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Deterioration of marine concrete exposed to wetting-drying action

Matthew Zhi Yeon Ting;
Kwong Soon Wong;
Muhammad Ekhlasur Rahman*;
Selowara Joo Meheron

*Faculty of Engineering & Science
Curtin University, Malaysia
E-mail: merahman@curtin.edu.my

Matthew Zhi Yeon, Ting
Department of Civil and Construction Engineering Faculty of Engineering and Science, Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
E-mail: matthew.ting@postgrad.curtin.edu.my

Kwong Soon, Wong
Department of Civil and Construction Engineering Faculty of Engineering and Science, Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
E-mail: wongkwongsoon@curtin.edu.my

Muhammad Ekhlasur, Rahman (Corresponding author)
Department of Civil and Construction Engineering Faculty of Engineering and Science, Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
E-mail: merahman@curtin.edu.my

Selowara Joo, Meheron
Department of Civil and Construction Engineering Faculty of Engineering and Science, Curtin University, Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
E-mail: meheron.sj@curtin.edu.my

Abstract

The adverse effects of hostile marine environment on concrete structure have inevitably resulted in huge economic loss and may contribute to catastrophic failure. Concrete is susceptible to weathering, particularly under wetting-drying action (WDA), although its current state of the art is well established. The diverse characteristics of WDA at different site locations have compromised the reliability of laboratory works. The objective of this study is to review the impact of WDA on concrete and to provide an overview of the research trend, aiming to identify the research gap. Concrete deterioration mechanisms in marine environment in respect of WDA are identified. The influential factors of WDA are analyzed. The physical and mechanical properties and corrosion resistance of concrete exposed to WDA are discussed. WDA aggravates concrete deterioration by hastening intrusion of inimical compounds such as chloride, sulphate and carbon dioxide. Chloride convection zone can be expanded by two to three times to cause a significant concrete cover loss. Physical damage of concrete starts with efflorescence staining, followed by mortar delamination, aggregate detachment and concrete spalling, leading to loss of mechanical properties. The use of mineral admixtures such as fly ash and silica fume improves concrete resistance against corrosion, but its refining effect may lead to over-accumulation of chloride, risking the long-term durability. Limited research works are identified on synergy between physical and chemical deteriorations, validation of simulated experiment, volume expansion, mass change and tensile strength of concrete.

Keywords: Wetting-drying action, Marine concrete, Deterioration mechanism, Concrete performance

1. Introduction

Phenomenal global warming and a consequent rise in seawater level are causing earth land to shrink. Approximately 70 % of the earth surface is covered by water which is mainly ocean (NOAA, 2018). Maritime structures are increasing in number because more coastal defense has to be constructed to counter the onslaught of sea action (Arns et al., 2017). Concrete has been widely used as construction material for maritime structures, such as breakwater, groin, seawall and harbour, due to better corrosion resistance than other materials like steel (Chilana et al., 2016). The proximity of coastal regions with marine environment can be up to 10 km from the coastline which is dependent on wind conditions (Pratolongo et al., 2019). Within this vicinity, aggressive marine environment will lead to concrete degradation. This can cause overall structural failure and catastrophic loss in the extreme case (Ibrion et al., 2020). Mitigation measures such as increase of concrete cover and strength, use of stainless steel and different repair strategies also greatly increase the life-cycle cost (Val and Stewart, 2003). Thus, it is essential to investigate the deterioration mechanisms so that more holistic solutions can be discovered.

Maritime structure can be subjected to four exposure conditions, including submerged, splash, tidal and atmospheric zones as illustrated in Figure 1(a) (Song et al., 2008). In atmospheric and submerged zones, on account of low chloride content and less oxygen exposure respectively, concrete is less prone to corrosion. Concrete corrosion in tidal and splash zones occurs more intensely due to the high chloride and oxygen contents and the alternating wetting-drying process. In this context, wetting-drying action (WDA) facilitates the deterioration of concrete. It induces the chloride accumulation and increases the intrusion (Y. Chen et al., 2016). The WDA also increases moisture transfer into concrete, by which the elements brought in can cause material deterioration (Jun

Zhang et al., 2011). In tidal zone, concrete experiences a regular WDA caused by sea tide. The tidal range can vary from 0 m to 12 m (Trenhaile, 2011). In splash zone, concrete is subjected to more cycles of WDA caused by wave and is liable to more damage.

The WDA has also brought about weathering and erosion of coastal structures for centuries. Past research concentrated on topic related to wetting-drying effect of rock and soil used for coastal defense. Gökceoğlu et al. (2000) found that WDA could weaken the intergranular bonds of clay-bearing rock. Rao et al. (2001) showed that lime-stabilized soil could be deteriorated by the same mechanism, causing it to lose cementation and increase porosity. During the last two decades, the studies have been focused on concrete structure due to the rapid advancement of concrete technology. The earlier research in this field analyzed the contributing factors. For example, Sahmaran et al. (2007) investigated the effect of exposure duration on concrete strength degradation. Medeiros et al. (2013) studied the effects of cycle number, height and position of the structure on chloride intrusion. Z. Yu et al. (2015) incorporated factors of temperature, relative humidity and exposure time to develop chloride diffusion model. The research was further extended to the cases with loading effects. F. Chen et al. (2017) studied the behavior of chloride intrusion into concrete subjected to compression. Fu et al. (2016) investigated the chloride intrusion into concrete under tensile loading. Gao et al. (2013) examined the cases with flexural loading. The recent studies enhanced concrete performance under WDA through incorporation of mineral admixtures such as granulated blast furnace slag (Qi et al., 2017), fly ash (Hoy et al., 2017), metakaolin (Valipour et al., 2017), palm oil fuel ash (Mohammadhosseini et al., 2017) and silica fume (Farahani et al., 2015). New research interest used fiber reinforced polymer (FRP) composite in concrete due to its higher corrosion resistance and strength-to-weight characteristic. Dawei Zhang et al. (2016) strengthened concrete beam with carbon FRP fabrics, while W. Tang et al. (2020) used glass FRP sheets. Garzón-Roca et al. (2015) replaced steel bars with carbon FRP bars. There exists abundant research related to WDA on concrete, but little attempt has been made by researchers to summarize the findings in order to identify the trends and gaps in this field. This paper aims to present a summary of the impacts of WDA on concrete and to provide insight into the latest research.

Marine concrete is designed for high strength and durability. The strength is required to resist abrasion and erosion. The durability, measured by permeability, has a bearing on concrete degradation related to WDA. There is little guideline in the existing standard to design high durability concrete. The standards provided by ACI (ACI211.1-91, 2002), BS (BS8110, 1997) and IS (IRC44, 2008) emphasize on the design of high strength concrete. High strength concrete is perceived to possess less porosity because of lower water demand. It contains less unreacted water that contributes to pore development and boosts durability (Kim et al., 2014). There is also little relevant guideline which can be relied on to carry out mix proportion design for marine concrete exposed to WDA. Designers are more inclined to do the design based on experimental results which is time-consuming and expensive. The difference in characteristics of WDA at different site locations also results in unique laboratory works. This review paper intends to give an overview of recent WDA experiment carried out by researchers including its influential factors to strengthen the knowledge in this domain.

Against this backdrop, the main objective of this paper is to review the impacts of WDA on concrete in marine environment. Figure 2 shows an overall diagram of the review. The concrete deterioration mechanisms and the influence of WDA on the mechanisms are identified and discussed. The influential factors of WDA on concrete are analyzed and compared. The physical and mechanical properties and corrosion resistance of concrete exposed to WDA are also reviewed. Upon this review, problems related to WDA can be outlined to enhance marine concrete.

The review of WDA research has provided a better understanding of the concrete deterioration mechanisms. Mitigation measures have been identified and presented in Section 2.3, which contributes to the sustainability in two aspects. The first aspect is the use of more sustainable materials, such as wastes and recycled materials, to improve marine concrete. This enhances the sustainability by reducing the depletion of conventional resources for concrete production. The other sustainability aspect of this study is to increase the resistance of concrete against deterioration and to prolong the life span of structure. The repair and reconstruction of structures can be minimized, which reduces maintenance costs and thus the carbon footprint.

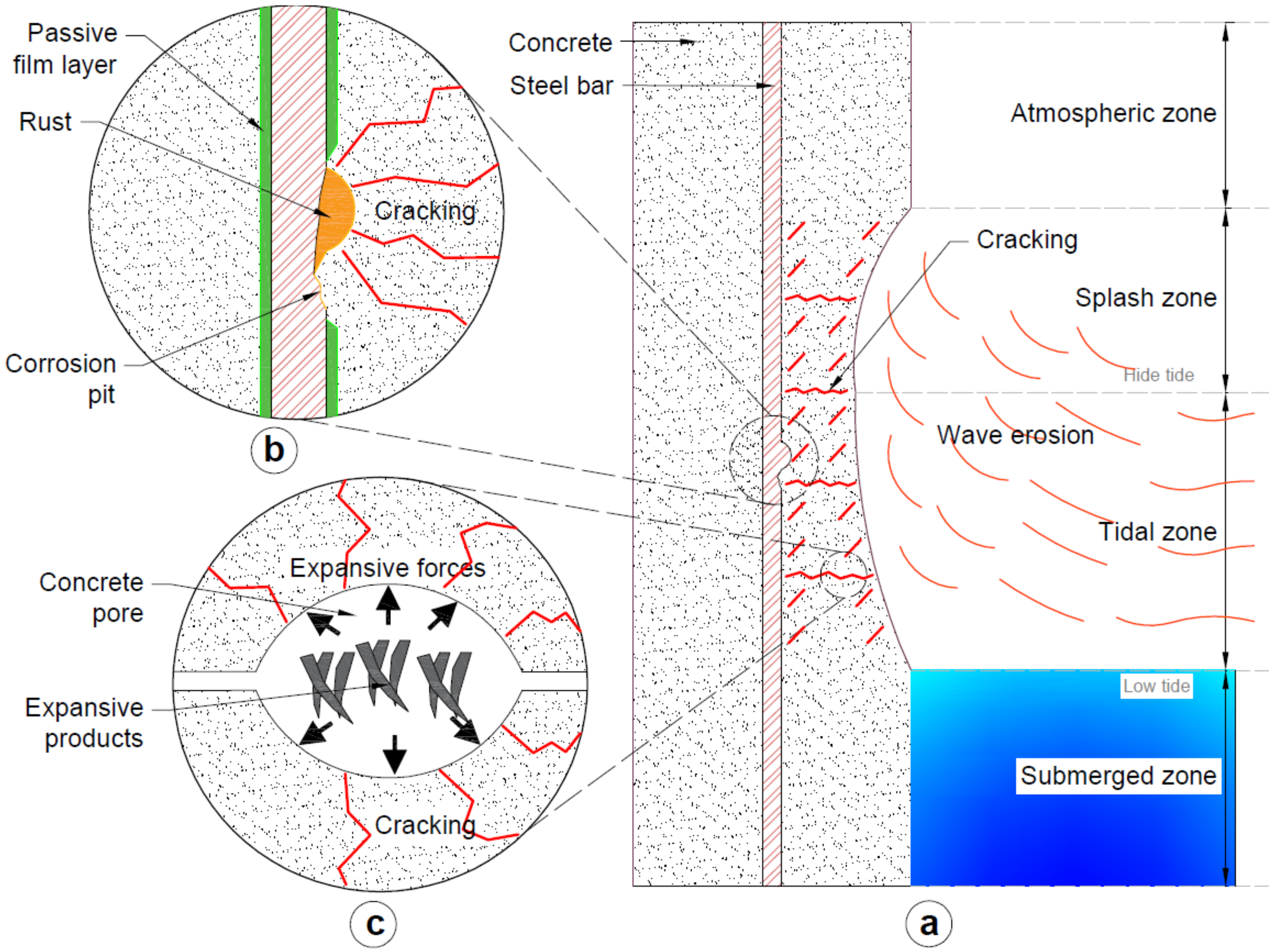


Figure 1: Concrete exposed to deterioration in marine environment: (a) Element of concrete structure, (b) steel corrosion and (c) damage by expansion (Mehta and Monteiro, 2006)

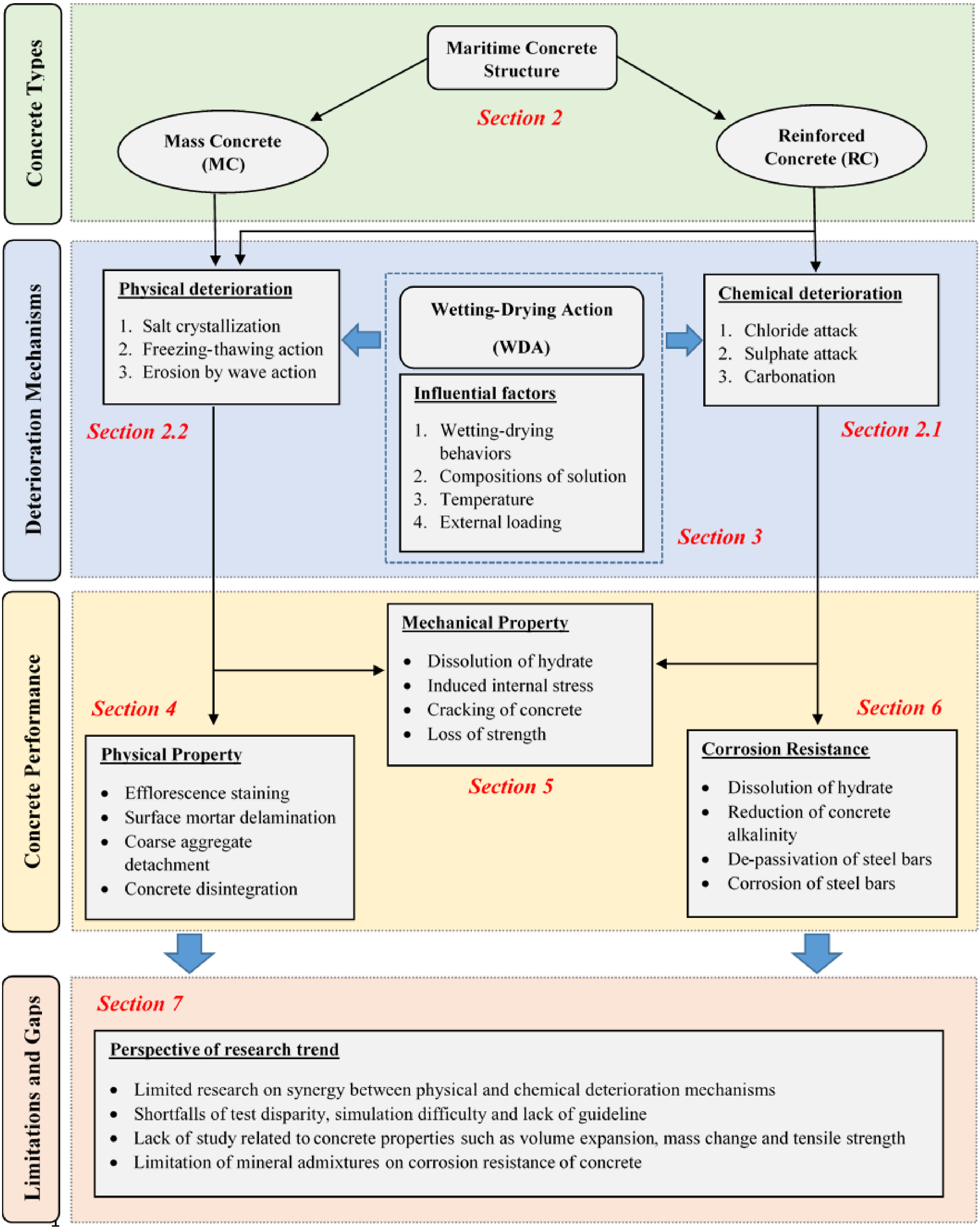


Figure 2: Flow chart of reviewing concrete deterioration exposed to WDA

2. Concrete deterioration mechanism in marine environment

From the durability perspective and based on its application, marine concrete can be classified into mass concrete (MC) and reinforced concrete (RC) (Alexander and Nganga, 2016). MC is a plain concrete with no reinforcement, while RC is reinforced with steel bars. MC is used for gravity-stabilizing purpose such as coastal armoring feature, which is only subjected to physical deterioration. The durability issue of MC is associated with deterioration of concrete and is critical if its strength is compromised. RC portrays more severe durability problem due to corrosion of embedded steel. The intrusion of deleterious compounds, themselves and subsequent reactions with concrete matrix which cause property changes, can reduce the passivity of steel and lead to corrosion (R. Zhang et al., 2010). Concrete performance deteriorates in aggressive marine environment and WDA can further aggravate it. The chemical and physical deterioration mechanisms of concrete are further elaborated.

2.1 Chemical deterioration

2.1.1. Chloride attack

Chloride from seawater causes corrosion of steel in RC. In alkaline environment of concrete, the surface of steel is surrounded by a thin passive oxide film which stabilizes the metal and prevents ionization. If the concentration of invading chloride reaches a threshold level, it reacts with and destroys the oxide film, exposing the steel to oxygen and water to cause corrosion (Khan et al., 2017). The deterioration process commences with localized corrosion and formation of rust. It causes approximately 2 to 6 times volume expansion of steel to exert stress which causes concrete cracking and performance loss as illustrated in Figure 1(b) (Apostolopoulos et al., 2019). Both bound and free chlorides exist in concrete. Bound chloride is immobilized in alkaline environment and is not deleterious to steel, while free chloride penetrates into concrete to cause corrosion.

The WDA increases the rate of chloride attack on concrete. Significant increment of chloride concentration can be found at the concrete surface after long-term exposure to WDA (Qi et al., 2018). The increased chloride concentration on concrete surface results in expansion of convection zone which is also referred to the depth of maximum chloride concentration. This zone is equivalent to loss of concrete cover for steel protection. Table 1 compares the convection zones of concrete under WDA and full immersion exposures which have been determined by researchers. Full immersion refers to the test conducted in fully immersed environment without being subjected to drying phase. The result shows comparatively deeper convection zone for concrete under WDA exposure than the fully immersed condition. The intrusion rate of chloride is increased by WDA through the following mechanisms: (i) chloride penetrates into concrete by sorption during initial wetting stage, (ii) water evaporates during drying stage while chloride only permeates by means of diffusion, and (iii) chloride further accumulates and penetrates through capillary suction during the subsequent wetting stage. The alternating WDA has consequently induced a steep concentration gradient which amplifies the diffusion rate.

Table 1: Convection zone for chloride intrusion into concrete

Literature	Convection zone (WDA exposure)	Convection zone (full immersion)*
Chrisp et al. (2002)	25 – 30 mm	N.D.
Simčič et al. (2015)	4 – 8 mm	N.D.
Ye, Jin, Jin, et al. (2016)	5 – 12 mm	N.D.
J. Wu et al. (2016)	10 – 15 mm	5 – 10 mm
Paul et al. (2016)	10 – 15 mm	0 – 5 mm
Qi et al. (2018)	2.5 – 7.5 mm	N.D.
Y. Wang et al. (2018)	2 – 6 mm	N.D.

*Concrete was fully immersed throughout testing period without being subjected to drying phase.
N.D. – Not determined in the study

2.1.2. Sulphate attack

Sulphate is another element of seawater which brings about durability problem to concrete. It reacts with calcium aluminate hydrate (C-A-H) and calcium hydroxide (CH) to form ettringite and gypsum which are expansive (Rozière et al., 2009). Figure 3 quantifies the reaction of sulphate attack. The ettringite and gypsum increase with duration of WDA, while the portlandite decreases. The accumulation of ettringite and gypsum exerts stress on concrete pore, causing it to crack and disintegrate as illustrated in Figure 1(c). The dissolution of CH and C-A-H also leads to loss of concrete strength. It can reduce concrete alkalinity and thereby reduces the corrosion resistance of steel. Concrete experiences more severe deterioration in the presence of magnesium sulphate (Jiang and Niu, 2016). Cation-exchange reaction can occur, by which magnesium (Mg) ion replaces Ca ion from calcium silicate hydrate (C-S-H) to form magnesium silicate hydrate (M-S-H). M-S-H does not provides cementation which results in further strength loss (Cheng, Shui, Gao, Lu, et al., 2020).

The WDA intensifies the sulphate attack on concrete deterioration. It increases the rate of capillary absorption and diffusion which facilitates sulphate penetration. The drying stage from WDA also causes concrete shrinkage and then micro-cracking. However, Z. Wu et al. (2017) and X.-t. Yu et al. (2018) claimed that the subsequent wetting stage could partially heal the cracks. Once re-wetted, the damaged C-S-H absorbs water, and swells to close the cracks. The crystallization of sulphate-based salt due to WDA also causes concrete damage. The precipitated salts exist in the form of thenardite and mirabilite crystals (Zhongya et al., 2019). These crystals are needle-shaped which exert stress in the confined concrete pores (Jiang and Niu, 2016).

The deterioration caused by sulphate attack exhibits in two stages which are enhancing and weakening stages. The findings have been confirmed in the separate studies carried out by Gao et al. (2013), Jinrui Zhang et al. (2017) and X.-t. Yu et al. (2018). The enhancing stage is attributed to the filling of concrete pores by ettringite and gypsum which improves the mechanical properties. The weakening stage is caused by expansion of ettringite and gypsum which induces concrete damage. Some studies, however, describe the sulphate attack as three stages of deterioration mechanism. A damaging stage which occurred prior to the enhancing stage was noted by Qi et al. (2017). The damaging stage was due to negative impact of WDA such as shrinkage cracking caused by repeated drying. After weakening stage, Müllauer et al. (2013) found that in the third stage, concrete would not undergo further deterioration. This was ascribed to exhaustion of reactants for formation of expansive products. Zhongya et al. (2019) discovered an incubation stage in between the enhancing and weakening stages under WDA in the actual environment. The stress generated by gradual formation of expansive products within this period was not sufficient to cause deterioration. This indicated that the accelerated laboratory test could alter the deterioration process.

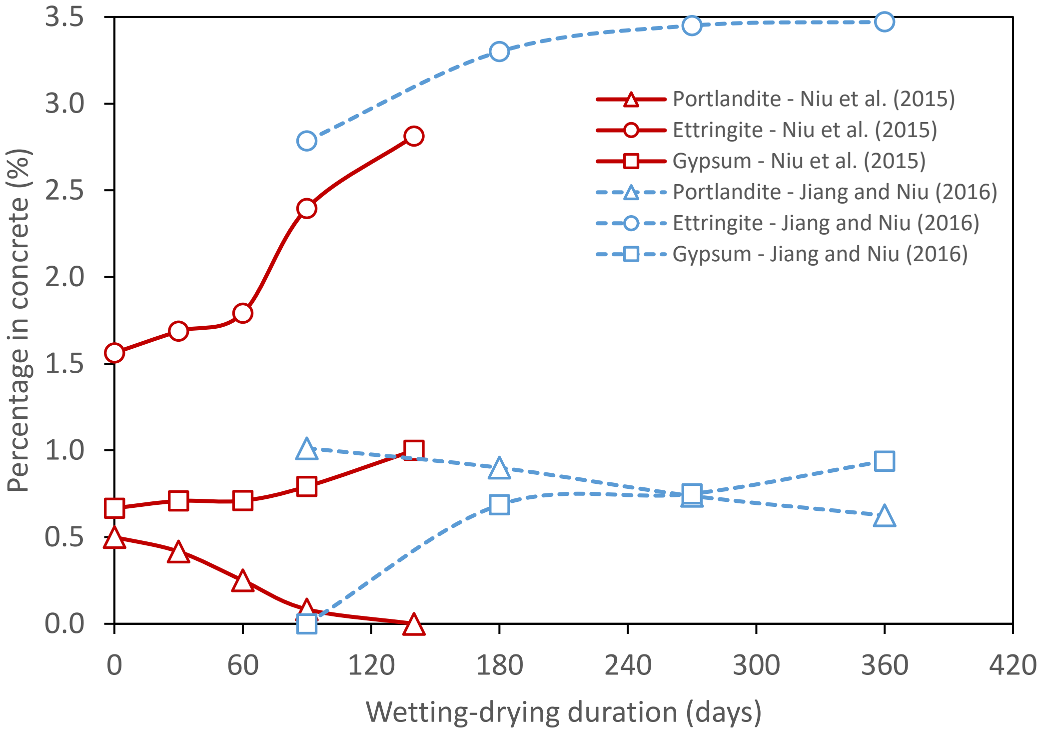


Figure 3: Relative composition of ettringite, gypsum and portlandite in concrete (Jiang and Niu, 2016; Niu et al., 2015)

2.1.3. Carbonation

In humid marine environment, moisture absorbed by concrete contains dissolved carbon dioxide (CO_2) which initiates carbonation. CO_2 is highly reactive with calcium elements such as CH and C-S-H in hydrated cementitious matrix. The chemical reactions of carbonation is presented as Eq. (1) and Eq. (2) (Samimi et al., 2018). The products of these two reactions are calcium carbonate. This leads to dissolution of portlandite and depletion of bonding medium, resulting in instability of anhydrous phase of cement paste (C.-F. Chang and Chen, 2006). The alkalinity of concrete gradually decreases with the reduction of hydroxide concentration which destroys the passivity of embedded steel, leading to corrosion.

$$Ca(OH)_2 + CO_2 + H_2O \rightarrow CaCO_3 + 2H_2O \quad (1)$$

$$C\text{-}S\text{-}H + 2CO_2 \rightarrow SiO_2 + 2CaCO_3 + H_2O \quad (2)$$

Research shows that the WDA intensifies deteriorating effect of concrete carbonation. Jerman et al. (2019) found that WDA caused microstructure of cementitious matrix to become coarser which speeded up intrusion of CO_2. H. Chang et al. (2018) showed that the accelerated capillary suction induced by WDA and the direct penetration of CO_2 into concrete during drying period caused more severe carbonation. Ye, Jin, Fu, et al. (2016) discovered that the carbonation was speeded up in chloride environment. However, Kuosa et al. (2014) demonstrated that the presence of chloride could retard concrete carbonation. The hygroscopic characteristic of chloride created water film to block concrete pores. Salt crystallization caused by WDA also filled up concrete pore and slowed down carbonation.

Carbonation can alter concrete property and negatively affect deterioration from chloride attack (H. Chang, 2017). Carbonation reduces chloride binding capacity of concrete which converts bound chloride to free chloride and accelerates steel corrosion. The bound chloride, existed as Friedel's salt in concrete, is decomposed during carbonation and is prevented from formation. This is due to the reduction of pH which gradually alters the surface charge of C-S-H and reduces its ability to bind chloride (Saillio et al., 2014). The carbonation also widens the chloride convection zone as shown in Figure 4. Ye, Jin, Fu, et al. (2016) found pronounced increment in the depth of chloride convection zone in concrete after being carbonated. H. Chang et al. (2018) demonstrated that under accelerated carbonation, the location of chloride maximum progressed deeper into concrete. Within the carbonated zone, concrete pores are refined which reduces chloride intrusion, but this tends to accumulate chloride at the carbonation front. The bound chloride is also decomposed into free chloride. This consequently leads to high concentration gradient and hastens chloride diffusion.

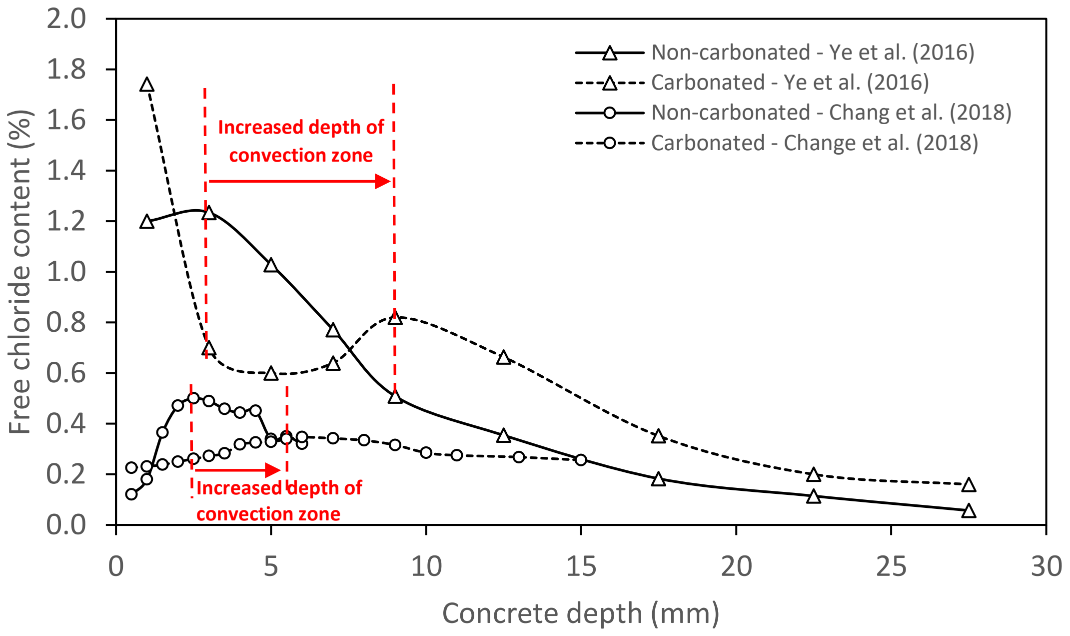


Figure 4: Chloride ingress profile before and after carbonation (H. Chang et al., 2018; Ye, Jin, Fu, et al., 2016)

2.2 Physical deterioration

2.2.1. Salt crystallization

In the absence of chemical interaction, salt crystallization occurs in saline environment and physically damages concrete. The damage is caused by internal stress arising from the formation of salt crystals in concrete pores when the pore solution becomes supersaturated (Thaulow and Sahu, 2004). Salt crystallization happens in two circumstances which are evaporation of pore solution with the capillary rise and WDA (Nadelman and Kurtis, 2019). A schematic illustration of the first mechanism is shown in Figure 5. Concrete in the close vicinity of salt source becomes saturated as the moisture is transferred through capillary suction. Concrete surface becomes drier when the surface is further away from the source as a result of evaporation. The concentration of pore solution increases and salt begins to precipitate after reaching the saturation point. Alternating cycles of WDA, on the other hand, causes repetitive exchange of pore solution and accumulates salt solution in concrete whereby crystallization takes place after saturation point. The salt precipitated on concrete surface is termed as efflorescence, while that formed within concrete pore is subflorescence which is the cause of concrete distress (Lee and Kurtis, 2017). Concrete is damaged through bulging when the pressure exerted by subflorescence exceeds tensile strength.

Saline environments such as salt-bearing soil, saline groundwater and seawater mainly contains chloride and sulphate salts. The damage by sulphate salt is more severe than chloride salt and it is receiving greater attention. Nadelman and Kurtis (2019) noticed the formation of micro-cracks and layers of efflorescence on mortar surface which were caused by crystallization of sulphate salt. Steiger and Asmussen (2008) found that sodium sulphate crystallized to form thenardite and mirabilite which caused damage to concrete. The phase conversion between thenardite and mirabilite could also result in concrete scaling (Haynes et al., 2008).

Some studies, on the contrary, shows that other types of salt cause more severe deterioration of concrete. Gentilini et al. (2012) found more significant destruction of specimen by chloride salt, while the sulphate salt appeared to provide stiffening effect. This was due to the chemical reaction of sulphate with cement hydrate, forming ettringite and gypsum, which strengthened concrete by filling up pores. Lee and Kurtis (2017) discovered that the damage of mortar caused by nitrate salt is more severe than sulphate salt. The samples exposed to sulphate salt were not damage, although heavy efflorescence was observed. This could be due to insufficient exposure duration to the salt. The result discrepancy could also be due to different source of salt used which exhibits different phase-transition characteristic with distinct crystallization behavior (Haynes et al., 2010).

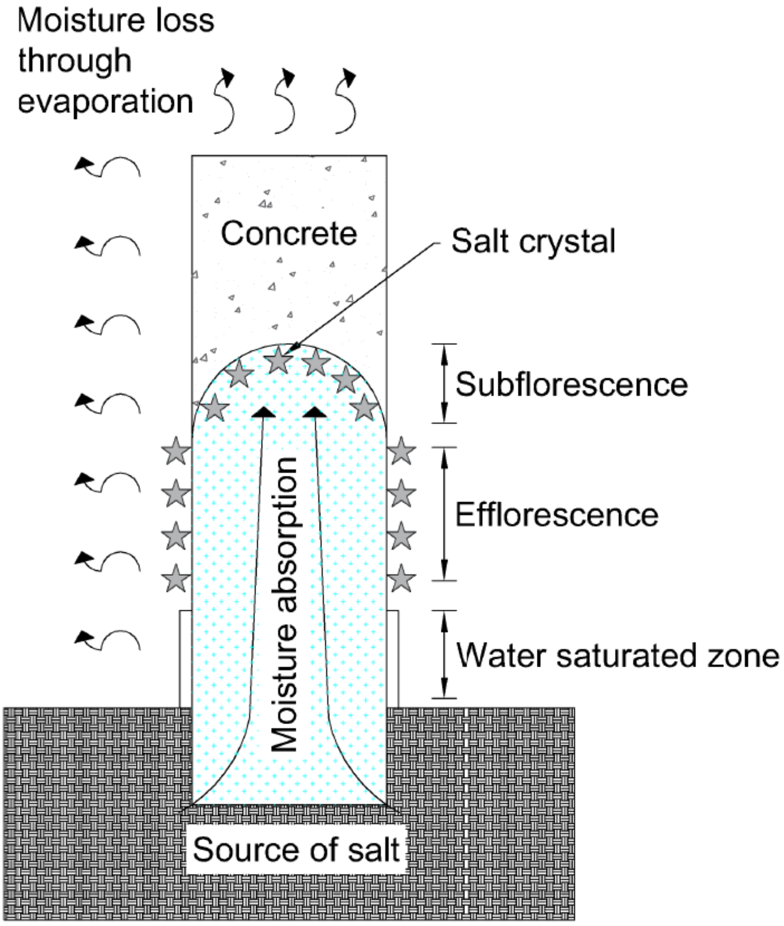


Figure 5: Salt crystallization by capillary rise and evaporation (Lee and Kurtis, 2017; Nadelman and Kurtis, 2019)

2.2.2. Freezing-thawing action

Freezing-thawing action (FTA) is a physical concrete deterioration mechanism occurs in wet and cold climate. Its occurrence is caused by crystallization of solvent inside capillary cavity of concrete. Liquid in pore at freezing temperature transforms to ice and expands to exert pressure on concrete. The damage depends on concrete pore characteristics such as size, volume and continuity. FTA is less destructive if the concrete possesses adequate pores which are interconnected and big enough to provide room for uniform expansion and thus less stress in concrete (H. Cai and Liu, 1998). Otherwise, internal cracking and spalling of concrete can occur, resulting in loss of mechanical properties and even further intrusion of deleterious substances (Z. Wang et al., 2014).

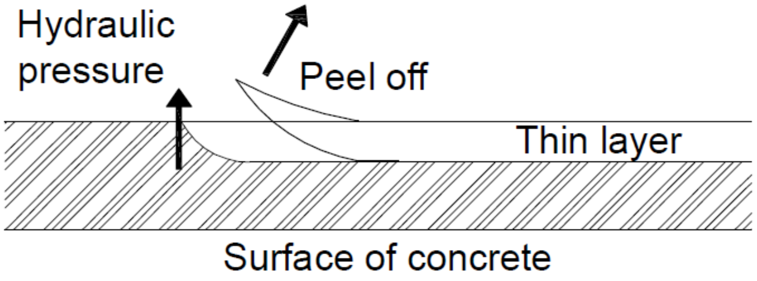
Salt-containing seawater can alter deterioration mechanism of FTA on concrete. Miao et al. (2002) found more damage was experienced by concrete exposed to FTA with sulphate solution. Sun et al. (2002) found the damage caused by FTA with chloride solution was twice than that with water. The differential thermal expansion of salt solution and cementitious matrix causes superficial spalling of concrete (Z. Wang et al., 2014). Chemical deterioration of concrete, such as sulphate attack, can also take place which is in synergy with FTA. However, Jiang et al. (2015) discovered that FTA with salt solution caused less damage than that with fresh water. The salt lowered freezing point of pore solution which made the damage less severe.

In actual environment, concrete experiences FTA during winter and WDA during rest of the year. Hamze (2014) found that the combined FTA and WDA had significant effect on causing micro-cracks. F. Liu et al. (2018) demonstrated that the combined FTA, sulphate attack and carbonation caused more severe damage to concrete with increased pore degradation. Nevertheless, the study related to combined effect of WDA and FTA is still limited and indeed required investigation.

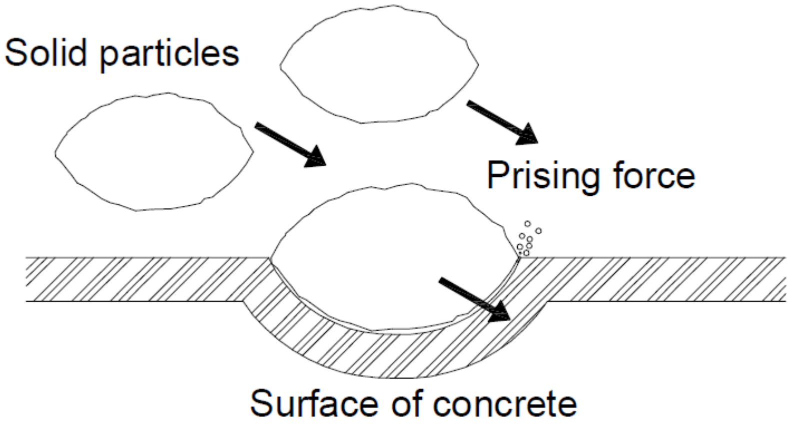
2.2.3. Erosion by wave action

Wave action can also cause physical concrete damages such as wear and tear. Wave often carries debris such as silt, sand, gravel, rock and ice. It can cause two types of action which are hydrodynamic force and abrasion by water-borne debris (Dandapat and Deb, 2016). The latter action causes more damage to concrete (Kryžanowski et al., 2009). The erosion of concrete due to abrasion occurs in three stages as shown in Figure 6. During initial stage, concrete is subjected to weak pre-abrasion by hydraulic pressure of flowing water, whereby concrete surface is slightly stripped off. Drifting water-borne debris follows on to exert prising force which generates more drastic damage such as superficial cracking. Combination of both actions abrades and scours off the mortar layer, disintegrating coarse aggregate and interfacial transition surface. Cavitation force from implosion of air bubble during wave striking can also induce destructive wearing damage on concrete (Elżbieta Horszczaruk, 2005). Concrete consequently loses mechanical strength and shield against corrosion.

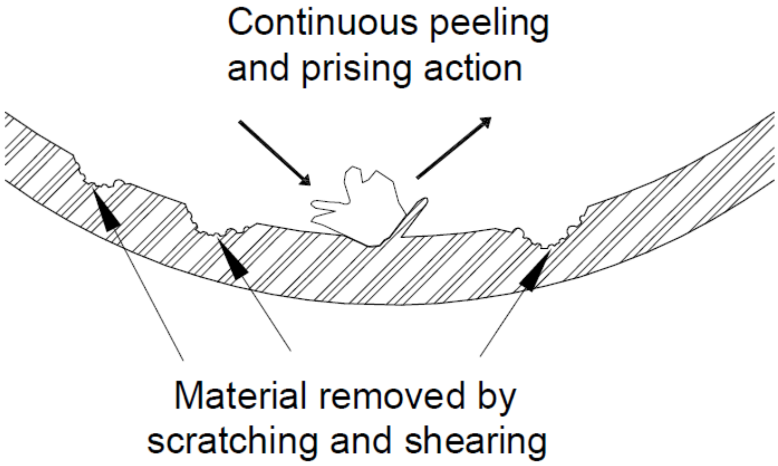
Research in this domain has made assessment on hydraulic structures subjected to abrasion. Abrasion resistance is often related to the strength of concrete. Kryžanowski et al. (2009) used compressive strength, tensile strength, elastic modulus and aggregate strength to assess abrasion resistance of concrete. Elżbieta Horszczaruk (2005) demonstrated that concrete compressive strength could accurately estimate the abrasion resistance. Y.-W. Liu et al. (2006) found that splitting tensile strength was more effective in predicting abrasion. The abrasion resistance of concrete also depends on other factors. Dandapat and Deb (2016) showed that concrete made from coarse aggregates having larger size, less angularity and flakiness exhibited stronger abrasion resistance. Xinhua Cai et al. (2016) discovered that wave abrasion force increased when impinging angle increased from 0 to 90^{o} as this caused greater concrete deformation. Higher impinging velocity of wave could further aggravate the damage. The degradation of concrete can occur together with other types of mechanism. Rosenqvist et al. (2017) showed that both leaching and FTA could cause superficial concrete damage and debilitate the abrasion resistance.



(a) Erosion peel



(b) Prising by solid particles



(c) Abrasive wear

Figure 6: Mechanism of abrasion from water-borne solid on concrete surface (Y.-W. Liu et al., 2006; Plum and Xufei, 1996)

2.3 Remarks and improvement approach

MC is prone to deterioration only if the mechanisms, such as sulphate attack, salt crystallization, FTA and erosion, causes loss of mechanical properties. The main concern for RC is corrosion of steel bar whereby carbonation and chloride attack come into play. However, other deterioration mechanisms that are critical to MC also have an impact on providing means for intrusion of chloride and carbon dioxide.

The deleterious compounds, which include chloride, sulphate and carbon dioxide, enter the concrete through capillary pore to actuate deterioration. The intrusion of these compounds can be minimized by reducing size, number and continuity of pore. The damage caused by physical deterioration can be mitigated by improving the concrete mechanical properties, especially the tensile strength, which prevents disintegration of concrete. Some of the existing methods for mitigating concrete deteriorations are also summarized in Table 2.

The WDA has great influence on the deterioration mechanisms of concrete. It increases intrusion rate of deleterious compounds into concrete which escalates the deterioration processes. Research concentrates on a single deterioration mechanism. In actual weathering scenario, however, there is occurrence of synergy between two or more mechanisms. It is recommended to study synergetic effect of various combinations, especially the combination of chemical and physical deteriorations.

Table 2: Concrete deterioration mitigation methods

Deterioration mechanism	Mitigation methods	Remark	Reference
Chemical deterioration			
1. Chloride attack	i) Additions of supplementary cementitious material (SCM) such as blast furnace slag, fly ash and silica fume	• Densify and refine pore structure through pozzolanic reaction	(Chrisp et al., 2002; Ye, Jin, Jin, et al., 2016)
	ii) Use of early carbonation curing method	• Pre-carbonate concrete in CO_2 environment to densify pore structure	(Duo Zhang and Shao, 2016)
2. Sulphate attack	i) Addition of SCM such as blast furnace slag and fly ash	• Densify and refine pore structure through pozzolanic reaction	(Gao et al., 2013; Qi et al., 2017)
	ii) Use of low tricalcium aluminate (C_3A) cement	• Reduce hydrates of C_3A to form ettringite to cause deterioration	(Haynes et al., 2008)
	iii) Use of recycle coarse aggregate (RCA)	• Higher water absorption of RCA lowers w/b ratio to increase strength	(Qi et al., 2017)
3. Carbonation	i) Addition of SCM such as blast furnace slag, fly ash and silica fume	• Densify and refine pore structure through pozzolanic reaction • Require prudent adding SCM since higher content reduces portlandite and consequently carbonation resistance	(Backus et al., 2013; Ye, Jin, Fu, et al., 2016)
	ii) Lower water-to-binder (w/b) ratio	• Reduce concrete pore and intrusion rate	(H. Chang et al., 2018)
	iii) Addition of γ-dicalcium silica (γ-C_2S) for CO_2 sequestration	• γ-C_2S reacts with CO_2 to form highly dense SiO_2 gel to fill up concrete pore	(Z. Chen et al., 2019)
Physical deterioration			
1. Salt crystallization	i) Lower w/b ratio	• Increase concrete strength against crystallization pressure • Reduce concrete pore and bring down flux of salt solution	(Lee and Kurtis, 2017)
	ii) Use of Portland limestone cement (PLC)	• Fine PLC reduces size and interconnectivity of concrete pore	(Nadelman and Kurtis, 2019)
2. Freezing-thawing action	i) Addition of air-entraining admixtures	• Increase volume and connectivity of concrete pore to increase escape boundary and reduce expansion stress	(Aygörmez et al., 2020; Hamze, 2014)
	ii) Steel fibre reinforcement	• Increase concrete ductility and retard cracking	(Miao et al., 2002; Sun et al., 2002)

3. Wave erosion	i) Use of round, non-flaky and large coarse aggregate	• Produce stockier, less brittle and mechanically stronger concrete	(Dandapat and Deb, 2016; Y.-W. Liu et al., 2006)
	ii) Steel fibre and polypropylene fibre reinforcement	• Provide better adhesion to cementitious matrix and reduce crack propagation	(EK Horszczaruk, 2009; Kryžanowski et al., 2009)
	iii) Addition of SCM such as fly ash and silica fume	• Increase concrete strength through pozzolanic reaction	(Xinhua Cai et al., 2016)

3. Influential factors of WDA

The characteristics of WDA have bearing on the intrusion of deleterious compounds into concrete. The characteristics vary with site location, climate and exposure conditions. Researchers have reproduced the characteristics in laboratory with the aim to study the influences of WDA on concrete performance. Accelerated test is also used to shorten the study period. This can lead to inaccurate prediction if irrelevant method is used. The influential factors of WDA are reviewed based on the experiments performed by various researchers.

3.1. Phenomenon of wetting and drying

The alternating wetting and drying of marine concrete is caused by tidal phenomenon. The characteristics of tide, particularly tidal cycle and tidal range, has great influence on WDA behavior. Tidal phenomenon can be classified into three types which are diurnal, semidiurnal and mixed tides. Diurnal tide exhibits one cycle of low and high tides per day, while semidiurnal tide displays two cycles per day (NOAA, 2019). Mixed tide is the case of semidiurnal tide having different amplitude of crest and trough. The tidal range can vary from near 0 to 12 m (Trenhaile, 2011). Considering the effects of tidal cycle and range, wetting and drying periods can vary in different tidal situations.

Table 3 summarizes the wetting and drying periods adopted by several researchers in their laboratory tests to simulate WDA at the field. J. Wu et al. (2016) conducted wetting-drying test by following the tidal conditions of Bohai Sea, East Sea and Yellow Sea in China, in which concrete was exposed to 8 hours of both wetting and drying for one tidal cycle. X.-t. Yu et al. (2018) used wetting-drying period from Chinese Standard: GB/T 50082-2009 (Standard, 2009) which adopted 16 hours of wetting, 2 hours of room temperature drying and 6 hours of oven drying at 60 ^{o}C. Niu et al. (2015) also used the same laboratory condition for simulating deterioration of shotcrete in a tunnel construction site of Western China. This exposure condition has included an oven drying period which is used to boost water evaporation and shorten test duration. Backus et al. (2013) used period of 1-day wetting and 6-day drying which they claimed this scenario as splash zone. Zhongya et al. (2019) adopted a regime of 8-day wetting and 7-day drying and compared with continuous immersion and actual wetting-drying environment of Chongqing, China. The study showed that the adopted conditions for laboratory test could shorten test period, but slightly change the actual degradation process.

3.2. Ion type and concentration

Concrete deterioration by WDA is also influenced by compositions of seawater especially chloride and sulphate, and their concentrations. Chloride and sulphate contents vary with salinity of seawater. Salinity is the total amount of non-carbonate salts which exist in combination with sodium, potassium and magnesium ions (Effler et al., 1986). The seawater has an average salinity of 3.5 % and the salt exists mostly as sodium chloride (Lehigh, 2011). Researchers thus use this concentration of chloride solution in their studies as shown in Table 3. The commonly used sulphate concentration is 5 %. It is assumed that this concentration can result in noticeable damage to concrete and is suitable for laboratory test. The ASTM (C1012, 2018) standard also recommends this concentration of sulphate solution for testing. Some studies also increase ion concentration to perform accelerated test. The chloride and sulphate concentrations have been increased up to 10 % and 15 % respectively. Yuan et al. (2016) showed the test duration was reduced by a factor of two if sulphate concentration at saturation point had been used. Different types of sulphate also cause different extent of concrete degradation. Jiang and Niu (2016) and Cheng, Shui, Gao, Yu, et al. (2020) demonstrated that concrete damage by $MgSO_4$ solution was more severe than Na_2SO_4 solution. An additional deterioration caused by cation-exchange reaction which replaced Ca ion in C-S-H with Mg ion, resulting in strength loss of concrete.

Researchers also use a composite solution containing chloride and sulphate salts as occurred in seawater. Jiang and Niu (2016) used composite solution of 10 % Na_2SO_4 and 3.5 % NaCl which reduced concrete deterioration. The presence of chloride reduced diffusion of sulphate as the Friedel's salt was formed from chloride to fill up pores in concrete which delayed sulphate attack. Cheng, Shui, Gao, Yu, et al. (2020) also found reduced chloride intrusion with the co-existence of sulphate. The intruded chloride amount could be further reduced if the sulphate concentration increased (Y. Chen et al., 2016). The modification of charge-equilibrium and mass-equilibrium status of ions in composite solution reduced the activity of chloride ion. The formation of ettringite by sulphate also refined and densified concrete pores, limiting penetration of chloride. The findings show that the concrete deterioration by composite solution, which better represent the actual situation, is lower than that with a single salt.

3.3. Temperature in drying stage

Concrete gradually loses its moisture through water evaporation in drying stage of WDA. As the ambient temperature increases, the relative humidity decreases which induces faster drying of concrete. The continual sun exposure raises concrete temperature up to 30–50 ^{o}C (Guan, 2011; Tan et al., 2014). Researchers also include an oven drying stage in their experiments to consider this effect. The temperature used can range from 45 to 80 ^{o}C as shown in Table 3. Higher temperature is used to increase water evaporation rate which substantially reduces test period.

Some studies, however, indicate that the elevated temperature can lead to negative consequences. It causes concrete shrinkage and then micro-cracking which affects intrusion behaviors and test result (X.-t. Yu et al., 2018). The elevated concrete temperature also induces greater moisture transfer and increases chloride content and penetration depth (Oh and Jang, 2007). Farahani et al. (2015) discovered that chloride diffusion rate increased by two times when temperature was raised from 28.5 to 34.5 ^{o}C. The increased temperature provided more energy for chloride diffusion. Alhozaimy et al. (2012) found that steel corrosion became more severe when temperature was increased from 30 to 40 ^{o}C, but decreased corrosion for the temperature range of 40 to 50 ^{o}C. The increased corrosion was due to catalytic effect provided by higher temperature for chloride to destroy steel passivity. The decreased corrosion was attributed to the lower oxygen solubility and the increased concrete pore discontinuity at this high temperature. Thus, postulation of using elevated temperature in WDA experiment remains controversial as it can alter the deterioration mechanism.

3.4. External loading

Concrete in service is subjected to stresses such as compression and tension which can affect the WDA test results. The stresses modify concrete pore characteristics and change the intrusion behavior. The resultant strain and the induced crack allow for further penetration of deleterious components into concrete.

Studies have also incorporated the loading effect on deterioration of concrete subjected to WDA. Gao et al. (2013) found that, with flexural loading, more severe deterioration was experienced by concrete subjected to WDA. The concrete deterioration also increased with flexural stress ratio (Ye, Jin, Fu, et al., 2016). This was due to the enlarged concrete pore under tensile strain increased the ingress of corrosive compounds. The damage caused by long-term flexural loading was also more severe than the short-term loading since the former caused permanent deformation such as creep (F. Chen et al., 2017). Fu et al. (2016) showed that cyclic uniaxial tensile loading had caused fatigue damage to concrete which increased the chloride intrusion by a factor of three. Paul et al. (2016) stated that the cracked concrete was intruded with significantly higher chloride than non-cracked concrete. The development of micro-cracks caused by flexural and tensile stress had speeded up the intrusion of corrosive compounds.

The effect of compressive stress in WDA on concrete has also been studied. Jinrui Zhang et al. (2017) pointed out that in the compression zone of concrete under flexural loading, concrete was actually strengthened. J. Wu et al. (2016) also observed similar scenario when concrete was compressively loaded. The compression closed the concrete pores and reduced permeability. But, the growth of salt crystal in pores could induce higher stress under compressive loading in the long term, causing greater damage to concrete (F. Chen et al., 2017).

3.5. Remarks

The influential factors of WDA such as wetting-drying periods, ion type, ion concentration, temperature and condition of external loading have significant impact on concrete deterioration mechanisms. Table 3 summarizes these influential factors that are used by researchers to duplicate WDA in actual environment. The wetting period can range from 0.3 hour to 1080 hours, while the drying period at ambient temperature ranges from 0.7 hour to 1172 hours. Some studies include an oven drying period of 5 hours to 168 hours in order to accelerate the test. The oven drying temperature varies from 45 to 80 ^{o}C. As for ion type in corrosive solution, the study mainly includes NaCl, Na_2SO_4 and $MgSO_4$ and composite of them. The simulated external loadings are compression, tension and flexural bending.

The WDA tests performed by researchers have achieved the objectives of respective studies. However, the laboratory experiments have inherent limitations such as difficulties in simulating the actual site situation, shortening the test period using accelerated test and predicting the long-term concrete durability. Further research is still required to improve the experiments.

Table 3: Laboratory-simulated field exposure conditions of WDA on concrete

Literature	Phenomenon of wetting and drying			Ion type and concentration		Drying temperature		External loading		Site location (which WDA was duplicated)
	Wetting period (hours)	Room drying period (hours)	Oven drying period (hours)	Solution type	Concentration (%)	Room temperature (ºC)	Oven temperature (ºC)	Loading type	Stress ratio	
Ye, Jin, Jin, et al. (2016)	24	48	-	NaCL	5	35 ± 0.5	-	-	-	-
Chrisp et al. (2002)	48	1176	-	NaCl	5.8	22 ± 2	-	-	-	-
Simčič et al. (2015)	0.3	0.7	-	NaCl	10	20 ± 2	-	-	-	-
J. Wu et al. (2016)	8	8	-	NaCl	3	-	-	Compressive	0, 0.3, 0.5, 0.7	Bohai Sea, East Sea and Yellow Sea in China
Paul et al. (2016)	72	96	-	NaCl	3.5	-	-	-	-	-
Qi et al. (2018)	21	6	45	NaCl	3.5	20 ± 2	60	Flexural	0, 0.3, 0.5	-
Y. Wang et al. (2018)	12	12	-	NaCl	3.5	20 ± 2	-	-	-	-
Qi et al. (2017)	21	6	45	Na_2SO_4	5	20 ± 2	60	-	-	-
J. Tang et al. (2018)	16	2	6	Na_2SO_4	0, 5, 10	20 ± 2	80 ± 5	-	-	-
Y. Chen et al. (2016)	21	6	45	Na_2SO_4 (Na_2SO_4 + NaCl)	5 (10 + 5), (10 + 5)	20 ± 3	60	-	-	-
Yuan et al. (2016)	16	2	8	Na_2SO_4	0, 3, 7, saturated	-	70	-	-	-
Xiaopei Cai et al. (2019)	12	6	6	Na_2SO_4	5	20	45	-	-	-
Jiang and Niu (2016)	168	192	-	Na_2SO_4 $MgSO_4$ ($MgSO_4$ + NaCl)	10 10 (10 + 3.5)	20 ± 3	-	-	-	-
Zhongya et al. (2019)	192	-	168	Na_2SO_4	0, 2.1, 15	-	45 ± 2	-	-	General use, Chongqing China
H. Zhang et al. (2019)	24	144	-	Na_2SO_4	5	20	-	-	-	-
X.-t. Yu et al. (2018)	16	2	6	Na_2SO_4	0, 5	20 ± 2	80 ± 2	-	-	Standard (GB/T 50082-2009)

Niu et al. (2015)	16	2	6	Na_2SO_4	10	20 ± 2	60	-	-	Tunnel construction site in Western China
Jinrui Zhang et al. (2017)	72	96	-	Na_2SO_4	5	23 ± 1	-	Flexural	0.4	-
F. Chen et al. (2017)	21	6	45	(Na_2SO_4 + NaCl)	(5 + 5)	20	60	Short-term flexural Long-term flexural	0, 0.35, 0.5 0.35, 0.5, 0.7	-
Cheng, Shui, Gao, Yu, et al. (2020) Cheng, Shui, Gao, Lu, et al. (2020)	18	1	5	NaCl (NaCl + $MgCl_2$) (NaCl + Na_2SO_4) (NaCl + $MgCl_2$ + Na_2SO_4)	3.3 (2.7 + 0.5) (3.3 + 0.4) (3.3 + 0.5 + 0.4), (3.2 + 0.5 + 0.4)	20 ± 2	60	-	-	-
Li et al. (2020)	720-1080	0.5	96	Na_2SO_4	0, 3, 5, 10	20 ± 2	40 ± 2	-	-	-
Gao et al. (2013)	21	6	45	Na_2SO_4	5	20 ± 3	60	Flexural	0, 0.2, 0.4, 0.6	-
Jerman et al. (2019)	48-72	48-72	-	Water	-	25	-	-	-	-
Malheiro et al. (2014)	24	144 (CO_2 environment)	-	NaCl	3.5	20	-	-	-	-
Ye, Jin, Fu, et al. (2016)	96	48, 48 (CO_2 environment), 96 (CO_2 environment)	48	NaCl	15	20 ± 5	60	Flexural	0, 0.3, 0.6	-
Backus et al. (2013)	24	144	-	NaCl	3.2	20 ± 1	-	-	-	Extreme splash zone
H. Chang et al. (2018)	24	144, 144 (CO_2 environment)	-	NaCl	3.5	20 ± 1	-	-	-	-

4. Physical properties of concrete exposed to WDA

4.1. Physical appearance

Concrete with aesthetic exterior look is indicative of its reasonably good performance. Assessment of concrete physical appearance is beneficial in early detection of concrete deterioration and hence mitigation can be expediently provided for prior to catastrophic failure.

Researchers assess concrete deterioration through its physical appearance. X.-t. Yu et al. (2018) found that mortar surface was severely damaged after being exposed to 270 days of WDA in 5 % Na_2SO_4 solution. The surface was covered with white powdery efflorescence and erosion pit, which gradually led to spalling and delamination. Jiang and Niu (2016) investigated the effect of solutions respectively comprising 10 % Na_2SO_4 (S1), 10 % $MgSO_4$ (S2) and composite of 10 % Na_2SO_4 plus 3 % NaCl (S3) on concrete physical appearance. Concrete exposed to S1 experienced some surface delamination and cracks near the edges. The damage on concrete exposed to S2 was more severe, wherein the surface was peeled off, uncovering coarse aggregate. Minimal scaling of surface was observed in concrete exposed to S3. The magnesium sulphate caused more severe damage to concrete, but chloride if combined with sulphate could reduce the effect. Y. Chen et al. (2016) also found that the concrete exposed to composite solution containing chloride was not damaged. The chloride ion was capable of delaying formation of corrosion products as discussed in Section 3.2.

Effect of fly ash (FA) and silica fume (SF) on physical appearance was studied by Zhongya et al. (2019). The concrete incorporated with FA and SF suffered more severe physical damage than normal concrete. The damages such as spalling and chipping of mortar occurred along corners and edges of concrete. Although addition of FA and SF refined concrete pore structure, salt crystals formed had indeed increased pressure in the pores and caused more damage.

4.2. Volume expansion

Concrete swells and expands after being deteriorated in marine environment. Zhongya et al. (2019) studied the concrete expansion exposed to full immersion (E1), indoor WDA (E2) and actual WDA (E3) using Na_2SO_4 solution for 720 days. The length of concrete increased with exposure time and the highest volume expansion was found to be 1.0 %, 1.6 % and 1.4 % for E1, E2 and E3 respectively. The WDA aggravated volume expansion of concrete. Expansion in E2 was higher than E3 because in the actual field situation, less cycles of WDA had been experienced by concrete. X.-t. Yu et al. (2018) investigated the effect of four exposure conditions on the mortar expansion for 270 days which were Condition 1 (0 % Na_2SO_4 with full immersion), Condition 2 (0 % Na_2SO_4 with WDA), Condition 3 (5 % Na_2SO_4 with full immersion) and Condition 4 (5 % Na_2SO_4 with WDA). There was no noticeable volume change observed from mortar in Condition 1, while the mortar under Condition 2 experienced slight but minimal reduction of volume which was caused by shrinkage during drying. Expansions of mortar were 0.8 % and 1.4 % for Condition 3 and Condition 4 respectively. The WDA had pronounced effect in accelerating concrete deterioration and then increased volume expansion.

4.3. Mass change

Mass change of concrete is also measured to determine extent of concrete deterioration caused by WDA. Y. Chen et al. (2016) reported the concrete mass increased with a maximum gain of 1.75 %. The mass gain was caused by salt crystallization and formation of ettringite and gypsum. Cheng, Shui, Gao, Yu, et al. (2020) also noticed mass gain of mortar up to 2.74 %. The mass gain was caused by continuous hydration produced more C-S-H which had higher surface area and increased water imbibition up to its saturation point. Qi et al. (2017) substituted aggregate of concrete with recycled coarse aggregate. The recycled aggregate concrete (RAC) at replacement level up to 50 % exhibited smaller mass gain than normal concrete, but significantly higher mass gain at higher replacement level. RAC possessed higher water absorption property whereby higher replacement level could increase mass gain. At low replacement level, RCA absorbed mixing water which in turn reduced effective w/b ratio and concrete strength increased. The concrete was less vulnerable to deterioration and hence exhibited lower mass gain.

Mass of concrete could also decrease when subjected to WDA. J. Tang et al. (2018) studied mass change of concrete exposed to 0 %, 5 % and 10 % Na_2SO_4 solutions. The concrete exposed to 5 % and 10 % Na_2SO_4 solutions exhibited mass gain, the mass reduced in 0 % solution. The mass loss was due to surface damages such as peeling and chipping of mortar layer caused by WDA. The mass gain in 5 % and 10 % Na_2SO_4 solution was ascribed to formation of ettringite and gypsum. Jiang and Niu (2016) noticed that concrete mass loss occurred in two stages which were steady and escalated stages. Concrete experienced constant mass loss during steady stage and after 150 days of exposure, it lost mass rapidly. Mortar layer gradually disintegrated to cause weight loss in escalated stage.

The contradiction in concrete mass change (i.e. mass gain or loss) described in the above literature is attributed to the difference in concrete mechanical properties. Higher strength concrete can resist damage caused by sulphate attack and salt crystallization, particularly the internal stress resulted from expansive products. Concrete mass increases with the accumulation of the products. Low strength concrete is more prone to the damage. The expansive products cannot be accumulated in the concrete, but can cause severe physical scaling and weight loss.

4.4. Remarks

The sulphate attack and salt crystallization under the influence of WDA are the main deterioration mechanisms which change the physical properties of concrete. Concrete surface is physically damaged with forming of efflorescence initially, followed by gradual delamination and peeling of mortar, which further cause detachment of coarse aggregate. This leads to cover loss and further disintegration of concrete.

Concrete can also experience volume expansion after exposing to the long-term deterioration mechanisms. Review of the literature shows this type of expansion is minimal with value in the range of 0.8–1.6 %. But, the expansion of concrete volume in a restrained structure can be detrimental as it induces stress to cause concrete cracking.

Mass change of concrete caused by the deterioration mechanisms depends on its strength. Concrete with high strength experiences mass increase, but low strength concrete suffers mass loss. The change of concrete physical properties in respect of their appearance, volume and mass changes can be used as material deterioration indicators.

5. Mechanical properties of concrete exposed to WDA

5.1 Compressive strength

The influence of WDA deteriorates the mechanical properties of concrete, of which the compressive strength is the most important assessment criterion used for concrete performance. The following investigates the deterioration of compressive strength associated with WDA.

X.-t. Yu et al. (2018) investigated compressive strength of mortar under the influence of WDA and sulphate solution. The compressive strength increased for 150 days but decreased significantly afterward. Li et al. (2020) found that the strength reduction started after 6 months of WDA. The formation of ettringite and gypsum from sulphate solution densified microstructure initially, but their subsequent accumulation caused strength reduction. The reduction was more severe under WDA. The WDA also caused formation of salt crystals in the pores when the solution became supersaturated during drying process. Internal stress was induced, causing damage and hence loss of strength. Zhongya et al. (2019) also studied compressive strength of concrete exposed to full immersion (E1), indoor WDA (E2) and actual WDA (E3) using sulphate solution. The strength of concrete exposed to E1 increased throughout exposure period, but slightly reduced towards the end of test period. The reduction was more prominent with the use of higher sulphate concentration. Concrete with E3 exposure exhibited similar trend as E1, but the strength loss occurred earlier with higher severity. The WDA accelerated the strength loss. The concrete exposed to E2 deteriorated two times faster than that in E3 exposure. The actual WDA could be imitated in laboratory with accelerated rate in the aspect of compressive strength.

J. Tang et al. (2018) found that the compressive strength of concrete exposed to WDA using tap water reduced by 29 % after 140 days. Although the sulphate deterioration was not involved in the test, the damage could be caused by shrinkage of concrete during drying cycles. Tap water also contained mineral by which salt crystallization had occurred to deteriorate concrete. Jiang and Niu (2016) investigated the effect of different sulfate solutions which were Na_2SO_4 (S1), $MgSO_4$ (S2) and composite of Na_2SO_4 plus NaCl (S3) on concrete compressive strength. In all cases, the strength slightly increased initially. It was followed by a constant reduction, then an accelerated reduction towards the end of test period. The strength reduced in the increasing order of S3, S1 and S2. The S3 contained chloride which delayed sulphate attack. Mg ion from S2 induced cation-exchange reaction which reduced C-S-H for bonding.

5.2 Tensile strength

Tensile strength is an essential mechanical property to prevent cracking of concrete. It can be assessed from both splitting test and flexural test. Limited research related to this property has been done. J. Tang et al. (2018) investigated the effect of WDA on concrete flexural strength. The flexural strength reduced when concrete was exposed to WDA using sulphate solution. The flexural strength reduction was greater than that of compressive strength. Concrete cracking as a result of sulphate attack and salt crystallization caused more loss of concrete capacity to resist tensile stress.

5.3 Modulus of elasticity

Relative dynamic modulus of elasticity (RDME) is also used to assess weathering of concrete subjected to WDA. It is the elasticity of concrete under dynamic loads such as longitudinal and flexural vibrations.

Jiang and Niu (2016) studied the effect of WDA on RDME of concrete exposed to sulphate solution. The RDME loss occurred in three stages which were steadydecreasing, constant and rapid-decreasing stages. The damage in first stage was caused by WDA and salt crystallization. In the second stage, concrete pores were densified by formation of ettringite and gypsum. The accumulation of these products induced stress which accelerated RDME loss in the last stage. J. Tang et al. (2018) determined the effect of sulphate concentration on concrete RDME. The RDME loss was higher when the sulphate concentration became higher as this produced more corrosion products. The study also showed that the RDME loss reduced with the use of coral reef sand as fine aggregate. Higher porosity of the sand had provided more space for ettringite and gypsum expansion.

Qi et al. (2017) used recycle coarse aggregate (RCA) to improve the concrete resistance against sulphate attack subjected to WDA. The incorporation of RCA at low replacement level of 30 % to 50 % reduced the RDME loss of concrete. The higher water absorption of RCA had reduced the effective w/b ratio of concrete and increased strength. The RDME loss increased for the replacement level higher than 50 %. The high porosity of RCA overwhelmed the positive effect and reduced the mechanical strength. The study also showed that the addition of mineral admixtures such as grounded blast furnace slag (GBFS) and fly ash (FA) reduced concrete permeability and hence loss of RDME. Y. Chen et al. (2016) demonstrated that the incorporation of 50 % GBFS and 30 % FA reduced RDME loss. The GBFS and FA improved the RDME of concrete by 15.7 % and 18.7 % respectively as the cementitious matrix was densified by pozzolanic reaction and secondary hydration.

Gao et al. (2013) studied the effect of long-term flexural loading on concrete subjected to sulphate attack under influence of WDA. The application of 40 % ultimate flexural loading caused slight reduction of concrete RDME. Higher loading level at 60 % resulted in concrete cracking which escalated the deterioration and hence further

RDME loss. The incorporation of GBFS into concrete slightly improved the RDME, while FA incorporation showed better improvement. F. Chen et al. (2017) also found greater RDME loss at higher level of applied flexural loading. The difference of RDME between tension zone and compression zone was compared. The RDME loss in tension zone was greater than that in compression zone. The tension induced cracking to cause concrete degradation, whereas compression prevented cracking.

5.4 Remarks

Concrete mechanical properties such as compressive strength, tensile strength and elastic modulus are damaged under the influence of WDA in marine environment. The deteriorating effect is mainly caused by sulphate attack and salt crystallization. The loss of mechanical properties is also highly dependent on applied external stress. Tensile stress induces concrete cracking, while compressive stress closes concrete pore to reduce damage. The incorporation of GBFS and FA improves the mechanical properties and shields concrete against weathering.

The published literature concerning the effect of WDA on tensile strength is limited. The tensile strength is perceived to be closely related to compressive strength as concrete having high compressive strength usually possesses higher tensile strength. This leads to misconception that WDA has similar impact on tensile strength to that on compressive strength. It is recommended to further conduct research in this area since their relationship is not linear.

6. Corrosion resistance of concrete exposed to WDA

In wetting-drying marine environment, concrete resistance to corrosion of embedded steel is important for ensuring long-term durability. The deterioration process is divided into two stages which are de-passivation and propagation stages (Chrisp et al., 2002). The de-passivation refers to the loss of steel passivity as a result of concrete property change in response to exposure of aggressive environment. The de-passivation of steel is caused by chloride attack and carbonation. This subsequently initiates the corrosion of steel and causes volume expansion. The concrete experiences damages such as cracking, reduction of bonding strength with steel and loss of steel mechanical properties throughout the propagation stage. This consequently leads to issues of structural safety, high maintenance cost and reduction of building lifespan. Therefore, the corrosion resistance of concrete subjected to WDA is reviewed.

6.1 Review of published works

Chrisp et al. (2002) studied the mechanism of WDA on corrosion resistance of concrete through determination of electrical conductivity in cover zone. The conductivity of concrete in wet condition was higher than that in dry condition. The difference of conductivity between two conditions diminished with increasing depth into concrete until it became zero. The conductivity in this zone was influenced by WDA and was referred as convection zone of concrete where maximum content of chloride was found. The convection zone of concrete extended to 30 mm in wetting-drying environment. Ye, Jin, Jin, et al. (2016) determined the chloride ingress of concrete subjected to salt fog WDA whereby a solution containing 5 % NaCl was sprayed to wet concrete periodically. The chloride ingress depended on orientation of concrete exposure surface. The highest chloride ingress was found on concrete when the surface was placed perpendicularly to the salt fog spray. The convection zone was found at the depth ranged between 5 and 12 mm.

J. Wu et al. (2016) studied the influence of combined WDA and compressive loading on chloride ingress. The WDA accelerated moisture transfer, by which chloride accumulated during drying and migrated further into concrete during wetting. The chloride ingress reduced with increase of compressive loading as this closed concrete pores and reduced permeability. Paul et al. (2016) performed rapid chloride migration test to investigate the effect of crack on chloride ingress of strain hardening cement composite (SHCC). Cracks were formed on beam specimens by bending at deformation level of 33 % and 66 % with respect to ultimate deformation. The chloride migration coefficient of SHCC increased with deformation level. The enlarged crack width of SHCC at higher deformation level provided more means of chloride penetration.

Effect of chloride ingress on mortar was also evaluated by Backus et al. (2013). Lower concentration of chloride was found on the mortar surface, but peak value was encountered at 5 mm depth inside the mortar after being exposed to WDA for 24 weeks. Occurrence of carbonation reduced the pH value of mortar which released bound chloride into free form at the carbonation front. H. Chang (2017) evaluated the chloride binding capacity of cement paste in three conditions which were C–I (carbonated and then exposed to chloride), C–II (exposed to chloride and then carbonated) and C–III (chloride introduced during paste mixing and then carbonated). The chloride binding capacity of paste reduced in the order C–I, C–III and C–II. In both C–II and C–III, chloride was absorbed into cement paste and then exposed to carbonation. Carbonation occurred to decompose Friedel's salt to form free chloride which substantially increased chloride content. C-S-H also lost its chloride binding capacity due to drop of pH value and change of surface charge. Cement paste in C–I exhibited higher binding capacity because carbonation occurred prior to chloride contact and hence it was not affected by carbonation. In actual situation, C–II is more representative of concrete deterioration, showing more acute damage caused by mutual effect of chloride attack and carbonation.

Backus et al. (2013) also studied and found that the incorporation of mineral admixtures such as GBFS, FA and SF improved chloride penetration resistance. The mineral admixtures increased chloride binding capacity of mortar. Qi et al. (2018) demonstrated that the incorporation of GBFS and FA refined and densified concrete pore structure through pozzolanic reaction. Simčič et al. (2015) showed that the use of FA with 20 % and 50 % replacement level provided filling effect on concrete through pozzolanic reaction. Although mineral admixture reduced chloride ingress by refinement of pore, considerable amount of chloride could accumulate on concrete surface (Ye, Jin, Jin, et al., 2016). This gradually induced high concentration gradient which facilitated chloride ingress in the long term.

6.2 Remarks

Concrete corrosion resistance is aggravated by WDA. The WDA promotes more rapid transfer of moisture into concrete to accelerate chloride penetration. Convection zone is created inside concrete with the surface exposed to WDA. A long-term exposure to WDA increases the depth of convection zone and causes loss of concrete cover. The synergy between chloride attack and carbonation reduces chloride binding capacity, leading to more severe corrosion. The addition of mineral admixtures such as GGBS, FA and SF can improve concrete shielding against chloride ingress. The admixtures refine and densify pore structure of concrete through pozzolanic reaction. But, chloride accumulates on concrete surface and increases its concentration gradient, jeopardizing long-term corrosion resistance of concrete.

7. Perspective of research trend

Research gaps and limitations related to concrete deterioration under the influence of WDA are identified. The research trends are recommended as follows.

1. The current research focuses on a single deterioration mechanism and multiple mechanisms but restricted to chemical types such as between chloride attack and carbonation as well as between chloride attack and sulphate attack. Physical weathering of concrete can occur simultaneously to cause scaling and cracking of its surface, degrading the shielding layer and making it more susceptible to chemical deterioration. For example, salt crystallization and wave erosion cause significant physical and mechanical damages on concrete. It is recommended to perform research on synergy between physical and chemical deteriorations of concrete.
2. Researchers have performed experiments to simulate wetting-drying environment, of which the behaviors of WDA vary differently from their respective laboratory works. Validation has not been conducted to prove the relevance and accuracy of the simulated environment. It is suggested to also conduct experiments based on real time wetting-drying phenomenon, so as to establish the relationship between laboratory and actual conditions.
3. The change of concrete physical properties is a part of deterioration process. The current research is performed using simple test specimens such as cubes and prisms. The volume expansion and mass change of concrete can cause deformation in structure, leading to problems in the aspects of stability and integrity. Future research is recommended to expand to larger scale of testing to match the actual situation in the field.
4. Further investigation is recommended to study the effect of WDA on tensile strength of concrete as the research is limited in the current literature.

5. The incorporation of mineral admixtures such as GBFS, FA and SF reduces concrete permeability. It also accumulates and increases chloride concentration gradient on concrete surface to facilitate chloride penetration. The impact on the long-term corrosion resistance of concrete is not comprehensively studied. More extensive research which includes longer test period is recommended.

8. Conclusion

The impacts of WDA on marine concrete are reviewed. Concrete deterioration mechanisms are identified and the influences of WDA on the processes are discussed. This research provides deeper insight into the effect of WDA on the physical and mechanical properties as well as on corrosion resistance of concrete. Upon the review, the following conclusions can be drawn.

1. The WDA aggravates chemical deteriorations of concrete such as chloride attack, sulphate attack and carbonation. It increases the intrusion of harmful substances by accumulating them at the wetting front, resulting in steep concentration gradient which increases the diffusion. Physical concrete deterioration includes salt crystallization, freezing-thawing action and wave erosion. In the actual environment, synergy exists between two mechanisms in which the physical mechanism has a catalytic effect on exacerbation of chemical deterioration.
2. Concrete deterioration is greatly influenced by wetting-drying characteristics, ion type, ion concentration, temperature and external loading. The wetting and drying periods used by researchers range from 0.3–1080 hours/cycle and 0.7–1172 hours/cycle respectively. A drying period with a temperature range of 45–80 ^{o}C is also used to accelerate water evaporation, but it can change the degradation process such as micro-cracking in concrete. The use of composite solution made from NaCl,

Na_2SO_4 and $MgSO_4$ better simulates the actual environment. The damage caused is less severe than the individual component due to mutual interaction. External tensile action develops crack to speed up intrusion of deleterious compounds, while the external compressive action prevents the intrusion by closing the concrete pores and cracks.

3. The WDA, together with sulphate attack and salt crystallization, has a significant impact on the physical properties of concrete. The deterioration begins with formation of efflorescence, and is followed by delamination of mortar and coarse aggregate detachment, which eventually leads to disintegration of concrete. Concrete can experience volume expansion up to 1.6 %. The mass change of concrete depends on its strength, wherein strong concrete experiences mass increase whilst weak concrete suffers loss.
4. Mechanical properties of concrete deteriorate progressively with WDA. The main deterioration mechanisms are salt crystallization and sulphate attack. Internal stress exerted by the formation of salt crystals, ettringite and gypsum damages the concrete. But, filling of pores by the products can cause a temporary strengthening of concrete. The addition of mineral admixture such as GBFS and FA can minimize the strength degradation.
5. Corrosion resistance of concrete is deleteriously affected by chloride attack and carbonation. WDA promotes increased transfer of moisture which increases chloride intrusion. This expands the depth of chloride convection zone in concrete which causes a significant loss of cover and accelerates the corrosion of steel. Although the addition of mineral admixtures improves concrete resistance against corrosion, its refining effect accumulates chloride and increases the concentration to accelerate intrusion in the long-term.

Shortfalls exist in the laboratory tests for duplicating WDA of the actual environment. Disparity of test results ensues due to simulation difficulties and lack of unified guidelines. Nevertheless, the findings still can provide a promising trend in the WDA research. The laboratory simulation of WDA can be further improved with the acquisition of large-scale field data.

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