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Modelling the impact of climat change on a novel Irish Concrete Bridge

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Abstract

This paper assesses the impact of climate change on the novel repair of Ferrycarrig Bridge, a reinforced concrete (RC) marine bridge on Ireland's south-east coast. Five unique repair solutions were applied to the seven crosshead beams on Ferrycarrig Bridge during works in 2007. The two solutions under examination herein involved replacement of the concrete around the sides of the crosshead beams with either 100% Ordinary Portland Cement (OPC) concrete or concrete in which 60% of the cement was made up of Ground Granulated Blast Furnace Slag (GGBS) and 40% OPC. Changes to environmental policy mean that the use of GGBS within RC structures is becoming increasingly popular. Thus, understanding its performance over time is imperative. Chloride ingress and concrete crack modelling are completed herein to compare how climate change will affect the service life of the crosshead beams in which the OPC and OPC+GGBS concrete solutions are applied. The results stemming from this modelling are used to quantify the impact of reinforcement corrosion and concrete deterioration on the crosshead beams' structural capacity. The findings indicate that without consideration of climate change, the OPC+GGBS concrete solution utilised in Ferrycarrig Bridge is 4.75 times more resistant to severe cracking caused by chloride-induced reinforcement corrosion than the OPC concrete solution. However, the durability of the OPC+GGBS concrete is more adversely affected by climate change with a lifetime reduction of 15.8% for the worst climate scenario as compared with a reduction of just 2.7% for the OPC concrete, reducing relative merit from 4.75 to 4.11.

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1. Introduction

The National Oceanic and Atmospheric Association (2015) note that global average temperatures on Earth have been increasing at an average rate of 0.17ºC per decade since 1970. As a result, Seo (2017) notes that the Paris Agreement's central objective is to hold the global average temperature rise to "well below 2ºC above pre-industrial levels" and to pursue efforts to limit this increase to 1.5ºC. However, a recent report from the Intergovernmental Panel on Climate Change (IPCC) (2021) notes that the global surface temperature averaged over 2081-2100 is very likely to be higher than that between 1850 and 1900 by 1.0ºC to 1.8ºC under the very low Greenhouse Gas (GHG) emissions scenario and by 2.1ºC to 3.5ºC in the intermediate scenario. These environmental changes may have a detrimental impact on our vital infrastructure. The deterioration rate of infrastructure depends not only on the construction processes utilised and the composition of the materials used but also on the surrounding environment. Changes to environmental conditions as a result of global warming may therefore cause an acceleration of the deterioration processes affecting the performance, safety and serviceability of concrete infrastructure worldwide. For instance, Stewart et al. (2011) found that corrosion rates may increase by 15% for a 2ºC temperature rise.

Suluguru et al. (2018) note that over ten billion tonnes of concrete is produced worldwide each year, making it the most utilised construction material in the world. Guo et al. (2020) therefore note that it is of great importance that climate change be involved into the durability, maintenance and design of RC structures and that an understanding its performance over time be gained. Without consideration for global warming, Bastidas-Arteaga et al. (2013) note that concrete infrastructure is already subject to processes that affect its performance over time. For example, chloride ingress and carbonation negatively impact the service life of RC structures, with Bastidas-Arteaga (2018) showing that global warming can cause lifetime reduction of 7% for a reinforced concrete bridge girder. It is thus important that climate change adaptation measures for RC structures be considered when designing and constructing new infrastructure.

One such adaptation measure is the use of Ground Granulated Blast Furnace Slag (GGBS) which has become an increasingly popular replacement material for Ordinary Portland Cement (OPC) due to its increased resistance to the undesirable process of chloride ingress. Ryan and O'Connor (2014) have shown that concrete containing 60% GGBS can result in the time to corrosion being 2.9 times longer than that of concrete containing 100% OPC. Moreover, as GGBS is a by-product of the iron and steel-making industries, it helps in the reduction of GHG emissions associated with the construction industry by partially replacing the energy intensive OPC content. Substitution rates vary depending on the particular SCM (e.g. 3-80% for GGBS), resulting in varying levels of emission reductions. However, Scrivener et al. (2016) have estimated that increasing the average substitution rate to 40% could result in an annual reduction of up to 400 million tons of CO_2 emissions. As such, the use of OPC alternatives (ternary cements) is now promoted through EN127-1 (European Standard for common cements).

While it has been established that using GGBS as a partial substitute for OPC improves the resistance of concrete structures against chloride ingress whilst simultaneously reducing the carbon footprint of the construction industry, the impact of climate change on such a material has been subject to limited research. Given that the use of ternary cements is now being promoted through European cement standards, gaining in depth knowledge of their performance in terms of durability and structural capacity over a range of potential future climate scenarios is crucial. As outlined above, numerous researchers have considered the impact of global warming on the performance of traditional OPC concrete with analysis showing that the increasing severity of climate change results in greater lifetime reductions for RC structures. However, limited research on the performance of SCMs when subjected to climate change exists.

Ferrycarrig Bridge, on the south-east coast of Ireland provides an opportunity to overcome this lack of knowledge. Ferrycarrig Bridge is a 126m long RC structure consisting of 8 equal spans and was constructed in 1980. The bridge was repaired in 2007 following the discovery of extensive cracking during a 2002 inspection. Although the damage was not caused by reinforcement corrosion, Transport Infrastructure Ireland (formerly the National Roads Authority of Ireland) elected to use five unique repair solutions on the bridge's seven crosshead beams. This has provided the opportunity to study the worldwide problem of reinforcement corrosion in an Irish marine environment. The five solutions applied are outlined in detail by Ryan and O'Connor (2014) but namely, they are; (a) CEM I: OPC, (b) OPC with silane treatment, (c) OPC with corrosion inhibitors, (d) OPC with 60% GGBS as partial replacement (OPC+GGBS) and (e) OPC with 70mm cover rather than 50mm. Ryan and O'Connor (2014) investigated the resistance of each repair solution against chloride ingress and found that the solution applied to crosshead beams 4 and 6 (OPC+GGBS) exhibited the greatest marine durability with a relative performance of 2.9 times greater than the OPC solution. Furthermore, Ryan and O'Connor (2013) have shown that the relative merit of OPC+GGBS improves with increasing probability of corrosion initiation due to the time dependent nature of the material. However, the studies by Ryan and O'Connor (2013) (2014) considered how the materials behaved only to the point of corrosion initiation and did not consider the impact of climate change on this behaviour. The impact of corrosion damage to the structural capacity of the crosshead beams was not considered by these researchers. The current research will thus build upon the previous work and compare how these two solutions (OPC and OPC+GGBS) perform over a range of potential future climate scenarios and how climate change will impact on the structural capacity of both sections.

2. Methodology

2.1. Climate Modelling

There is significant uncertainty surrounding the impact of climate change as a result of unknowns relating to societal policies and the response of the earth to global warming. A number of potential future scenarios have been proposed by the IPCC to account for this uncertainty. RCP4.5 and RCP8.5 are used to represent two potential future scenarios in this research. RCP4.5 represents an intermediate scenario, with GHG emissions peaking around 2040 and declining thereafter. RCP8.5 assumes that emissions will continue to rise during the 21st century. This pathway is generally thought of as the basis for the worst-case climate scenario. Air temperature and humidity have been established as the two principal environmental factors impacting on the chloride ingress process. Yoon et al. (2007) note that increasing temperature and humidity may result in changes to the concrete degradation process, as ions become more mobile and salts become more soluble. Therefore, the current study considers how both air temperature and relative humidity vary as a result of climate change and the corresponding impact of these changes on the deterioration of concrete containing OPC and OPC+GGBS. Changes in temperature and relative humidity as a result of climate change are modelled using a linear time-variant function in line with the work completed by Bastidas-Arteaga et al. (2011).

2.2. Chloride Ingress Modelling

A number of different approaches have been taken by researchers in the modelling of chloride induced concrete deterioration. Researchers such as Ryan and O'Connor (2014) and Liberati et al. (2014) have taken a simplified approach whereby Fick's second law is used to estimate the chloride concentration at a given time and position. The key drawback of the Fick's law approach is that it does not consider the impact of climatic parameters on the chloride ingress process. This approach is therefore unsuitable for a study quantifying the impact of climate change on the deterioration of RC structures. Moreover, this approach is only valid for a material exposed to a constant concentration of chloride ions at its surface. This approach is therefore not valid for a study involving marine infrastructure exposed to a varying chloride content. The chloride ingress model developed by Bastidas-Arteaga et al. (2011) was thus utilised in this study. This approach accounts for: (1) chloride ion binding capacity; (2) time-dependency of temperature, humidity, and surface chloride concentration; (3) concrete ageing; and (4) chloride transport in unsaturated conditions. This model applies a numerical approach that combines the finite element method with a finite difference scheme to solve the governing equations of chloride penetration in unsaturated concrete. The governing equations for this method are presented herein. Interaction between the following three phenomena is considered: (1) chloride transport, (2) moisture transport and (3) heat transfer. The approach utilised is outlined below in brief.

Chloride ingress by capillary sorption or convection become important mechanisms in partially saturated RC structures. Accordingly, diffusion and convection both contribute to the chloride ingress process. The following equation represents the change in the total chloride concentration, C_{tc}, as a function of the spatial gradient of free chlorides, C_{fc}:

$$\frac{\partial C_{tc}}{\partial t} = div\left(D_c w_e \vec{\nabla}(C_{fc}) \right) + div\left(D_h w_e C_{fc} \vec{\nabla}(h) \right) \tag{1}$$

where t is the time, D_c is the effective chloride diffusion coefficient, w_e is the evaporable water content, C_{fc} is the concentration of free chlorides, D_h is the effective humidity diffusion coefficient, and h is the relative humidity.

Moisture flow within the concrete is modelled using Fick's law and is expressed in terms of pore relative humidity, h:

$$\frac{\partial w_e}{\partial t} = \frac{\partial w_e}{\partial h}\frac{\partial h}{\partial t} = div\left(D_h \vec{\nabla}(h) \right) \tag{2}$$

Fourier's heat conduction law is used to model heat transfer within the concrete structure through application of the energy conversion requirement:

$$\rho_c c_q \frac{\partial T}{\partial t} = div\left(\lambda \vec{\nabla}(T) \right) \tag{3}$$

where ρ_c is the concrete density, c_q is the specific heat capacity of the concrete, λ is the concrete thermal conductivity, and T is the temperature inside the concrete at time t.

The gathering of appropriate parameters for use with this model was crucial to the attainment of accurate results. The reference chloride diffusion coefficient is a coefficient measured at standard conditions (T=23°C and Relative Humidity = 100%). Changes in this parameter have a significant impact on the results obtained from this model. A value of $3x10^{-11}$ m^2s^{-1} was utilised for the OPC concrete in accordance with that applied by Bastidas-Arteaga et al. (2011). As this parameter has not been explicitly measured for concrete composed of 60% GGBS and 40% OPC, a number of assumptions had to be made. A value of $2.18x10^{-11}$ m^2s^{-1} was ultimately utilised. This value was obtained through some extrapolation of apparent chloride diffusion coefficients measured by Ryan and O'Connor (2013) in combination with the value noted by Bastidas-Arteaga et al. (2011) for the OPC concrete.

The methodology developed by Martín-Pérez et al. (2001) has been implemented in this model to solve the system of partial differential equations developed. Application of this model allows for the time to corrosion initiation to be determined for both concrete mixes for all three climate scenarios considered.

2.3. Concrete Crack Modelling

Corrosion-induced cracking is a disruptive and costly failure mechanism that ultimately results in structural distress if not dealt with appropriately. The process of concrete cracking may be separated into two distinct phases: crack initiation and crack propagation. Crack initiation accounts for the time required for corrosion products to fill the porous zone around the steel reinforcement before expansive pressures are induced within the concrete. The current study utilises the model developed by El Maaddawy and Soudki (2007) to predict the time to crack initiation for both the OPC and OPC+GGBS concrete mixes for each climate scenario. This model makes use of Faraday's law to predict the time from corrosion initiation to crack initiation. Crack initiation is characterised by the attainment of 0.05mm wide cracks (i.e. visible to the naked eye).

The time from corrosion initiation to corrosion cracking (T_{cr}) in accordance with the work of El Maaddawy and Soudki (2007) is given by:

$$T_{cr} = \left[\frac{7117.5\left(D + 2\delta_0\right)(1 + \nu + \psi)}{i E_{ef}} \right] \left[\frac{2C f_{ct}}{D} + \frac{2\delta_0 E_{ef}}{(1 + \nu + \psi)\left(D + 2\delta_0\right)} \right] \tag{4}$$

where D is the reinforcing bar diameter (mm), δ_0 is the thickness of the porous zone (mm), v is Poisson's ratio, ψ is a parameter that considers the relationship between the reinforcing bar diameter and the concrete cover C, i is the corrosion rate (μA/cm^2), f_{ct} is the concrete tensile strength (MPa) and E_{ef} is the effective elastic modulus of concrete (MPa).

The current study utilises the model developed by Mullard and Stewart (2011) to model the concrete crack propagation process. This empirical model builds on previous work by other researchers and takes account of concrete confinement as well as the rate of loading of real RC structures in comparison with accelerated corrosion rates. The time to severe cracking referred to herein is the time at which 1.0mm wide cracks appear in the concrete.

Concrete spalling and delamination are undesirable phenomena that follow the concrete cracking process. Spalls are areas where concrete has broken away from the structure, while delamination refers to the failure mode by which the concrete fractures into layers. As concrete spalling and delamination occur, the cross-sectional area of an RC member is reduced, having a significant impact on the member's load-bearing capacity.

Vu and Stewart (2000) and Rodriguez et al. (1997) consider that once cracking and spalling have occurred that the cover concrete is no longer effective in supporting any load. Therefore, in the current research, concrete cover that is "severely cracked" (i.e. 1.0mm wide cracks) is deemed ineffective and will not contribute to the structural resistance of the beam. Another phenomenon of structural deterioration considered by researchers is the reduction in reinforcing bar diameter. This is the most widely considered damage mechanism by researchers in their assessment of reduced structural capacity. Faraday's law is frequently used by researchers such as Bastidas-Arteaga et al. (2013) to determine the reduction in reinforcement bar diameter as a result of corrosion and was used to determine the loss in reinforcement bar diameter in this study:

$$d_u(t) = d_0 - 0.0232 \int_{t_{ini}}^{t} i_{corr}(t)\, dt \tag{5}$$

where $d_u(t)$ is the residual bar diameter (mm), d_0 is the original bar diameter (mm) and $i_{corr}(t)$ is the corrosion rate at time t (μA/cm^2).

In order to assess the structural capacity of the crosshead beams, three different cross-sections were analysed. These sections were: (A) Original section - 2008, (B) Damaged OPC section - 2108 and (C) Damaged GGBS section - 2108. The damaged beams have been considered at the end of their 100-year design life. Modelling these three sections allows for the original structural capacity of the crosshead beams to be compared with those that have been damaged by chloride induced corrosion. Figure 1 below shows the three sections that were modelled.

2.4. Application to Ferrycarrig Bridge

While the methodology described above is applicable to any RC marine structure subject to the effects of chloride ingress, this research focused on its application to Ferrycarrig Bridge on the south-east coast of Ireland. Of great importance in obtaining reliable results was the use of accurate climate change projections. Nolan and Flanagan (2020) have evaluated how climate change is likely to impact the future climate of Ireland on behalf of the Irish Environmental Protection Agency. The method of high-resolution regional climate modelling was utilised for this purpose. Temperature and relative humidity data from Johnstown Castle weather station has been utilised in this research as this is the closest weather station to Ferrycarrig Bridge. Data from 2008 (year of bridge repair completion) is treated as base year data with both temperature and relative humidity varying thereafter. The mean air temperatures for the middle of the current century (2050) are 9.85°C, 10.41°C and 10.61°C for the "No Climate Change" scenario, RCP4.5 and RCP8.5 respectively. The corresponding mean air temperatures for the end of the current century (2100) are 9.85°C, 10.63°C and 11.32°C for the "No Climate Change" scenario, RCP4.5 and RCP8.5 respectively.

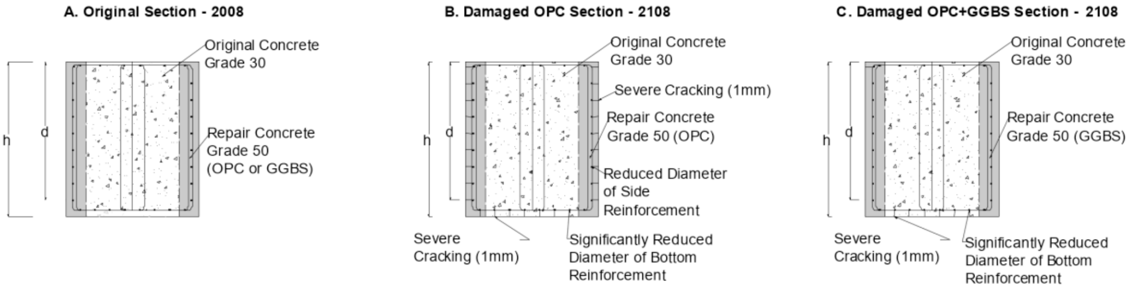

Fig. 1. Cross-sections modelled in structural analysis

3. Results and Discussion

3.1. Chloride Ingress

The left side of Table 1 presents the time to corrosion initiation for each concrete mix for the three climate scenarios considered. The relative merit of OPC+GGBS over OPC is also presented, with a decreasing merit associated with increased climate change severity noted. These relative merit values have been determined by dividing the time to corrosion for OPC+GGBS by the value for OPC for each respective climate scenario. It is noted that the exposure time before corrosion initiation means that climate change may only have a limited impact on the OPC concrete. The longer time to corrosion initiation experienced by the OPC+GGBS results in a more significant impact from climate change, thus explaining the decreasing relative merit. It is likely that only modest temperature and relative humidity changes will occur in the 30 years following 2008. This explains why climate change only contributes to a small decrease in the structure's life for the OPC solution applied to Ferrycarrig Bridge. Further simulations were completed to verify this theory. Rather than starting simulations in 2008, they were commenced in the year 2050. The yearly variations in both temperature and relative humidity as projected by Nolan and Flanagan (2020) are greater between 2050 and 2100 than between 2008 and 2050. These simulations resulted in a 4.24% decrease in time to corrosion for RCP8.5, as compared to the 3.28% decrease noted above. This highlights that the limited severity of climate change is also contributing to the small service life decreases noted for OPC. This trend was noted by Stewart et al. (2011) and Bastidas-Arteaga et al. (2010) and was primarily attributed to the fact that without consideration for the effects of global warming, RC structures subject to maritime conditions are already high-risk in terms of corrosion initiation.

Table 1. Time to corrosion initiation (left) and time to severe crack (right) (years)

	Corrosion Initiation			Severe Cracking		
	No Climate Change	RCP4.5	RCP8.5	No Climate Change	RCP4.5	RCP8.5
OPC	33.89	32.78	32.78	40.38	40.33	39.21
GGBS	187.50	166.67	156.67	191.89	171.40	161.54
Relative Merit	5.54	5.08	4.78	4.75	4.36	4.11

3.2. Concrete Cracking

The right side of Table 1 presents the time to severe cracking for both concrete types for the three climate scenarios considered. It is noted that the attainment of 1.0mm wide cracks occurs significantly later in the OPC+GGBS concrete than the OPC concrete. This is primarily due to the increased time to corrosion initiation discussed in section 3.1.

Both cracking models utilised only consider physical parameters of the structure in question. As such, the type of concrete (OPC or OPC+GGBS) did not influence the results from either model. However, the differences between the chloride ingress resistance of each concrete mix resulted in different corrosion rates as a result of the differing air temperatures experienced by each mix in each different climate scenario. From the table above it is noted that the decrease in time to the attainment of severe cracking with increasing climate change magnitude is more appreciable for OPC+GGBS than for OPC. For example, RCP8.5 causes a 15.8% decrease as compared with the "No Climate Change" scenario for OPC+GGBS. On the other hand, a reduction of just 2.7% is noted for OPC. As the time to severe cracking is dominated by the corrosion initiation process, the greater time to corrosion initiation for OPC+GGBS is recognised as the principal cause of this phenomenon. Similar to the chloride ingress results, the relative merit of the OPC+GGBS mix over the OPC mix decreases with increasing climate change severity.

3.3. Structural Analysis

Table 2 presents results from the structural analysis work completed during this research. As previously outlined, the structural capacity of three different cross-sections has been assessed. Section A represents the condition of the crosshead beams following the 2007 repair while Section B and Section C represent the condition of the crosshead beams at the end of their design life for both the OPC and OPC+GGBS respectively. A 100 year design life has been assumed, resulting in the end of design life occurring in 2108 given that repairs were concluded in 2008. The damage resulting from exposure to RCP8.5 has been considered here as it results in a more significant reduction in strength as compared to the other climate scenarios considered. The mid-span cross-sections of the beams have been modelled given that this is the location of greatest sagging moment along the beams.

As expected, the structural capacity of the original section exceeds that of both damaged sections. It is evident from the results below that the GGBS section significantly outperforms the OPC section. In fact, corrosion has not initiated in the side bars (surrounded by OPC+GGBS) in section C. The only damage impacting the structural capacity of this section is the corrosion of the bottom bars (surrounded by OPC). Section B on the other hand has been significantly damaged by the end of its design life with all bars around the sides and bottom of the section becoming damaged due to corrosion.

Table 2. Failure moment comparison

	Failure Moment (kNm)	% Difference
A. Original Section – 2008	3258.8	-
B. Damaged OPC Section – 2108	2788.4	14.5
C. Damaged GGBS Section - 2108	3096.7	4.9

4. Conclusion

This research presents an assessment of the impact of climate change on two of the repair solutions applied to the crosshead beams of Ferrycarrig Bridge during its 2007 repair. The lack of research concerning the relative impact of climate change on concrete containing supplementary cementing materials was recognised by the authors prior to the completion of this study. The work presented in this paper focuses on Ferrycarrig Bridge in Ireland. However, the methodology applied and results obtained are applicable to RC marine structures in general. Results from the modelling completed during this research have revealed the following:

Without consideration for climate change, the OPC+GGBS concrete is 4.75 times more resistant to severe cracking caused by chloride-induced corrosion than OPC concrete. The durability of OPC+GGBS concrete is more adversely affected by climate change than OPC concrete with a lifetime reduction of 15.8% associated with the worst-case climate change scenario considered. The associated reduction for OPC concrete is just 2.7%. The lack of durability of OPC concrete in a marine environment means that it is not appreciably impacted by the choice of climate change scenario, with both scenarios considered here resulting in a reduction of 1.11 years in the time to severe cracking. It is also noted that the structural capacity of the OPC+GGBS section significantly outperforms the OPC section at the end their 100 year design lives when failure moment is utilised as the assessment criterion.

It may therefore be concluded that the use of Ground Granulated Blast Furnace Slag as a partial replacement for Ordinary Portland Cement within concrete significantly improves the durability of RC structures within a marine environment, even after its relative benefit is reduced by climate change. The use of GGBS should therefore still be prioritised in future RC infrastructure projects in chloride rich environments. It is noted however that the deign life of the OPC+GGBS concrete structures may be notably reduced by climate change effects.

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