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Evaluating the strength of corroded tunnel lining under limiting corrosion conditions

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ABSTRACT

Reinforced concrete strength (RCS) is one of the most important parameters in tunnel lining, which ensures a safe, reliable service life. Chloride and carbon penetration are the most common durability problems in tunnels and significantly affect the sustainability of RCS. Using experimental tests, a procedure was developed to evaluate the RCS of tunnel linings under corrosion conditions. The corrosion conditions were classified into three levels: light, medium and heavy, which represent the duration of the corrosion acceleration technique used for 4, 6 and 8 days, respectively. The variables that were studied in the experiments were the corrosion rate, steel bar diameter, concrete cover and concrete strength. Axial loads and bending moments about the longitudinal axis of the specimens were applied. The purpose of the experimental design was to study stress conditions in tunnel linings. Cracks were observed during the time-based bending–compression test when loads were applied accordingly. The test results show that the overall metal loss, at a constant corrosion index, depends on the diameter of the steel bars. Furthermore, the effect of the concrete cover thickness on the loss of strength was found to be significant. The group of specimens, (35-mm and 50-mm concrete covers with 10-mm diameter bars) showed bearing capacity losses of 32% and 35% due to corrosion rates (J_r) of 24% and 28%, respectively. It was also found that a linear relationship exists between the corrosion rate and residual strength. At a constant corrosion index, the concrete strength C30 had a significant effect on the RCS compared with the concrete strength C25. Based on the theoretical and experimental results, the evaluation procedure includes three primary steps: bond strength, cracking and specimen performance. The test procedure is a simple method to evaluate the tunnel lining strength for corrosion resistance by designing specimens with similar tunnel lining conditions.

1. Introduction

Many reinforced concrete (RC) tunnels around the world are deteriorating as they age. Corrosion is one of the primary reasons for steel area loss, which can be described by a linear function (material loss). This type of corrosion reduces the material strength (Ting and Nowak, 1991).

In general, the objective of a design is to "achieve a suitable criterion to make the structure which is being designed stable during its intended life". To construct a durable and reliable concrete structure (CS), it is necessary that the design is durable and can ensure the required service life (FIB (CEB-FIP), 1999).

Durability is the capability of maintaining the serviceability of a structure over a specified period of time. Structures contain elements that can last more than 100 years, such as tunnel linings, foundations, walls, and floor slabs, whereas other components require frequent maintenance. The durability of a structure refers to its resistance against environmental effects (Mays, 1992).

Al-Sulaimani et al. (1990) studied the corrosion of reinforcement and bond deterioration of bending beams, which were designed to fail during tests. These beams, each with dimensions of 150 mm × 150 mm × 1000 mm, were reinforced with two 10-mm top bars, two 12-mm bottom bars and 6-mm links at 50-mm interval. The bottom bars were corroded by applying a constant current density of 2 mA/cm^2. The shear span during the loading test was 300 mm. It was observed that the bond strength increased as the amount of corrosion increased up to a certain level but then progressively decreased when the corrosion level became extremely high. It was also observed that the reduction in the load carrying capacity was affected by the reduction in the bar cross-sectional area. Moreover, it was concluded that a corrosion level up to 1.5% does not affect the ultimate load in flexure; however, at a 4.5% corrosion level, the ultimate load is reduced by approximately 12% because of the reduction in the bar diameters.

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Table 1
Properties of reinforcement steel bars (ASTM A36).

Steel bar type	*D* (mm)	Yield stress (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus ($\times 10^5$ N/mm^2)
HRB335(20MnSI)	10–14	305–312	365–370	2.0–2.1

Annual increases in bond strength can be hindered by the formation of a firm corrosion layer, which also increases the confinement around the steel bar that allows bond strength increases, which may decrease dramatically after longitudinal corrosion cracks develop. As a result, this rapid change decreases bond strength (Amleh and Ghosh, 2006).

Wang (2008) studied the effects of corrosion on a harbor tunnel in China. Chloride ions are regarded as the primary reason for corrosion in coastal area tunnels. The research findings demonstrated that the decrease in the carrying capacity of the tunnel lining structure that leads to tunnel damage is due to corrosion. The study analyzed the effect of chloride ion diffusion on concrete with such variables as the chloride ion diffusion coefficient for concrete, critical chloride ion concentration, and concrete cover thickness. The model was based on the concrete cracking stress as a result of the corrosion rate, probability distribution and reliability analysis. Using elasticity theory, the model could analyze the expansion force, which increased and caused cracks, which corroded the RC.

Gulikers (2003) focused on special aspects related to the conditional assessment of passive steel reinforcement in tunnel structures. The electrochemical behavior of embedded passive steel reinforcement in concrete with restricted one-sided access to oxygen was studied using a simplified numerical model. The adopted approach was applied to a reinforcement arrangement used in tunnel linings. Numerical simulation was performed for a wide range of oxygen diffusion coefficients, DOx, fixed values of the geometrical arrangement and electrochemical characteristics. The numerical analysis clearly demonstrated that the steady-state potential of passive steel embedded in saturated water reacts sensitively in the presence of oxygen.

Chen et al. (2010) studied the subsea tunnel between Qingdao and Jiaozhou and selected the environment and load mechanisms as fundamental parameters that describe tunnel behavior. Moreover, the authors measured the durability of concrete lining under the combined action of a compressive load and carbon penetration. A critical compressive load test, accelerated carbonation test, natural carbonation test and capillary suction test were performed. The results showed that the critical compressive load can accelerate carbon penetration. Due to the combined action of the critical compressive load and carbon penetration, the durability of the concrete lining decreased.

Tian et al. (2012) performed a fast freeze–thaw cycle test, accelerated carbonation test, and natural carbonation test. The durability of concrete lining under the combined action of a freeze–thaw cycle and carbonation was tested. The results showed that the freeze–thaw cycle apparently accelerated carbon penetration in concrete. The decrease in the durability of concrete lining was caused by the combined effect of the freeze–thaw cycle and carbon penetration. Furthermore, the carbonation depth in the concrete lining was modeled. The results showed that the depth exceeds the actual thickness of the RC lining.

Sun Fu (2007) studied the service life of the Xiang'an Tunnel based on theoretical and laboratory experiments, where it was concluded that the main factors affecting durability are the tunnel depth, service life under safe conditions, chloride diffusion coefficient, electrochemical corrosion and eccentric cylinder model with rapid corrosion. The results showed that these characteristics were better able to predict the actual life of a tunnel lining.

According to structure performance requirements, there are four criteria used to predict and assess the service life of a structure, which are related to the erosion of carbonation and the effect of chloride ions: (1) cracking due to rust expansion, (2) crack width, (3) steel bar corrosion limitation, and (4) ultimate bearing capacity (Oh et al., 2009).

Tunnels are regarded as unique structures because they are surrounded by rock masses that can be subjected to different environmental conditions. A tunnel lining is a complex element in a

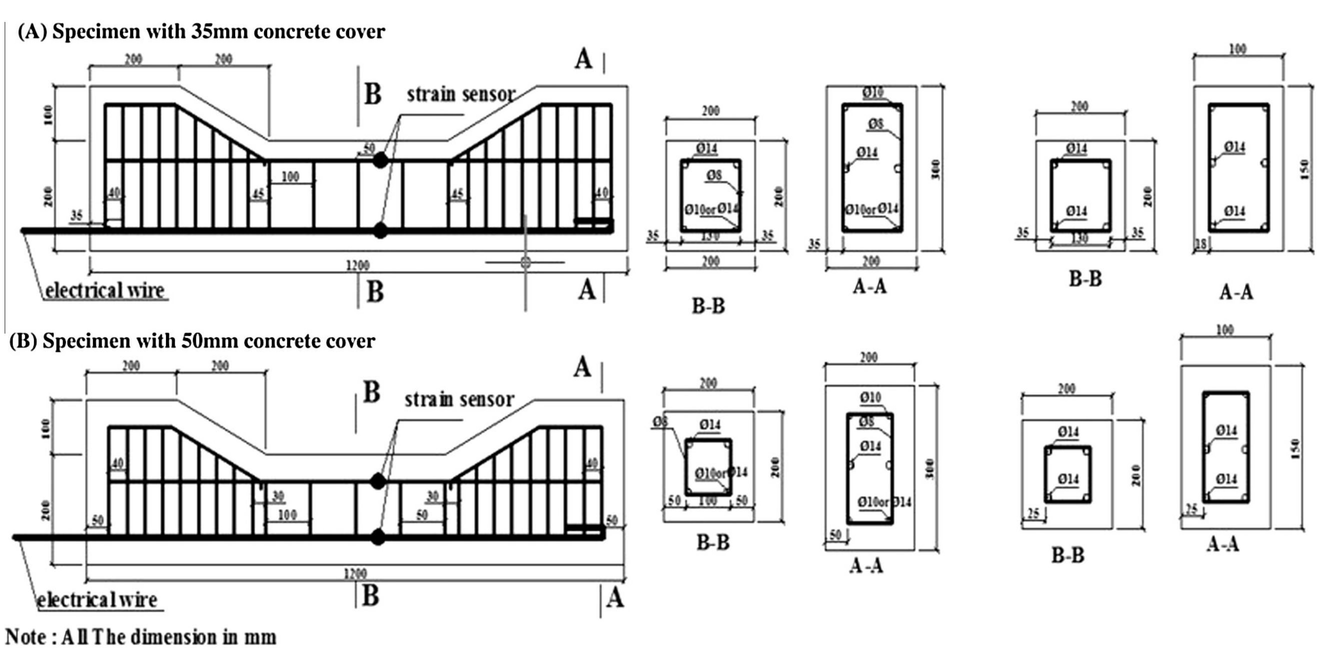

Fig. 1. Details of RC specimens.