.

CRedit authorship contribution statement

Aissa Bouaissi: Validation, Visualization. **Ana Armada Bras:** Writing – original draft, Writing – review & editing. **Filbert Hilman Juwono:** Supervision, Visualization. **Muhammad Noor Hazwan Jusoh:** Supervision, Writing – original draft, Writing – review & editing. **Mohd Mustafa Al Bakri Abdullah:** Visualization, Writing – original draft, Writing – review & editing. **Ismallianto Isia:** Visualization, Writing – original draft. **Shayfull Zamree Abd Rahim:** Validation, Visualization. **Tony Hadibarata:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Noor Fifinatasha Shahedan:** Data curation, Investigation, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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