REVIEW ON EFFECTS OF WATER TO CEMENT RATIO AND CHLORIDE PENETRATION IN REINFORCED CONCRETE STRUCTURE

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DEDICATION

This project report is dedicated to my father, who taught me to be patient in seeking knowledge as there is ‘no pain no gain’. It is also dedicated to my mother, who taught me to be optimistic person in facing challenges to become a better person.

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ABSTRACT

Corrosion become the main concern in structure durability which can result in catastrophic failure. Besides, inadequate or wrong selection of water-cement ratio can cause the insufficient readiness of reinforced concrete structure (RC) to the aggressive environment. This issue might arise due to the material cost saving by reducing the material of concrete and at the same time the quality of concrete might be jeopardized during the construction as the consequences of the acts are untraceable in the early stage. The poor quality of concrete in term of penetrability properties can cause the easiness transport of chloride ions into the internal medium of concrete structure. Therefore, the purpose of this research is to highlight the common and frequent problem on the structure deterioration that often related to the chloride-induced corrosion. The pattern and failure mode of concrete and steel were observed using the secondary data collection method from previous study to analyse the intended various factors that contributed to the corrosion of the RC. After all the possible factors that influence the corrosion was determined, the data comparison were done to study their effect on the chloride penetration that led to the occurrence of corrosion. As a result, water-to-cement (w/c) ratio was the main parameter that highlighted as the main cause of the chloride ions penetration that led to the corrosion of reinforced structure at the first place which eventually end up with structure failure. Different parameters were investigated on the degree of corrosion such as the sodium chloride (NaCl) concentration as aggressive agent, the immersion time, and the intended quality concrete casted. The findings show that the lowest chloride penetration depth was 5 mm with w/c ratio of 0.25, and the highest penetration was at the depth of 33 mm with w/c ratio of 0.55 in 3% NaCl solution for 6 months. It can be seen that when w/c ratio increase by 0.1, the chloride penetration depth will increase to approximately 30 to 60%. This results highly prove that the quality of concrete structure plays a significant role in delaying the chloride-induced corrosion. Moreover, these findings can increase the knowledge and awareness of construction practitioner on the importance of designing the adequate quality of concrete structure and ensure the quality was well-maintained to avoid the economic issue arise in future due to corrosion.

ABSTRAK

Hakisan menjadi perhatian utama dalam ketahanan struktur yang boleh mengakibatkan kegagalan struktur bangunan. Pemilihan nisbah air-simen yang tidak betul atau salah mengakibatkan kesediaan struktur konkrit bertetulang tidak mencukupi terhadap persekitaran yang agresif. Masalah ini mungkin timbul kerana penjimatan kos bahan dengan mengurangkan bahan konkrit dan pada masa yang sama kualiti konkrit akan terjejas semasa pembinaan. Kurangnya kualiti konkrit dari segi sifat penerapan boleh menyebabkan berlakunya penyerapan ion klorida ke medium dalaman struktur konkrit yang mengakibatkan hakisan tetulang konkrit. Oleh itu, tujuan penyelidikan ini adalah untuk mengetengahkan masalah yang kerap berlaku pada kemerosotan ketahanan struktur yang sering berkaitan dengan hakisan yang disebabkan oleh klorida. Kaedah pengumpulan data sekunder dari kajian sebelumnya untuk menganalisis pelbagai faktor yang dimaksudkan boleh menyumbang kepada pengaratan koknrit bertetulang. Setelah semua kemungkinan faktor yang mempengaruhi kakisan dikenalpasti, perbandingan data dilakukan untuk mengkaji kesannya terhadap penembusan klorida yang menyebabkan berlakunya hakisan. Hasil yang diperoleh menunjukkan, nisbah air dan simen (a/s) adalah parameter utama yang menyebabkan penembusan ion klorida sehingga hakisan struktur bertetulang berlaku dan akhirnya berakhir dengan kegagalan struktur. Parameter yang berbeza disiasat berdasarkan tahap kakisan seperti kepekatan natrium klorida (NaCl) sebagai agen agresif, masa rendaman, dan kualiti konkrit yang dihasilkan. Hasil kajian menunjukkan, kedalaman penembusan klorida yang terendah ialah 5 mm dengan nisbah a/s 0.25, dan penembusan tertinggi pada kedalaman 33 mm dengan nisbah a/s 0.55 dalam larutan NaCl 3% selama 6 bulan. Apabila nisbah a/s meningkat sebanyak 0.1, kedalaman penembusan klorida akan meningkat sekitar 30 hingga 60%. Hasil ini membuktikan bahawa kualiti struktur konkrit berperanan penting dalam melambatkan hakisan yang disebabkan oleh klorida. Lebih-lebih lagi, penemuan ini dapat meningkatkan pengetahuan dan kesedaran kontraktor mengenai pentingnya prencangan awal bagi menghasilkan kualiti struktur konkrit yang mencukupi dan memastikan kualitinya dijaga dengan baik untuk mengelakkan masalah kerugian timbul pada masa akan datang kerana hakisan

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LIST OF ABBREVIATIONS

ACI	-	American Concrete Institute
BS	-	British Standard
RC	-	Reinforced structure
NaCl	-	Sodium chloride
Fe_2O_3	-	Iron oxide
$Ca(OH)_2$	-	Calcium hydroxide
$CaCl_2$	-	Calcium chloride
NaOH	-	Sodium hydroxide
$3CaO.Al_2O_3$	-	Tricalcium aluminate
H_2O	-	Water
$3CaO.Al_2O_3.CaCl_2.10H_2O$	-	Calcium Chloroaluminate (Friedels Salt)
$FeCl_2$	-	Ferrous chloride
$Fe(OH)_2$	-	Ferrous hydroxide
HCl	-	Hydrochloric acid
O_2	-	Oxygen
$Fe(OH)_3$	-	Iron (III) hydroxide
OC	-	Ordinary cement
C-S-H/CSH	-	Calcium silicate hydrate
Ca_2O_4Si	-	Calcium silicate
OPC	-	Ordinary Portland cement
SEM	-	Scanning electron microscopy
HPC	-	High performance concrete
NC	-	Normal concrete
SCI	-	Steel-concrete interface
ITZ	-	Interfacial transition zone
EDX	-	Energy dispersive X-ray
E	-	Ettringite
DC	-	Direct current
EN	-	European Standard

LIST OF SYMBOLS

w/c	-	Water-to-cement
ppm	-	Parts per million
Cl^-/m^3	-	Chlorides ion per volume
pH	-	Potential of hydrogen
I_{corr}	-	Corrosion rate
M	-	Molar
mmol/l	-	Millimoles per litre
V	-	Volt
mA	-	Milliampere
R^2	-	Correlation coefficient

CHAPTER 1

INTRODUCTION

1.1 General

Malaysia shows a continuous growth in cement demand since 2009 due to the growing number of building construction that mainly use cement as material construction for concrete structure (Malaysia Competition Commision, 2017). The most important elements in structure building are strength and durability that should be considered during designing. Obviously, structure made with cement concrete can provide both the strength and durability at the same time had been proven can last for hundreds of years (Marinković *et al.*, 2014). Normally, all concrete structures are reinforced with the reinforcement steel to enable the structure to sustain the designated load and at the same time to improve its tensile properties (Naaman, 2001). However, the use of reinforcement steel as a part of the structure has always become the main weakness of the reinforcement concrete as reinforcement corrosion rate is the most important factors that limit the service life of concrete structures until now (Tian *et al.*, 2020). The only protection for reinforcement against corrosion is to provide the protection medium that is called as ‘concrete cover’ that can act as the first protective layer from the exposed surrounding environment that contains water and oxygen which can promote the corrosion process to happened (Nguyen *et al.*, 2020). The efficient role of concrete cover is highly depending on the quality of concrete design mixture. Due to that concern, several codes of practices have specified the minimum design class of concrete for various climatic conditions to prevent the aggressive chemical ingress into contact with the reinforcement (Subramanian and Geetha, 1997). In addition, it is proven that one of the factors that affect the most on reinforced concrete structure deterioration is the corrosion of reinforcement which already become the main concern in third world countries as well resulted in serious building damages and even in losses of lives (Chemrouk, 2008). Various environmental factors lead to the corrosion damage of structure especially that exposed to the marine environment which influenced by seawater composition. Chloride has always been considered as the most critical factors that degrade the concrete structure in the marine environment as it can cause an intense corrosion of reinforcement when penetrated into the concrete (Tian *et al.*, 2020).

1.2 Problem Background

Durability performance of structure building has become one of the main concerns in the life span of a building. Concrete as the main material used for building which used since past until now making the durability of the concrete become the significant attention over the past several decades and it still become the research interest until now (Tang *et al.*, 2015). The durability of structures is defined as its ability to withstand weathering action, chemical attack, abrasion or any deterioration to maintain their original form, quality and serviceability (Monteiro, 2006; Tang *et al.*, 2015; Bolina *et al.*, 2020). The said ability is very crucial in protecting the reinforcement bar through the quality of concrete medium that provide the physical barrier from contaminated by the aggressive environment. Among the common chemical attacks in construction industries; carbonation, corrosion, chloride attack, sulphate attacks, acid attack and etc, corrosion have been recognized as the expensive problem of damaged to reinforced steel structures and primary durability issue which regard on chloride-induced (Costa and Appleton, 2002; Moradi-Marani *et al.*, 2010; Dousti *et al.*, 2013; Yi *et al.*, 2020).

Structure deterioration occurred often related to the corrosion that can be triggered by surrounding environment and the durability of the structure itself to withstand them. Corrosion happened when the harmful substances especially with highly chlorine content in the ambient environment are able to penetrate into the first layer protection of concrete structure due its porous properties and cause the deterioration. Throughout years, concrete will still experience the corrosion during its service life as the harmful substance in the environment can still penetrate into this layer (Beushausen *et al.*, 2019). The tendency of the corrosion on structure sometimes misunderstood to be the environment factor only. However, the condition of the structure to combat the known aggressive surrounding environment plays an important role to avoid the corrosion from the early stage. Hence, the most important elements in the structure itself is the concrete medium which act as the first protection layer of concrete to shield the reinforcement bar (Cui and Alipour, 2018).

The minimum strength class of concrete structure according to the specifications have been highlighted in various codes such as ACI code, European Code, British Standard and etc that need to be considered in different exposure classes. However, this crucial minimum strength class of concrete specification is often jeopardized during the construction work due to saving cost and time issue. The situation become worse when the special attention of chloride-induced corrosion on concrete are neglected as per highlighted in Code of Practice British Standard (BS) and Eurocode 2. Due to the lack of knowledge and awareness of the construction practitioner according to Dhir *et al.*, 2008, more studies are required to highlight the significant of concrete cover in combating the structure deterioration especially in reinforcement corrosion. This research might possibly as well help in developing more knowledge in investigating the causes of long-term structure deterioration due to reinforcement corrosion.

1.3 Problem Statement

In developing countries, the occurrence of the building collapse frequently relate to the poor quality of concrete (Ede *et al.*, 2017). According to Love and Matthews (2020), contractors more emphasizing the safety issue during the construction and ignored the importance of quality of construction which actually being interrelated. It is very crucial to increase the awareness on the significance of constructing the good quality of construction to avoid the structure deterioration that led to the collapsed incident. This is due to the long-term of the deterioration that highly affect the durability of concrete which can only be detected visually at the stage where it is impossible to be repaired as it required the huge cost for its recovery. Durability performance of structure building has become one of the main concerns in the life span of a building. Concrete as the main material used for building which used since past until now making the durability of the concrete become the significant attention over the past several decades and is still a research until now (Tang *et al.*, 2015). The durability of structures is defined as its ability to withstand weathering action, chemical attack, abrasion or any deterioration to maintain their original form, quality and serviceability (Monteiro, 2006; Tang *et al.*, 2015; Bolina *et al.*, 2020). However, the use of reinforcement steel as a part of the structure has always become the main weakness of the reinforcement concrete as reinforcement corrosion rate is the most important factors that limit the service life of concrete structures until now (Tian *et al.*, 2020). The said ability is very crucial in protecting the reinforcement bar through acting as the cover concrete that provide the physical barrier from contaminated by the aggressive environment. Among the common chemical attacks in construction industries; carbonation, corrosion, chloride attack, sulphate attacks, acid attack and etc, corrosion have been recognized as the expensive problem of damaged to reinforced steel structures and primary durability issue which regard on chloride-induced (Costa and Appleton, 2002; Moradi-Marani *et al.*, 2010; Dousti *et al.*, 2013; Yi *et al.*, 2020).

The main factor that believed to drive the quality of concrete from original design is the economic issue. Cost issue frequently highlighted in research from few decades until recent as it is still an arguably criteria for measuring the success of any project especially related to the size and complexity of construction project (Shehu *et al.*, 2014; Perera *et al.*, 2020). Due to that matter, inadequate durability design and poor construction quality has led to the severe and rapid structure deterioration caused by the corrosion of reinforcement steel in concrete especially in marine environment (Marić *et al.*, 2020). Corrosion happened when the harmful substances especially with highly chlorine content in the ambient environment are able to penetrate into the first layer protection of concrete structure due its porous properties and cause the deterioration. Throughout years concrete will still experience the corrosion during its service life as the harmful substance in the environment can still penetrate into this layer (Beushausen *et al.*, 2019). Hence, the most important elements in the structure itself is the quality of the concrete in the terms of low penetrability that can be manipulated through the selection of correct water-to-cement (w/c) ratio during the design stage. This will result in the ability of concrete to delay the chloride penetration at the same time the concrete cover purpose can be achieved efficiently as the first layer protection of concrete structure provided at the early stage of construction. Therefore, this research will highlight the common symptom and pattern of failure due to chloride-induced corrosion, the factors that influence the degree of corrosion due to succeed chloride penetration and the significance of water-to-cement ratio to resist chloride penetration.

1.4 Objective of Study

This study will focus on investigating the impact of corrosion towards reinforced concrete that highly govern by chloride ions penetrated to the concrete and eventually lead to the reinforcement corrosion. The following objectives are to investigate the factors that can influence the level of corrosion occurred and to investigate the influence of water-to-cement (w/c) ratio in delaying the chloride-induced corrosion:

(a) To determine the different impacts of corrosion on reinforced concrete structure due to various factors.

(b) To investigate the factors that influenced the degree of corrosion on reinforced concrete due to chloride ions penetration.

(c) To determine the significance of w/c ratio on the chloride penetration of concrete.

1.5 Scope of Study

This study will focusing on the common problem that has become a big concern in reinforced concrete (RC) structure which is corrosion of reinforcement that triggered by chloride-induced event. The long-term of structure deterioration can only be seen after many years of construction as found on the aging construction building. Hence, it is hard to promote the awareness of contractors, designers and engineers on the durability aspect related to reinforcement corrosion. Therefore, this research can become an additional effort in highlighting the significance of quality of concrete in resisting the chloride penetration into the concrete. This quality aspect is already emphasized as one of the requirements when the concrete structure is constructed in marine environment.

This research is conducted using secondary data collection method to review on the factors that led to the different degree of corrosion such as concentration of aggressive environment, exposure time, and quality of concrete. The accelerated corrosion method of experiment was used in previous studies to shorten the impact of corrosion and the different level of corrosion can be determined via the visual of deteriorated concrete structure when its durability was exploited. Then, the influences of the three factors said on the chloride penetration depth will be identified. Among the said factors, w/c ratio value was found to be the most influenced factor as it led to the determination of quality of concrete that can resist the chloride-induced corrosion. However, there is limitation in obtaining the related sources due to the difficulties in finding the same concentration of sodium chloride (NaCl) used and the same period exposure chosen in conducting their laboratory chloride immersion test. Besides, the methods of data taken in evaluating the degree of corrosion are various for instance the chloride diffusion coefficient, half cell-potential, corrosion rate and etc. The exploitation of quality concrete often occurred due to the reducing cost of construction material without thinking the consequences in bearing more cost in repairing the corrosion damages. The outcomes of this research can show the future impact of chloride-induced corrosion when the quality of concrete is jeopardized. Besides, it can highlight the significance of selecting the correct w/c ratio in combating the corrosion for longer time.

1.6 Significance of Study

This study can highlight and emphasize the importance of controlling and selecting the correct quality of concrete structure in protecting the reinforcement from corroded. In addition, the exposure on the impact during the post-corrosion can give a better awareness to not underestimate the corrosion effect once it happened. In real life, this study can help the investigator in shorten the investigation process by narrowing the scope when the structure deterioration due to corrosion that contributed by the under designed or poor constructed reinforced structure that failed to perform its purpose. Besides, this research can promote the easiest and the most basic method in combating the chloride-induced corrosion without adopting the new type of concrete development and technology which cause the additional cost bearing in the construction project.

REFERENCES

Ababneh, A. N. (2003) ‘The coupled effect of moisture diffusion chloride penetration and freezing-thawing on concrete durability.’

Abedini, M. and Mutalib, A. A. (2020) ‘Investigation into damage criterion and failure modes of RC structures when subjected to extreme dynamic loads’, *Archives of Computational Methods in Engineering*. Springer, 27(2), pp. 501–515.

Ahmad, S., Elahi, A., Barbhuiya, S. A. and Farid, Y. (2012) ‘Use of polymer modified mortar in controlling cracks in reinforced concrete beams’, *Construction and building materials*. Elsevier, 27(1), pp. 91–96.

Ahmed, S. (2019) ‘Causes and effects of accident at construction site: A study for the construction industry in Bangladesh’, *International Journal of Sustainable Construction Engineering and Technology*, 10(2), pp. 18–40.

Aktan, H. M., Fu, G., Dekelbab, W. and Attanayaka, U. (2003) *Investigate causes & develop methods to minimize early-age deck cracking on Michigan bridge decks*.

Al-Akhras, N. and Aleghnimat, R. (2020) ‘Evaluating corrosion deterioration in self-compacted reinforced concrete beams and prisms using different tests’, *Construction and Building Materials*. Elsevier, 256, p. 119347.

Arredondo-Rea, S. P., Corral-Higuera, R., Gómez-Soberón, J. M., Gámez-García, D. C., Bernal-Camacho, J. M., Rosas-Casarez, C. A. and Ungsson-Nieblas, M. J. (2019) ‘Durability parameters of reinforced recycled aggregate concrete: Case study’, *Applied sciences*. Multidisciplinary Digital Publishing Institute, 9(4), p. 617.

Aspers, P. and Corte, U. (2019) ‘What is Qualitative in Qualitative Research’, *Qualitative Sociology*. Qualitative Sociology, 42(2), pp. 139–160.

Association, P. C. (2002) ‘Types and causes of concrete deterioration’, *Portland Cement Association: Skokie, IL, USA*.

Awoyera, P., Adesina, A., Olalusi, O. B. and Viloria, A. (2020) ‘Reinforced concrete deterioration caused by contaminated construction water: An overview’, *Engineering Failure Analysis*. Elsevier, p. 104715.

Bentz, D. P. (2000) 'Fibers, percolation, and spalling of high-performance concrete', *Materials Journal*, 97(3), pp. 351–359.

Bérodier, E. M. J., Muller, A. C. A. and Scrivener, K. L. (2020) 'Effect of sulfate on C-S-H at early age', *Cement and Concrete Research*, 138, p. 106248.

Beushausen, H., Torrent, R. and Alexander, M. G. (2019) 'Performance-based approaches for concrete durability: State of the art and future research needs', *Cement and Concrete Research*. Elsevier, 119, pp. 11–20.

Bolina, F. L., Gil, A. M., Fernandes, B., Hennemann, G. G., Gonçalves, J. and Tutikian, B. F. (2020) 'Influence of design durability on concrete columns fire performance', *Journal of Materials Research and Technology*. Elsevier.

Brown, P. W. and Bothe Jr, J. V (1993) 'The stability of ettringite', *Advances in Cement Research*. Thomas Telford Ltd, 5(18), pp. 47–63.

Build, N. T. (1989) 'Concrete, repairing materials and protective coating: embedded steel method, chloride permeability', *NT Build*, 356.

Cabrera, J. G. (1996) 'Deterioration of concrete due to reinforcement steel corrosion', *Cement and Concrete Composites*, 18(1), pp. 47–59.

Cabrera, J. G., Dodd, T. A. H. and Nwaubani, S. O. (1993) 'Effect of Curing Temperature on the Chloride Ion Diffusion of Superplasticized Cement and Fly Ash pastes', *Special Publication*, 139, pp. 61–76.

Campbell-Allen, D. and Roper, H. (1991) *Concrete structures: materials, maintenance and repair*.

Castellote, M., Andrade, C. and Alonso, M. C. (1999) 'Changes in concrete pore size distribution due to electrochemical chloride migration trials', *Materials Journal*, 96(3), pp. 314–319.

Castro, P., Veleva, L. and Balancan, M. (1997) 'Corrosion of reinforced concrete in a tropical marine environment and in accelerated tests', *Construction and building Materials*. Elsevier, 11(2), pp. 75–81.

Charalambidi, B., Markou, P., Drakakaki, A. and Oungrinis, K.-A. (2020) 'Challenges on contemporary architectural technology on durability of reinforced concrete structures', *International Journal of Structural Integrity*. Emerald Publishing Limited.

Chemrouk, M. (2008) 'Influence of Poor Workmanship and Construction Defects on the Durability and Strength of Concrete', *CONCRETE DURABILITY: ACHIEVEMENT AND ENHANCEMENT*, p. 153.

Chen, F., Li, C.-Q., Baji, H. and Ma, B. (2019) 'Effect of design parameters on microstructure of steel-concrete interface in reinforced concrete', *Cement and Concrete Research*. Elsevier, 119, pp. 1–10.

Cherif, R., Hamami, A. E. A. and Ait-Mokhtar, A. (2020) 'Effects of leaching and chloride migration on the microstructure and pore solution of blended cement pastes during a migration test', *Construction and Building Materials*. Elsevier, 240, p. 117934.

Chia, K. S. and Zhang, M.-H. (2002) 'Water permeability and chloride penetrability of high-strength lightweight aggregate concrete', *Cement and concrete research*. Elsevier, 32(4), pp. 639–645.

Chindaprasirt, P., Chotithanorm, C., Cao, H. T. and Sirivivatnanon, V. (2007) 'Influence of fly ash fineness on the chloride penetration of concrete', *Construction and Building Materials*. Elsevier, 21(2), pp. 356–361.

Costa, A. and Appleton, J. (2002) 'Case studies of concrete deterioration in a marine environment in Portugal', *Cement and concrete composites*. Elsevier, 24(1), pp. 169–179.

Cui, Z. and Alipour, A. (2018) 'Concrete cover cracking and service life prediction of reinforced concrete structures in corrosive environments', *Construction and Building Materials*. Elsevier, 159, pp. 652–671.

Delatte, N. (2009) *Failure, distress and repair of concrete structures*. Elsevier.

Demis, S. and Papadakis, V. G. (2019) 'Durability design process of reinforced concrete structures - Service life estimation, problems and perspectives', *Journal of Building Engineering*, 26, p. 100876.

Dhawan, S., Bhalla, S. and Bhattacharjee, B. (2014) 'Reinforcement Corrosion in Concrete Structures and Service Life Predictions–A Review', in *9th International Symposium on Advanced Science and Technology in Experimental Mechanics, New Delhi, India*, pp. 1–6.

Dhir, R. K., Harrison, T. A., Zheng, L. and Kandasami, S. (2008) *Concrete Durability: Achievement and Enhancement: Proceedings of the International Conference Held at the University of Dundee, Scotland, UK on 8-9 July 2008*. IHS BRE Press.

Diamond, S. (1986) 'Cement paste microstructure in concrete', *MRS Online Proceedings Library (OPL)*. Cambridge University Press, 85.

Double, D. D. (1983) 'New developments in understanding the chemistry of cement hydration', *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*. The Royal Society London, 310(1511), pp. 53–66.

Dousti, A., Moradian, M., Taheri, S. R., Rashetnia, R. and Shekarchi, M. (2013) 'Corrosion assessment of RC deck in a jetty structure damaged by chloride attack', *Journal of performance of constructed facilities*. American Society of Civil Engineers, 27(5), pp. 519–528.

Dransfield, J. (2003) '4 - Admixtures for concrete, mortar and grout', in Newman, J. and Choo, B. S. B. T.-A. C. T. (eds). Oxford: Butterworth-Heinemann, pp. 3–36.

Ede, A. N., Olofinnade, O. M., Bamigboye, G., Shittu, K. K. and Ugwu, E. I. (2017) 'Prediction of fresh and hardened properties of normal concrete via choice of aggregate sizes, concrete mix-ratios and cement', *International Journal of Civil Engineering and Technology*. IAEME, 8(10), pp. 288–301.

EN, B. S. (2000) '206-1 Concrete-Part 1: Specification, performance, production and conformity', *British Standards Institution*.

Esser, F. and Vliegenthart, R. (2017) 'Comparative research methods', *The international encyclopedia of communication research methods*. Wiley Online Library, pp. 1–22.

Fauzi, M. A., Rosseli, S. R., Hasbul, J. and Ridzuan, A. R. M. (2016) 'COMBINED EFFECT OF STEEL SLAG AS A PARTIALLY REPLACED MATERIAL FOR COARSE AGGREGATES AND WATER–CEMENT RATIO ON THE CHLORIDE RESISTANCE OF CONCRETE', *e-Academia Journal,* 5(2).

Fazilati, M. and Golafshani, E. M. (2020) 'Durability properties of concrete containing amorphous silicate tuff as a type of natural cementitious material', *Construction and Building Materials*. Elsevier, 230, p. 117087.

Gharehbaghi, K. and Sagoo, A. (2016) 'Reducing deterioration and corrosion of reinforcements in transportation structures', *Journal of Civil Engineering and Environmental Technology*. Krishi Sanskriti Publishing, 2(1), pp. 19–22.

Glass, G. K. and Buenfeld, N. R. (2000a) 'Chloride-induced corrosion of steel in concrete', *Progress in Structural Engineering and Materials*. Wiley Online Library, 2(4), pp. 448–458.

Glass, G. K. and Buenfeld, N. R. (2000b) 'The influence of chloride binding on the chloride induced corrosion risk in reinforced concrete', *Corrosion Science*. Elsevier, 42(2), pp. 329–344.

Gonzalez, A., Schorr, M., Valdez, B. and Mungaray, A. (2020) 'Bridges: Structures and Materials, Ancient and Modern', in *Infrastructure Management and Construction*. IntechOpen.

Hansapinyo, C., Vimonsatit, V., Matsushima, M. and Limkatanyu, S. (2020) 'Critical amount of corrosion and failure behavior of flexural reinforced concrete beams', *Construction and Building Materials*. Elsevier, p. 121448.

Hansson, C. M. (1984) 'Comments on electrochemical measurements of the rate of corrosion of steel in concrete', *Cement and concrete research*. Elsevier, 14(4), pp. 574–584.

Hassani, M. S., Asadollahfardi, G., Saghravani, S. F., Jafari, S. and Peighambarzadeh, F. S. (2020) 'The difference in chloride ion diffusion coefficient of concrete made with drinking water and wastewater', *Construction and Building Materials*. Elsevier, 231, p. 117182.

Haussmann, D. A. (1967) 'Steel corrosion in concrete', *Materials protection*, pp. 19–23.

Hewlett, P. and Liska, M. (2019) *Lea's chemistry of cement and concrete*. Butterworth-Heinemann.

Hox, J. J. and Boeije, H. R. (2005) 'Data collection, primary versus secondary'. Elsevier.

Hunkeler, F. (2005) 'Corrosion in reinforced concrete: processes and mechanisms', *Corrosion in reinforced concrete structures*. CRC Roca Raton, FL, pp. 1–45.

Islam, M. S., Kaushik, S. K. and Islam, M. M. (2005) 'Physical and mechanical behavior of concrete in seawater under high hydrostatic pressure', *J. Inst. Eng. Malaysia*, 66, pp. 46–52.

Jamshidi, F. and Dehestani, M. (2020) 'Time to cracking in concrete cover length due to reinforcement corrosion via a simplified fracture mechanics approach', *Construction and Building Materials*. Elsevier, 258, p. 119588.

Jo, B. W., Sikandar, M. A., Chakraborty, S. and Baloch, Z. (2017) 'Strength and durability assessment of portland cement mortars formulated from hydrogen-rich water', *Advances in Materials Science and Engineering*.

Hindawi, 2017.
Johnston, M. P. (2017) ‘Secondary data analysis: A method of which the time has come’, *Qualitative and quantitative methods in libraries,* 3(3), pp. 619–626.
Jones, A. E. K. (1997) *Development of an holistic approach to ensure the durability of new concrete construction*. British Cement Association.
Jumaat, M. Z., Kabir, M. H. and Obaydullah, M. (2006) ‘A review of the repair of reinforced concrete beams’, *Journal of Applied Science Research*. Journal of Applied Science Research, 2(6), pp. 317–326.
Keleştemur, O. and Yildiz, S. (2006) ‘Effect of various NaCl concentration on corrosion of steel in concrete produced by addition of styrofoam’, *Gazi University Journal of Science*, 19(3), pp. 163–172.
Kim, M.-Y., Yang, E.-I. and Yi, S.-T. (2007) ‘Evaluation of Chloride Penetration Characteristics using a Colorimetric Method in Concrete Structures’. IASMiRT.
Kim, M.-Y., Yang, E.-I. and Yi, S.-T. (2013) ‘Application of the colorimetric method to chloride diffusion evaluation in concrete structures’, *Construction and Building Materials*. Elsevier, 41, pp. 239–245.
Koleva, D. A., Hu, J., Fraaij, A. L. A., Van Breugel, K. and De Wit, J. H. W. (2007) ‘Microstructural analysis of plain and reinforced mortars under chloride-induced deterioration’, *Cement and concrete research*. Elsevier, 37(4), pp. 604–617.
LeBow, C. J. (2018) ‘Effect of Cement Content on Concrete Performance’.
Li, L., Chen, M., Guo, X., Lu, L., Wang, S., Cheng, X. and Wang, K. (2020) ‘Early-age hydration characteristics and kinetics of Portland cement pastes with super low w/c ratios using ice particles as mixing water’, *Journal of Materials Research and Technology*. Elsevier, 9(4), pp. 8407–8428.
Liang, Y. and Wang, L. (2020) ‘Prediction of corrosion-induced cracking of concrete cover: A critical review for thick-walled cylinder models’, *Ocean Engineering*. Elsevier, 213, p. 107688.
Liu, J., Tang, K., Pan, D., Lei, Z., Wang, W. and Xing, F. (2014) ‘Surface chloride concentration of concrete under shallow immersion conditions’, *Materials*. Multidisciplinary Digital Publishing Institute, 7(9), pp. 6620–6631.
Liu, J., Xing, F., Dong, B., Ma, H. and Pan, D. (2014a) ‘Study on surface permeability of concrete under immersion’, *Materials*. Multidisciplinary

Digital Publishing Institute, 7(2), pp. 876–886.

Liu, J., Xing, F., Dong, B., Ma, H. and Pan, D. (2014b) 'Study on water sorptivity of the surface layer of concrete', *Materials and structures*. Springer, 47(11), pp. 1941–1951.

Love, P. E. D. and Matthews, J. (2020) 'Quality, requisite imagination and resilience: Managing risk and uncertainty in construction', *Reliability Engineering & System Safety*. Elsevier, 204, p. 107172.

Lu, Z., Su, L., Xian, G., Lu, B. and Xie, J. (2020) 'Durability study of concrete-covered basalt fiber-reinforced polymer (BFRP) bars in marine environment', *Composite Structures*. Elsevier, 234, p. 111650.

Ma, H., Hou, D., Lu, Y. and Li, Z. (2014) 'Two-scale modeling of the capillary network in hydrated cement paste', *Construction and Building Materials*. Elsevier, 64, pp. 11–21.

Ma, H. and Li, Z. (2014) 'Multi-aggregate approach for modeling interfacial transition zone in concrete', *ACI Materials Journal*. American Concrete Institute, 111(2), p. 189.

Malaysia Competition Commision (2017) 'Draft Final Report : Market Review of Building Materials in the Construction Industry', (October), pp. 1–203.

Malhotra, V. M. and Mehta, P. K. (1994) 'Concrete technology: past, present, and future: proceedings of V. Mohan Malhotra symposium', in. American Concrete Institute.

Mangat, P. S. and Molloy, B. T. (1992) 'Factors influencing chloride-induced corrosion of reinforcement in concrete', *Materials and Structures*. Springer, 25(7), pp. 404–411.

Marić, M. K., Ožbolt, J. and Balabanić, G. (2020) 'Reinforced concrete bridge exposed to extreme maritime environmental conditions and mechanical damage: Measurements and numerical simulation', *Engineering Structures*. Elsevier, 205, p. 110078.

Marinković, S. B., Malešev, M. and Ignjatović, I. (2014) 'Life cycle assessment (LCA) of concrete made using recycled concrete or natural aggregates', in *Eco-Efficient Construction and Building Materials*. Elsevier, pp. 239–266.

Mather, B. (1964) *Effects of sea water on concrete*. ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS.

Mehta, P. K. and Monteiro, P. J. M. (2014) *Concrete: microstructure, properties,* *and materials*. McGraw-Hill Education.

Melchers, R. E. (2020) 'Long-Term Durability of Marine Reinforced Concrete Structures', *Journal of Marine Science and Engineering* .

Mohammed, T. U., Otsuki, N. and Hamada, H. (2003) 'Corrosion of steel bars in cracked concrete under marine environment', *Journal of materials in civil engineering*. American Society of Civil Engineers, 15(5), pp. 460–469.

Monteiro, P. (2006) *Concrete: microstructure, properties, and materials*. McGraw-Hill Publishing.

Moradi-Marani, F., Shekarchi, M., Dousti, A. and Mobasher, B. (2010) 'Investigation of corrosion damage and repair system in a concrete jetty structure', *Journal of performance of constructed facilities*. American Society of Civil Engineers, 24(4), pp. 294–301.

Naaman, A. E. (2001) 'Reinforced Concrete', in Buschow, K. H. J., Cahn, R. W., Flemings, M. C., Ilschner, B., Kramer, E. J., Mahajan, S., and Veyssière, P. (eds) *Encyclopedia of Materials: Science and Technology*. Oxford: Elsevier, pp. 8095–8109.

Nasirzadeh, F., Kashi, M. G., Khanzadi, M., Carmichael, D. G. and Akbarnezhad, A. (2019) 'A hybrid approach for quantitative assessment of construction projects risks: The case study of poor quality concrete', *Computers & Industrial Engineering*. Elsevier, 131, pp. 306–319.

Navaratnam, S., Ngo, T., Christopher, P. and Linforth, S. (2020) 'The use of digital image correlation for identifying failure characteristics of cross-laminated timber under transverse loading', *Measurement*. Elsevier, 154, p. 107502.

Nguyen, M. H., Nakarai, K., Kai, Y. and Nishio, S. (2020) 'Early evaluation of cover concrete quality utilizing water intentional spray tests', *Construction and Building Materials*. Elsevier, 231, p. 117144.

Noon, R. K. (2000) *Forensic engineering investigation*. New York: CRC Press.

Pattanaik, S. C., Gopalkrishnan, E. and Patro, S. K. (2015) 'A study on deterioration of reinforced cement concrete structures in Mumbai', *The Indian Concrete Journal*, 89, pp. 1–8.

Perera, B., Samarakkody, A. L. and Nandasena, S. R. (2020) 'Managing financial and economic risks associated with high-rise apartment building construction in Sri Lanka', *Journal of Financial Management of Property and Construction*. Emerald Publishing Limited.

Perkins, P. H. (1976) *Concrete structures: Repair waterproofing and protection*.

Pickvance, C. G. (2001) ‘Four varieties of comparative analysis’, *Journal of housing and the built environment*. Springer, 16(1), pp. 7–28.

Pugliese, F. and Di Sarno, L. (2019) ‘CRITICAL REVIEW OF MODELS FOR THE ASSESSMENT OF THE DEGRADATION OF REINFORCED CONCRETE STRUCTURES EXPOSED TO CORROSION’, *https://www. seced. org. uk/index. php/proceedings/category/48-session-9-seismic-design-and-analysis-general*.

Qu, F., Li, W., Dong, W., Tam, V. W. Y. and Yu, T. (2020) ‘Durability performance deterioration of concrete under marine environment from material to structure: A critical review’, *Journal of Building Engineering*. Elsevier, p. 102074.

Ratner, B. (2009) ‘The correlation coefficient: Its values range between+ 1/− 1, or do they?’, *Journal of targeting, measurement and analysis for marketing*. Springer, 17(2), pp. 139–142.

Rattanachu, P., Toolkasikorn, P., Tangchirapat, W., Chindaprasirt, P. and Jaturapitakkul, C. (2020) ‘Performance of recycled aggregate concrete with rice husk ash as cement binder’, *Cement and Concrete Composites*. Elsevier, 108, p. 103533.

Rerkpiboon, A., Tangchirapat, W. and Jaturapitakkul, C. (2015) ‘Strength, chloride resistance, and expansion of concretes containing ground bagasse ash’, *Construction and building materials*. Elsevier, 101, pp. 983–989.

Revathy, J., Suguna, K. and Raghunath, P. N. (2009) ‘Effect of corrosion damage on the ductility performance of concrete columns’, *American Journal of Engineering and Applied Sciences*, 2(2), pp. 324–327.

Richardson, B. (2002) *Defects and Deterioration in Buildings: A Practical Guide to the Science and Technology of Material Failure*. Routledge.

Romagnoli, R., Batic, R. O., Vetere, V. F., Sota, J. D., Lucchini, I. T. and Carbonari, R. O. (2002) ‘The influence of the cement paste microstructure on corrosion and the adherence of reinforcing bars as a function of the water–cement ratio’, *Anti-Corrosion Methods and Materials*. MCB UP Ltd.

Sánchez, I., Nóvoa, X. R., De Vera, G. and Climent, M. A. (2008) ‘Microstructural modifications in Portland cement concrete due to forced ionic migration tests. Study by impedance spectroscopy’, *Cement and concrete research*.

Elsevier, 38(7), pp. 1015–1025.

Saran, A. A. and Magudeswaran, P. (2017) ‘SEM analysis on sustainable high performance concrete’, *Int J Innov Res Sci Eng Technol*, 6(6), pp. 10237–10246.

Shehu, Z., Endut, I. R., Akintoye, A. and Holt, G. D. (2014) ‘Cost overrun in the Malaysian construction industry projects: A deeper insight’, *International Journal of Project Management*. Elsevier, 32(8), pp. 1471–1480.

Slater, J. E. (1983) *Corrosion of metals in association with concrete: a manual sponsored by ASTM Subcommittee G01. 14 on Corrosion of Reinforcing Steel, and Metal Properties Council*. ASTM International.

Soylev, T. A. and François, R. (2003) ‘Quality of steel–concrete interface and corrosion of reinforcing steel’, *Cement and Concrete Research*. Elsevier, 33(9), pp. 1407–1415.

Srewil, Y. (2006) ‘Cracks of concrete and repair works & case study’.

Su, R. K. L. and Zhang, Y. (2019) ‘A novel elastic-body-rotation model for concrete cover spalling caused by non-uniform corrosion of reinforcement’, *Construction and Building Materials*. Elsevier, 213, pp. 549–560.

Subramanian, N. and Geetha, K. (1997) ‘IConcrete cover for durable RC structures’, *ratio*, 5, p. 10.

Tamai, H., Sonoda, Y. and Bolander, J. E. (2020) ‘Impact resistance of RC beams with reinforcement corrosion: Experimental observations’, *Construction and Building Materials*. Elsevier, 263, p. 120638.

Tang, S. W., Yao, Y., Andrade, C. and Li, Z. J. (2015) ‘Recent durability studies on concrete structure’, *Cement and Concrete Research*, 78, pp. 143–154.

Tian, Y., Wen, C., Wang, G., Hu, J. and Mai, Z. (2020) ‘Marine field test for steel reinforcement embedded in mortar: Coupled influence of the environmental conditions on corrosion’, *Marine Structures*. Elsevier, 73, p. 102788.

Wang, S., Wei, X. and Fan, Z. (2016) ‘The Early Hydration Characteristics of Portland Cements with Superplasticizer Using Electrical Measurements’, *American Journal of Civil Engineering and Architecture*, 4(5), pp. 153–158.

Wasim, M., Ngo, T. D. and Abid, M. (2020) ‘Investigation of long-term corrosion resistance of reinforced concrete structures constructed with various types of concretes in marine and various climate environments’, *Construction and Building Materials*. Elsevier, 237, p. 117701.

Wegian, F. M. (2010) ‘Effect of seawater for mixing and curing on structural concrete’, *The IES Journal Part A: Civil & Structural Engineering*. Taylor & Francis, 3(4), pp. 235–243.

Wei, J., Wang, C.-G., Wei, X., Mu, X., He, X.-Y., Dong, J.-H. and Ke, W. (2019) ‘Corrosion evolution of steel reinforced concrete under simulated tidal and immersion zones of marine environment’, *Acta Metallurgica Sinica (English Letters)*. Springer, 32(7), pp. 900–912.

Yalciner, H., Eren, O. and Sensoy, S. (2012) ‘An experimental study on the bond strength between reinforcement bars and concrete as a function of concrete cover, strength and corrosion level’, *Cement and Concrete Research*. Elsevier, 42(5), pp. 643–655.

Yalçın, H. and Koç, T. (2004) ‘Betonarme Demirlerinin Korozyonu ve Önlenmesi’, in. CMS.

Yi, Y., Zhu, D., Guo, S., Zhang, Z. and Shi, C. (2020) ‘A review on the deterioration and approaches to enhance the durability of concrete in the marine environment’, *Cement and Concrete Composites*. Elsevier, p. 103695.

Yilmaz, S. and Ozmen, H. B. (2016) *High performance concrete technology and applications*. BoD–Books on Demand.

Ylmén, R. (2013) *Early Hydration of Portland Cement*. Chalmers University of Technology.

Yu, X.-H., Qian, K., Lu, D.-G. and Li, B. (2017) ‘Progressive collapse behavior of aging reinforced concrete structures considering corrosion effects’, *Journal of Performance of Constructed Facilities*. American Society of Civil Engineers, 31(4), p. 4017009.

Zhang, Z., Zhang, W., Zhai, Z. and Chen, Q. (2007) ‘Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part 2—Comparison with Experimental Data from Literature’, *Hvac&r Research*, 13, pp. 871–886.

Živica, V. (2003) ‘Influence of w/c ratio on rate of chloride induced corrosion of steel reinforcement and its dependence on ambient temperature’, *Bulletin of Materials Science*. Springer, 26(5), pp. 471–475.