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Durability Design of Segmental Linings for Intended Service Life of Tunnels

M. Bakhshi and V. Nasri
AECOM, New York, USA

ABSTRACT

In one-pass lining systems, the durability of tunnel structure is directly related to durability of concrete segments acting as both the initial support and the tunnel final lining. In this paper, most-frequent degradation mechanisms of concrete linings are discussed including chloride- and carbonation- induced corrosions, sulfate, acid and freeze-and-thaw attacks, and alkali-aggregate reactions. Mitigation method for each specific degradation mechanism is explained. A durability factor specific to railway and subway tunnel known as stray current corrosion is presented. Mitigation methods for this specific corrosion together with coupling effects with other conventional damage mechanisms are explained. Prescriptive approaches for durability design based on major codes and standards are explained and comparison is made between these methods. Exposure classes as the main inputs to the prescriptive approaches are elaborated and requirements specified by the codes and standards are presented and analyzed. The need for moving from prescriptive approach to performance-based for tunnel segmental lining is demonstrated and future studies are discussed.

Keywords: Corrosion, Lining, Segment, Service Life, Stray Current, Tunnel.

1.0 INTRODUCTION

Tunnels as important underground structures are typically designed for a service life of more than 100 years. Mechanized tunneling method with Tunnel Boring Machines (TBMs), as the most common excavation method, is often associated with continuous installation of one-pass precast concrete segments in the form of rings behind TBM cutterhead. In these tunnels, durability of tunnel is directly related to durability of concrete segments acting as both the initial support and the tunnel final lining. In this paper, most-frequent degradation mechanisms of concrete linings are briefly discussed. This includes corrosion of reinforcement by chloride attack and carbonation, as well as sulfate, and acid attacks as major deterioration processes caused by external agents. Alkali-aggregate reactions caused by internal chemical reactions and frost attack and freeze-and-thaw damages are also explained. Stray current-induced corrosion as one major durability concern specific to railway and subway tunnel linings is discussed. Mitigation methods for stray current corrosion including use of FRC segments are presented and durability of segments under coupling effects of stray current with other conventional degradation factors are explained. Prescriptive approach for durability design based on European standard (EN 206-1:2013 and Eurocode EN 1992-1-1:2004) and American Code ACI 318 (2014) is explained and comparison is made between two methods. Exposure classes related to environmental actions as the main inputs to both prescriptive approaches are explained separately. Using these two major standards, recommendations made on concrete strength class, maximum water-to-cement (w/c) ratio, minimum cement content, minimum air content and other requirements to ensure typical service life of tunnels are explained.

2.0 CONVENTIONAL DEGRADATION MECHANISMS IN TUNNEL LININGS

Durability issues of bored tunnels need to be addressed from the perspective of degradation mechanisms specific to tunnel segmental linings. Due to different geological environments surrounding tunnels and also specific use of each tunnel, tunnel linings are exposed to different aggressive environments. Possible degradation and damage mechanisms in bored tunnels include corrosion of reinforcement by chloride attack and carbonation, sulfate and acid attacks, alkali-aggregate reactions, and freeze-and-thaw damages. These mechanisms will be briefly discussed.

2.1 Reinforcement Corrosion

<u>Corrosion of reinforcement induced by chloride attack</u>
Chloride-induced corrosion of reinforcement is the main cause of degradation in tunnels lined with reinforced concrete. As shown in Table 1, ITA (1991) report presents thirteen major tunnels that are significantly damaged and corroded due to chloride ingress before 1991 (Abbas, 2014).

Table 1. Damaged/Corroded tunnels due to chloride ingress (ITA, 1991; Abbas, 2014)

Tunnels	Location	Tunnel type	Dia.	Compl. Year
Basel/Olten Hauenstein	Switzerland	Railway	-	1916
Northern Line Old Street to Moorgate	U.K.	Metro	3.5 m	1924
Shimonoseki/ Moji Kanmon	Japan	Railway	-	1944
Mikuni National Route 17	Japan	Highway	7.6 m	1959
Uebonmachi-Nipponbashi	Japan	Railway	10 m	1970
Dubai	U.A.E	Road	3.6 m	1975
Tokyo Underground	Japan	Road	-	1976
Berlin Tunnel Airport	Germany	Road	-	1978
Second Dartford	U.K.	Road	9.6 m	1980
Mass Transit Railway	Hong Kong	Metro	5.6 m	1980
Ahmed Hamdi	Egypt	Road	10.4 m	1980
Stockholm Underground	Sweden	Metro	-	1988

Chloride-induced corrosion is even a greater durability issue specifically in sub-sea, sea outfall, and road/rail tunnels. In sub-sea and outfall tunnels, and tunnels exposed to brackish groundwater, the intrusion of chloride ions present in sweater and salt water into reinforced concrete can cause steel corrosion. In cold region road/rail tunnels, major durability issue is the ingress of chloride ions present in deicing salts sprayed from vehicles during the snow fall. Chloride induced corrosion due to water infiltration initiates from the lining extrados, while corrosion due to de-icing salts sprayed from vehicle tires starts from lining intrados.

Rust as the reaction product has a greater volume than the steel and cause expansion resulting in excessive tensile stresses, cracking, delamination, and spalling in the concrete (Fig. 1).

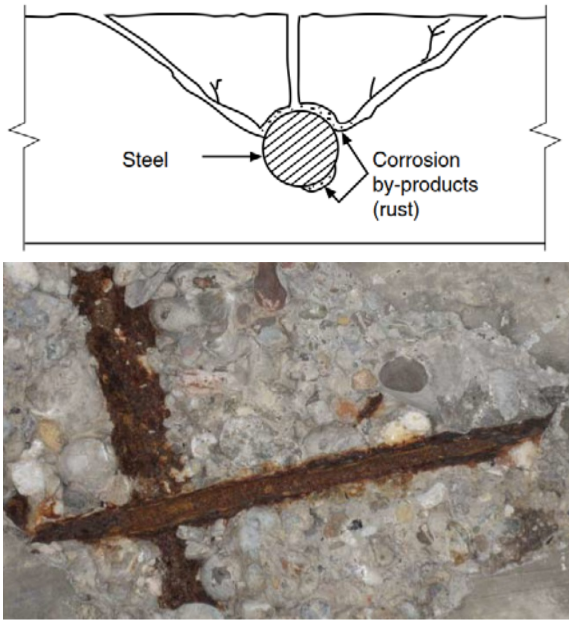

Fig. 1. Loss of reinforcement section and cracks caused by chloride-induced steel corrosion (PCA, 2002; Romer, 2013)

Corrosion of reinforcement induced by carbonation

Carbonation-induced corrosion in general is considered as a minor durability issue in reinforced concrete structures compared to chloride-induced corrosion.

This is mainly due to limited impact area of carbonation and reduced strength zone limited to the extreme outer layer. In bored tunnels, carbonation is unlikely to occur due to the fact that generally extrados of tunnel lining is permanently wet and intrados is constantly dry. It is well-known that high rates of carbonation occur when the relative humidity is maintained between 50% and 75% (PCA, 2002). In low relative humidity, the degree of carbonation is insignificant and above this range, moisture in concrete pores restricts penetration of CO_2 (ACI 201.2R, 2016). In tunnels, only portal areas and entrance zones can maintain a relative humidity in the aforementioned range as lining in such areas is exposed to cyclic wet and dry conditions. Also high rate of carbonation requires elevated atmospheric carbon dioxide (CO_2) levels which is only a case in heavily trafficked road runnels because of CO_2 emission from car exhaust. Therefore, carbonation is a major durability factor in portal areas and entrance zones of heavily trafficked road runnels. Carbonation can also occur in tunnel linings exposed to bicarbonate (HCO_3) ground water which often formed by the reaction of carbon dioxide with water and carbonate bedrocks such as limestone and dolomite.

Following codes and standards, both chloride-induced and carbonation-induced corrosion can be mitigated by using a concrete with low w/c ratio, high compressive strength and high cement content. This in conjunction with considering a sufficient concrete cover over reinforcement provide with a high quality and dense concrete that can delay the initiation time of corrosion also known as propagation time beyond the service life of structure. Further details regarding code recommendations to reduce chloride attack are provided in Section 4. Other effective mitigation methods that are not in the codes include using cements with high amount of C_3A, and addition of corrosion inhibitors to concrete mix.

2.2 Sulfate Attack

Sulfate attack is a major durability issue for concrete structures in contact with soil or water containing deleterious amounts of water-soluble sulfate ions. Tunnels as underground structures, regardless of their specific use, can be exposed to external sulfate attack from common sources such as sulfates of sodium, potassium, calcium, or magnesium found in in the surrounding ground or dissolved in natural ground water. Ancient sedimentary clays and the weathered zone (< 10m) of other geological strata, as well as contaminated grounds and groundwater generally contain significant sulfate concentrations (BTS, 2004). In tunnel linings exposed to such conditions, sulfate attack is a major concrete degradation mechanism.

In tunnels, usually ettringite and gypsum can be produced as a result of a sulfate attack which in turn results in expansion of cement. The reason is that ettringite and gypsum as products have higher volume than reactants (e.g. ettringite volume is ~2.2 times higher). As a result concrete cracks and loses strength.

Note that there is also another type of sulfate attack, known as internal sulfate attack, which is caused by sulfate present in cement and commonly related to delayed ettringite formation (DEF). DEF, however, is observed in high-temperature concrete (>70ºC) when initial concrete temperature are high due to hot aggregates, or in case of mass concrete with excessive heat of hydration. This is never the case for precast concrete tunnel segments. Therefore, it is expected that damages in tunnel linings due to sulfate attack start on segment extrados and at the interface between lining and the ground where sulfate from ground or groundwater can penetrate the concrete.

Sulfate attack can be mitigated by using cements with low amount of C_3A (<8%), use of high content of active mineral components, low w/c ratio and use of blended cements with pozzolans. Codes and standards recommendations to mitigate sulfate attack are based on using a concrete with low w/c ratio, high compressive strength and high cement content. In addition codes require use of sulfate-resisting cements such as type II portland cement (ASTM C150, 2017) or in severe cases type V (ASTM C150, 2017) plus pozzolan or slag cement.

2.3 Acid Attack

Acid attack is a chemical attack that can be a major durability issue when concrete structure is exposed to high concentrations of aggressive acids with high degrees of dissociation. The deterioration of concrete by acids is primarily the result of decomposition of the hydration products of the cementitious paste (ACI 201.2R, 2016). Sulfuric and hydrochloric nitric acids are main inorganic (mineral) acids, and acetic, formic and lactic acid are main organic acids with rapid rate of attack on concrete at ambient temperature. Acids reduce the pH or alkalinity of the concrete, and once the pH reduces to less than 5.5 to 4.5, severe damages are imminent as cement hydration products such as Portlandite (CH, $Ca(OH)_2$) and C-S-H starts to decompose when pH drops to around 12 and 10, respectively (ACI 201.2R, 2016). This is the main reason that no concrete materials have a good resistance to acids.

In tunnels, concrete lining can be attacked from external sources in the surrounding ground and groundwater as well as from internal sources within the tunnels. Concerning external sources, acidic materials may be found on polluted sites used for industrial waste, agricultural applications, animal feed and manure, or from natural sources such as peat soils, clay soils, and alum shales. These geological strata, for example, contain sulfide bearing minerals such as pyrite that produce sulfuric acid on oxidation (ACI 201.2R, 2016). That being said, the rapid deterioration of concrete only normally occurs when concrete is subject to the action of highly mobile acidic water (BTS, 2004). With external acidic groundwater this is rarely the case, since ground waters are not usually highly mobile.

Regarding internal sources for acid attack, flow of acid-containing runoff from outside the tunnel is not a major concern. However, sulfuric acid solutions result from decay of organic matter by bacterial action in sewage and wastewater tunnels is the primary mechanism of degradation in these tunnels. This is due high attack rate of sulfuric acid and continuous movement of the acidic materials inside the tunnel as gravitational flow of sewage in these tunnels is always guaranteed. Note that sewage is not aggressive to concrete buy itself but hydrogen sulfide produced by anaerobic bacteria reaction with the sludge is subsequently oxidized by aerobic bacteria to form sulfuric acid. In addition to decomposition of the cement hydration products, sulfuric acid is particularly aggressive to concrete because the calcium sulfate formed from the acid reaction may drive sulfate attack of adjacent concrete that was unaffected by the initial acid attack (ACI 201.2R, 2016 ; PCA, 2002).

Acid attacks can be mitigated with providing a dense and high quality concrete by lowering w/c ratio and increasing compressive strength and cement content. As presented in Section 4, codes and standards provide specific limits to achieve very high density and relatively impermeable concrete to reduce the damage due to acid attack. Type of cement has an insignificant role on mitigation of acid attacks. When concrete is exposed to very server acid attacks, a surface protection method such as coatings, waterproofing membranes or a sacrificial layer should be considered.

2.4 Alkali-Aggregate Reaction

Alkali-Aggregate Reaction (AAR) is a chemical reaction between reactive aggregates and cement. In most concrete, aggregates are chemically inert or non-reactive. However, AAR as a chemical attack can be a major durability concern when aggregates contain materials that can be reactive with alkali hydroxides in cement phase. The AAR generates expansive products and may result in damaging deformation and cracking of concrete over a period of years. AAR has two main forms of alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). ASR is often major concern compared to ACR as aggregates containing reactive silica are more common (PCA, 2002) whereas aggregates susceptible to ACR are less common and usually unsuitable for use in concrete. Reactive forms of silica can be found in aggregates such as chert, volcanic glass, quartzite, opal, chalcedony, and strained quartz crystals. Damage to concrete only normally occurs when concrete alkali content is high, aggregate contains an alkali-reactive constituent, and concrete is under wet conditions (BTS, 2004). ASR reactions can be summarized as:

Alkalis + Reactive Silica → Gel Reaction Product
Gel Reaction Product + Moisture → Expansion

Because sufficient moisture is needed to promote destructive, PCA (2002) reports the internal relative humidity of 80% as a threshold, below which the alkali-silica reactivity can be virtually stopped.

Concrete tunnel linings are not different from general types of concrete elements as far as alkali-aggregate reaction sources which are internal reactive aggregates. Therefore, degradation mechanism of AAR does not depend on the specific use of each tunnel. Sub-sea tunnels may be more susceptible due to exposure to warm seawater containing dissolved alkalis which may aggravate alkali-silica reactivity. AAR can be mitigated by using inert aggregate, controlling the amount of soluble alkalis in concrete, and using blended cements with pozzolans.

2.5 Frost Attack and Freeze-And-Thaw Damages

Frost attack and freeze-and-thaw damages are durability concerns in concrete structures built in cold regions. Water expands by about 9% when it freezes and as a result, the moisture in concrete capillary pores exerts pressure on the concrete solid skeleton. This leads to development of excessive tensile stresses in the concrete and rupture of cavities. Successive cycles of freeze-thaw can disrupt paste and aggregate and eventually cause significant expansion and cracking, scaling, and crumbling of the concrete (PCA, 2002). Frost damage is considerably accelerated by deicing salts (ACI 201.2R, 2016).

Frost damage at early ages is not noted in precast concrete produced under high quality control conditions. In well-cured concrete with durable aggregate, surface scaling, that is, the loss of paste and mortar from the surface of the concrete is the most common form of frost damage. Therefore, surface scaling is the only frost damage that can possibly occur in precast tunnel segments. Since the increase in volume when water turns to ice is about 9%, more than 90% of capillary pores volume must be filled with water in order for internal stresses to be induced by ice formation (BTS, 2004). Moisture content near saturation level is usually the case for tunnel linings as often times tunnels are built under the water table and concrete lining can be near saturation level. However, along most of tunnel alignment, the temperature rarely falls under the freezing point because tunnel is embedded in the ground. Tunnel entrances, portals and shafts are parts of tunnel system that should be designed for exposure to cycles of freezing and thawing because of saturation level and exposure to freezing temperature.

Freeze–thaw attacks are mitigated by controlling w/c ratio, compressive strength and cement content. However, the most effective method to mitigate the freeze–thaw attacks is controlling the air content in the mix to a minimum value of 4% using air-entraining admixtures. Codes and standards often provide limits for maximum w/c ratio and minimum compressive strength. Certain codes, in addition, require use of frost-resistant aggregate (EN 206-1, 2013).

3.0 STRAY CURRENT CORROSION IN SEGMENTAL TUNNEL LININGS

3.1 Stray Current Corrosion Problem

Stray current corrosion is a type of corrosion specific to rail tunnels where corrosion is caused by traction current resulting in accelerated oxidation of metals and rapid migration of the chloride ions (ITA, 1991). As shown in Fig. 2, inspection of removed segments from tunnels with high conductivity between running rails and lining reinforcement has shown extensive corrosion of the outer reinforcement layer (Buhr *et al.*, 1999).

Electric trains consume at least 20% less power than diesel-powered trains (Kemp, 2007), has much less carbon footprint during operation, and provide sustainable solutions to the public transportation.

Therefore, government agencies around the world are promoting electric trains and all modern railway systems take advantages of railway electrification. Power transmission is provided by overhead catenary wire or a conductor rail also known as third rail. Due to construction limitations and maintenance costs, the running rail connected to nearby substations is often used as traction loop through which the return circuit is made. Therefore, running rails in modern railway systems are used for the purpose of mechanical support and guideway as well as electric conductors in the traction and signaling circuits (Brenna *et al.*, 2010). Running rail has a limited conductivity, and insulation between the rail and the ground is sometimes reduced or constructed poorly form the beginning. This causes a fraction of the traction

Fig. 2. Extensive corrosion of the outer reinforcement layer in Bucharest Metro on segments taken from Gorgului station prior to re-construction and repair of the station (Buhr *et al.*, 1999)

current to leave the rail, leak into the ground and flow back along the running rail on the return path to the traction substation by the earth diversion, which is referred to as stray current. Fig. 3(a) shows a simplified electronic circuit of the electric railway system for modeling the stray current. Based on this simplified model, stray current (I_s) can be determined as follows

$$I_s = \frac{R_R\ I_T}{R_T+R_R+R_S} \quad (1)$$

Where I_T is the train (overhead catenary system) current, R_R is the running rail resistance, R_s is the ground resistance at the traction substation, and R_T is the ground resistance as seen at the train. This equation further presents effect of insulation problem between the rail and ground as reduced R_T or R_s results in increased stray current. When trains run in a lined tunnel, stray current leaks to the tunnel lining and through the concrete reinforcement. This is shown schematically in Fig. 3(b) with a cathode formed at reinforcement where stray current enters the rebar and an anode is formed where stray current leaves the rebar and flows back to substation. Corrosion and severe damage to concrete are anticipated due to hydrogenation and the accumulation of corrosion products. As shown in Fig. 3(c), in cathode, rebar is disengaged from the concrete due to trapped hydrogen isostatic pressure, and in the anode, the rebar is oxidized in contact with electrolytic material, i.e. concrete, and accumulation of corrosion products exerts excessive pressure leading to cracking. Following reaction equations were presented by Wang *et al.* (2018) (see Fig. 3(d)) which depend on the reduction reaction environment.

<u>Cathode:</u>
Hydrogen evolution corrosion

$$4H^{+}+4e^{-} = 2H_2\uparrow \quad (2)$$

(Anaerobic alkaline environment)

$$4H_2O+4e^{-} = 4OH^{-}+2H_2\uparrow \quad (3)$$

(Anaerobic environment)

<u>Anode:</u>
Oxygen absorption corrosion

$$O_2+2H_2O+4e^{-} = 4OH^{-} \quad (4)$$

(Aerobic acidic environment)

Note that this type of corrosion is not limited to the reinforcement in concrete lining and severe corrosion of metal utilities and steel pipelines embedded in the ground has been observed in the proximity of tracks.

3.2 Mitigation Methods for Stray Current Corrosion

Some major mitigation methods for stray current corrosion include: decreasing rail resistance, improving rail to ground insulation using isolated rail fastening systems or pads, keeping the substation as close to the point of maximum current as possible, developing monitoring systems, devices and measurement apparatus (Brenna *et al.*, 2010). All of these measures are effective for reducing the amount of stray current, and therefore are considered as general measures for stray current corrosion mitigation of all metals embedded in the ground or reinforcement in both cast-in-place and precast segmental linings.

Brenna *et al.* (2010) used FEM simulations to study specific case of reinforcement corrosion in precast segments due to stray current. In their simulations, stray current was assumed to be developed by the traction power of surface tramway line in close proximity of tunnel and not from catenary system of subway train inside the tunnel (Fig. 4(a)). While this simulation pertains to a particular subway line under construction in Milan located under already existing and working surface tramway line, results of this study can be extended to general segmentally lined tunnels. Fig. 4(b) shows conduction field in the ground and equipotential surfaces around the segmental ring under tramway track voltage of 8V corresponding to rush hour condition. As shown in Fig. 4(c), the contact between two adjacent segments is a particularly critical aspect of the model. The current leaves the upper segment (segment #6), flows into the ground and then returns within the adjacent segment (segment #5). Parts of reinforcement where current leaves the rebar constitute the anode in which corrosion can initiate depending on the reinforcement-to-ground potential difference. For example, in this research, the difference of potential between reinforcing bars and ground for segment #6 as a result is greater than or close to the maximum value allowed by the standard, EN 50122-2 (2010), indicating possibility of corrosion initiation. Therefore, one can assume that a potential mitigation method for stray current corrosion in

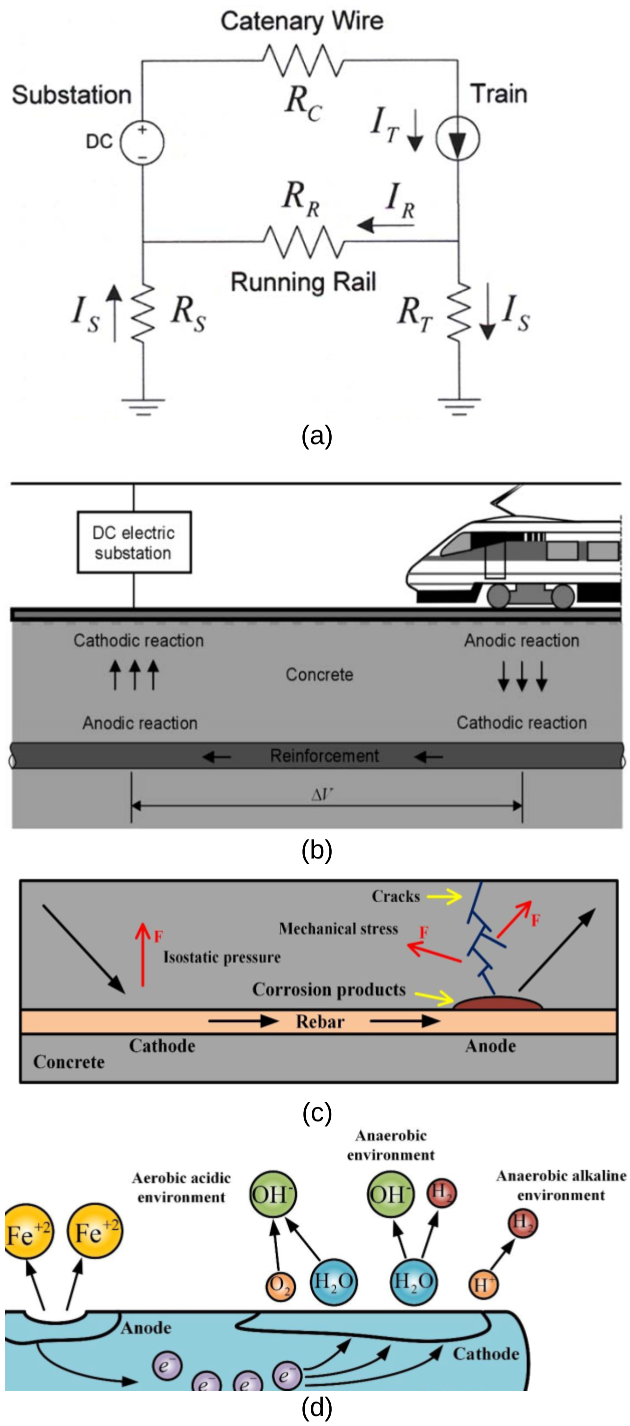

Fig. 3. a) Modeling stray current leakage with simplified electronic circuit of the electric railway system (Niasati and Gholami, 2008); b) Schematics of stray current from a train catenary system picked up by steel reinforcement in concrete (Bertolini *et al.*, 2007), c) corrosive effect of stray current on reinforced concrete (Wang *et al.*, 2018); d) electrochemical reactions in cathode and anode due to stray current (Wang *et al.*, 2018)

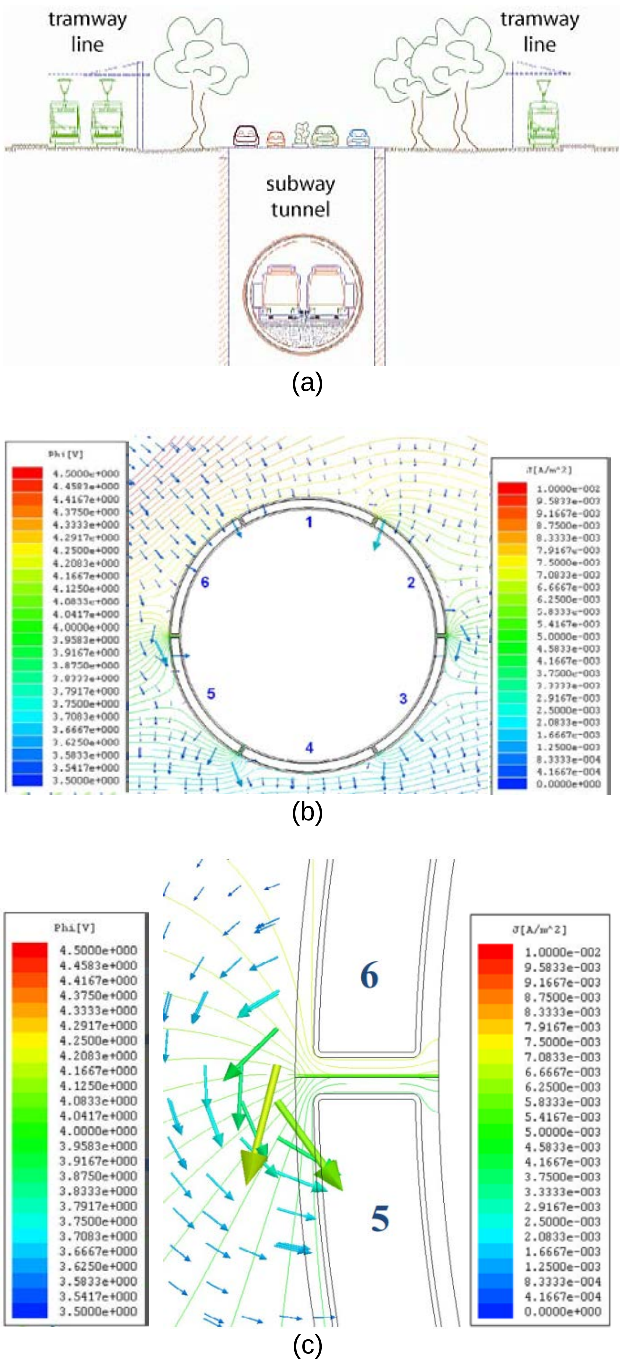

Fig. 4. Brenna *et al.* (2010) FEM simulation: a)Typical tunnel section used for simulation of stray current in the lining due to surface tramway line traction power; b) conduction field in the ground and equipotential surfaces around segmental ring as results of simulation; c) equipotential surfaces and current field in the lining and in the ground near contact area of segments

precast segments is an equipotential connection between reinforcing bars of adjacent segments and of adjacent rings in order to avoid zones with high output current density. As shown in Fig. 5, Dolara *et al.* (2012) modeled this solution using copper plates connecting reinforcement cages of segments together for the same tramway line project studied by Brenna *et al.* (2010). The traces of reinforcing bars in adjacent segments were depicted with red dashed lines connected together with a plate connection. The equipotential connections between the reinforcing bars of all segments in a ring constitute a path with extremely low electrical resistance that allows the current to flow from a segment to the adjacent one without passing into the ground. FEM simulation by

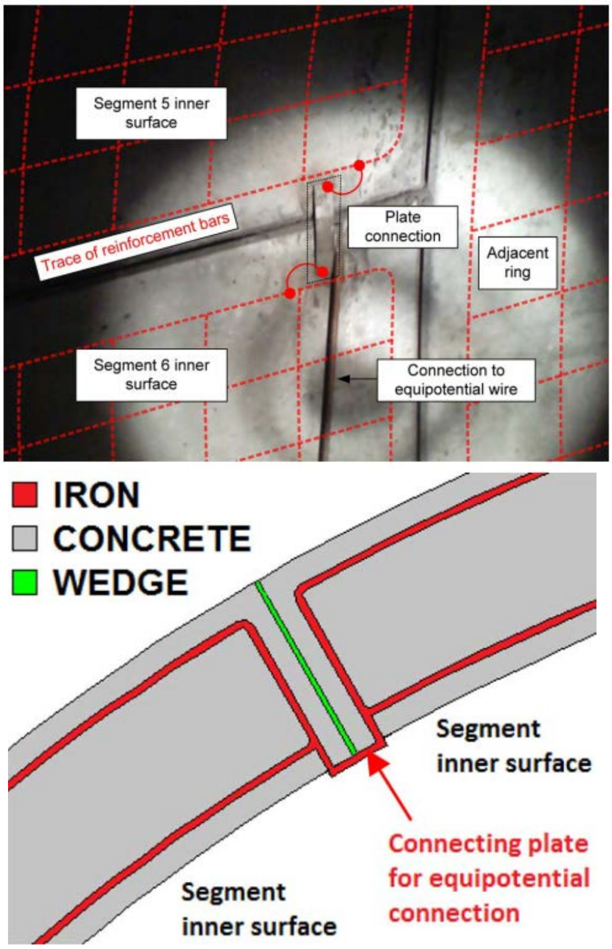

Fig. 5. Stray current mitigation using equipotential connection provided by copper plates/straps connecting reinforcement cages of segments by Dolara *et al.* (2012)

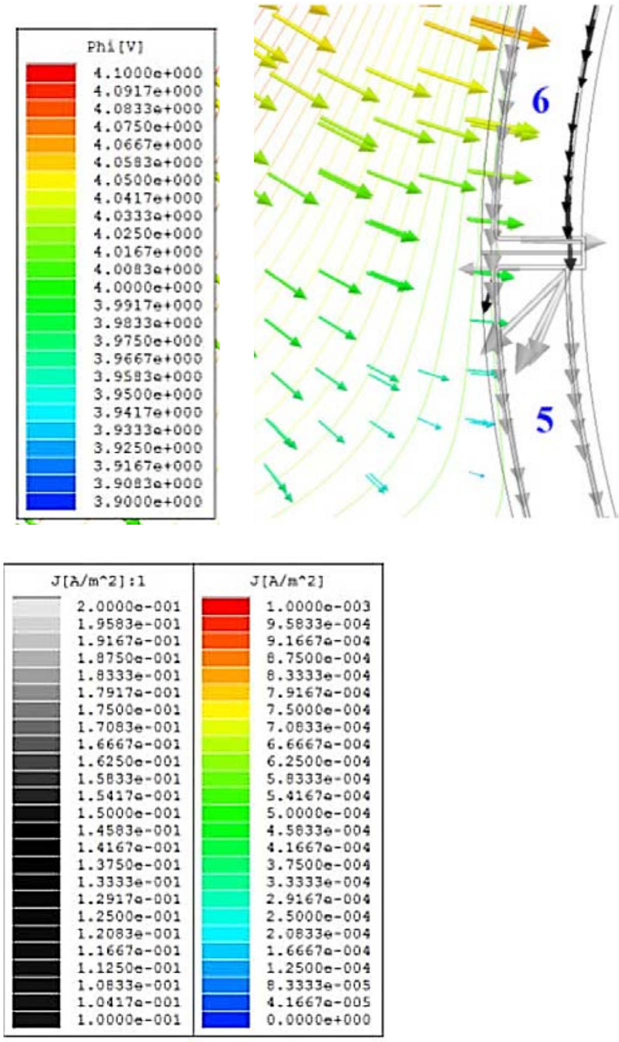

Fig. 6. Effect of connection plates between adjacent segment reinforcement cages on equipotential surfaces and current field near contact area of segments as results of FEM simulation by Dolara *et al.* (2012). Stray current flows from a segment to adjacent one without passing into the ground.

Dolara *et al.* (2012) shows that electrically connected bars behave like a cylindrical metallic shield that allows the stray current to be distributed in an almost uniform way both in entering and leaving the top and the bottom of the tunnel. In this case, the anode is the ring outer surface near the invert and the maximum potential difference between the bars and ground is reduced by more than 15 times. The conclusion is that equipotential connection reduces bar-to-ground voltage to values well below the standard limits (EN 50122-2, 2010) for corrosion initiation, and provides an effective method to prevent stray current corrosion in segments.

Another mitigation method for stray current induced corrosion is use of fiber-reinforced concrete (FRC) segments (Tang, 2017; Solgaard *et al.*, 2013). Results of studies on stray current corrosion of FRC show that steel bars are more likely to pick up current than short steel fibres under same conditions (Edvardsen *et al.*, 2017). This can be due to the fact that the chloride threshold for the corrosion of steel bars in concrete is between 0.15-0.6% by mass of cement (ACI 318, 2014). However, steel fiber-reinforced concrete demonstrates a higher corrosion resistance compared to steel bar reinforced with a chloride threshold level for corrosion at 4% by mass of cement (Tang, 2017). The discontinuous and discrete nature of steel fibres or the length-effect is the main factor to be accounted for this higher corrosion resistance as fibers rarely touch each other and there is no continuous conductive path for stray currents through the concrete (ACI 544.1R-96, 2009).

3.3 Durability under Coupling Multi-Factors

Precast concrete tunnel segments may be subjected to the coupling effects of degradation factors such as carbonation, sulfate and chloride-induce corrosion of steel bars by groundwater and surrounding ground. For subway tunnel, stray current is another major factor that accelerates the steel corrosion. A literature review on experiments conducted on coupled effect of stray current and other degradation factors reveals that the majority of previous works (Srikanth and Sankaranarayanan, 2005; Xiong, 2008; Geng, 2008) has been focused on the material scale level which cannot truly reflect the durability aspects of full-size concrete members (Zhu and Zou, 2012; Geng and Ding, 2010). The study conducted by Li *et al.* (2014), however, pertains to durability of concrete tunnel segments in large-scale and considers various factors of carbonation, sulfate, and chloride penetration coupled with stray current corrosion. Their research consists of groups of samples nearly in the size of segments used in the practice. Fig. 7a shows the dimension of segments and arrangement of reinforcement. Fig. 7b shows schematics of the test setup demonstrating series connections between 6 segment samples in a group to ensure equal current flow of 1A among all segments. Segment reinforcement as anode and stainless steel tube placed in corrosion pools as cathode were connected to DC power supply to simulate the stray current. For simulation of chloride and sulfate penetration from the surrounding ground and groundwater, extrados side of segments was immersed in solutions of 3.5% NaCl, and 3.5% NaCl + 5% Na_2SO_4. Intrados side of the segments was exposed to a relative humidity of 70%±5% and a temperature of 20o±5 representing inside environment of the tunnel. For segment samples studied also for coupled effect of carbonation, intrados side of segments was exposed to a carbonation setup simulating a CO_2 environment with concentration of 20%, temperature of 20o±5, and relative humidity of 70%±5%. Segments are made of concrete with water–cement ratio of 0.28-0.33, compressive strength of 60-70 MPa, and steel bars of 6.5mm diameter with yield and ultimate strengths of 472 and 586 MPa. After casting and standard curing, samples were immersed in corrosion solution for 18 days and were exposed to carbonation setup for 28 days. Free chloride ion was determined from powders collected using drilling at 5mm intervals along the segment thickness. Results show that stray current accelerates the migration of chloride ions, and also changes the penetration distribution of chloride ion in the section. It is well-known that in general corrosion condition and in the absence of stray current, largest concentration of chloride ions is always near the exposure surface to corrosion solution. However, results of Li *et al.* (2014) study reveals that presence of stray current causes the chloride ions to gradually gather to the surface of steel bar, resulting in the largest concentration of chloride ions at the reinforcement level and a parabolic distribution from the extrados side to intrados along the thickness. One major conclusion is that chloride ion concentration is higher for segments immersed in chloride solutions (Cl^-) than the ones immersed in solution with both chloride and sulfate ($Cl^- + SO_4^{2-}$). This can be due to the concrete pores that may be filled by ettringite produced by reaction of SO_4^{2-} ions in the solution with hydration products, resulting in obstruction of channels through which chloride ions migrate. Another argument is that SO_4^{2-} ions firstly react with C_3A producing ettringite while decreasing the opportunity of integration of Cl^- ion and C_3A. As a result it is more likely to be absorbed by C-S-H, altering the combination form of Cl^- ions (Li *et al.*, 2014). Another major outcome is that carbonation depth is only 1-4 mm, leading to a conclusion that carbonation is not a controlling durability factor for concrete segments compared with the chloride and sulfate ions and stray current corrosion. Other results specific to reinforcement include much more significant corrosion of the reinforcement layer near the extrados compared to intrados, and more corrosion damage on stirrups than main transverse reinforcing bars.

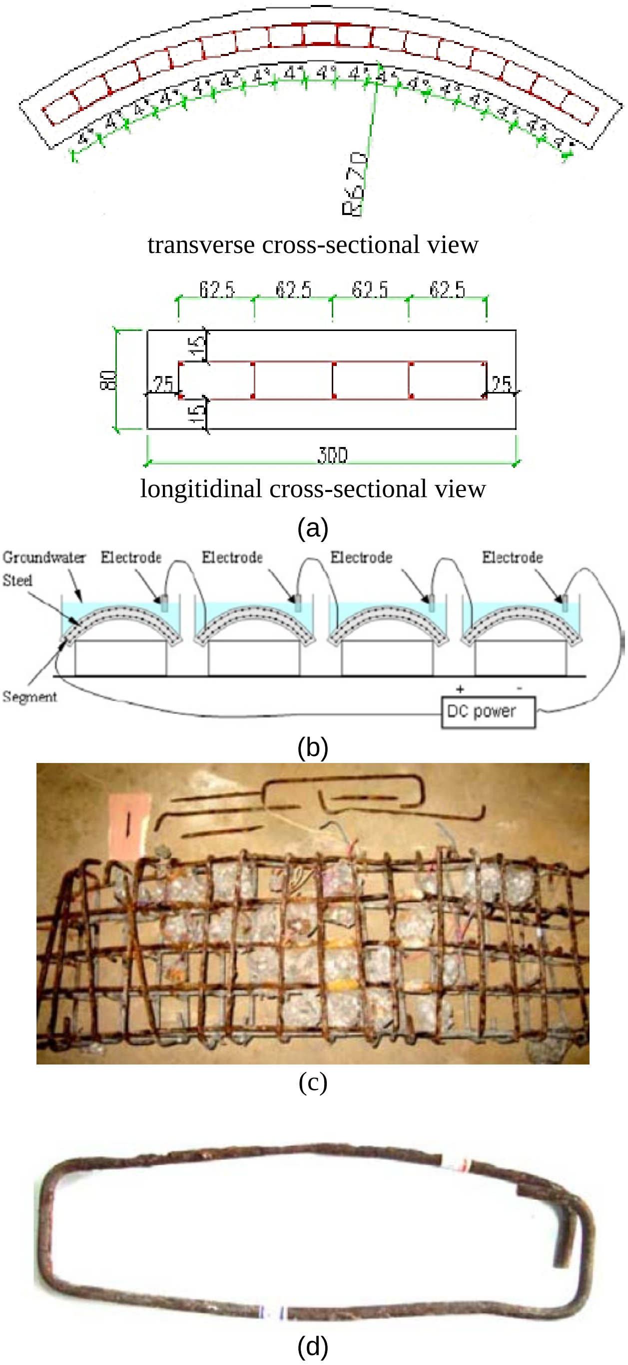

Fig. 7. Li *et al.* (2014) study on stray current coupled with multi degradation factors: a) size and layout of experimental segment samples and reinforcement (in mm); b) schematics of test setup for combined effect of corrosion solution and stray current; c&d) steel bar corrosion in main reinforcement and stirrups

4.0 PRESCRIPTION-BASED APPROACHES

Durability design according to prescriptive approaches is the most-common method in tunnel and concrete industries that are performed in accordance with major national and international structural codes. Such codes specify characteristics of concrete such as concrete strength or maximum w/c ratio based on exposure or environmental classes the concrete element is exposed to. EN 206-1 (2013) in combination with Eurocode EN 1992-1-1 (2004) as one of the world's most well-known codes provide the most comprehensive perspective based specifications for concrete exposed to environmental actions. According to EN 1992-1-1 (2004), main exposure classes are XC for risk of carbonation induced corrosion, XD for risk of chloride-induced corrosion from other sources than sea water, XS for risk of chloride-induced corrosion from sea water, XF for risk of freeze-thaw and frost attack, and XA for chemical attacks. Depending on the severity of exposure, ranges as XC1 to XC4, XD1 to XD3, XS1 to XS3, XF1 to XF4, and XA1 to XA3 are provided, along with description of environment for each sub-class, and informative examples where exposure classes may occur. For specific case of tunnel linings, suggested exposure classes according to Helsing and Mueller (2013) for CO_2 carbonation are XC3 to XC4, for seawater chloride-induced corrosion is XS2 to XS3, for deicing salt chloride-induced corrosion is XD2 to XD3, for frost exposure is XF3 to XF4 and for harmful ions other than chloride (Mg^{2+}, SO_4^{2-}) is XA1 to XA3. It's north worthy to mention that the concrete requirement specified by this standard include the assumption of an intended design service life of 50 years. However, almost all tunnels are designed for a service life of over 100 years. In order to take it into account, Table 4.3N of Eurocode EN 1992-1-1 (2004) can be adopted recommending an increase in exposure class by 2 for all environmental conditions in order to consider the requirement for a service life of 100 years. Main specified requirements by EN 206-1 (2013) and EN 1992-1-1 (2004) corresponding to these exposure classes include maximum w/c ratio, minimum strength class, and minimum cement content. This is due to the fact that density and quality of concrete outer layer (cover) as the main protection layer, is achieved by controlling the maximum water/cement ratio, minimum cement content and may be related to a minimum strength class of concrete (EN 1992-1-1, 2004). Range of specified requirements, and minimum air content for freeze/thaw attack can be found in EN 206-1 (2013), Table F.1. This table also presents other requirement such as aggregate characteristics for XF exposure classes, and sulfate-resisting cement for XA exposure classes. For corrosion protection of steel reinforcement when concrete is exposed to carbonation (XC classes) or chloride ions (XD/XS classes), values of minimum concrete cover required by EN 1992-1-1 (2004), Table 4.4N for S4 structural class should be considered. For extreme classes of XC4 and XD3/XS3 which are usually the case for tunnel lining designed for 100-year service life, minimum required covers are 30 mm and 45 mm, respectively.

American Code ACI 318 (2014) is another well-known and widely-used concrete code in the world that can be used for durability requirements of tunnel segments. ACI 318 (2014) approach, similar to EN 206-1 (2013) and EN 1992-1-1, is also based on exposure categories F, S, W, and C defined in ACI 318 (2014), Table 19.3.1.1, and requirements in Table 19.3.2.1. However, few major differences exist between the American (ACI) and European (EN) codes. First, ACI 318 has an additional exposure category, W, which is defined for durability of concrete in general in contact with water but not exposed to freezing/thawing, chlorides, or sulfates. Second, exposure category C, applies to concrete exposed to all conditions that require protection against corrosion of reinforcement. Therefore, category C in ACI 318 (2014) can be compared to XC, XD/XS exposure classes in EN 206-1 (2013) and EN 1992-1-1 (2004) which provide much more insight into how the specified requirements are set differently as related to the sources of corrosion. Third, ACI 318 (2014) only considers sulfate attack requirements corresponding to category S, while EN 206-1 (2013) and EN 1992-1-1 (2004) cover a wide range of chemical attacks to different types of ions, and acids, not only sulfate. Another major difference is that ACI 318 (2014) does not have any requirements for minimum cement content. Also in contrast to EN 1992-1-1 (2004), for corrosion protection of reinforcement, minimum concrete cover required by ACI 318 (2014) is a function of casting type, i.e. cast-in-place or precast concrete manufactured under plant conditions. For precast segments, ACI 318 (2014) only categorizes the minimum cover based on two exposure classes of exposed or non-exposed to weather or in contract with the ground. Other considerations in ACI 318 (2014) are member types categorized as walls or others, and size of rebars for concrete exposure to weather or in contact with the ground. Since steel bars smaller than metric bar size No. 19 (imperial bar size #6) are commonly used in segments, for all different exposure classes of precast segments, ACI 318 specifies a constant minimum cover of 38 mm (1.5 in). This is in contrast with EN 1992-1-1 (2004) which requires different minimum concrete covers ranging from 10-45 mm based on the sources of corrosion that can be carbonation, chloride ions other than sweater and seawater exposure.

Despite all these differences between ACI and EN approaches, a case example for an extreme exposure class/category, such as concrete exposed to chloride-induced corrosion, can provide some insight into how different the requirement can be between these two codes. For this purpose, requirement of ACI 318 (2014) category C2 is compared with EN class XS3/XD3. ACI would require a maximum w/c ratio of 0.4 and a minimum compressive strength of 35 MPa, while EN would require a maximum w/c ratio of 0.45, a minimum compressive strength of 35 MPa, and a minimum cement content of 340 kg/m3. Concrete cover specified by ACI 318 (2014) as minimum 38 mm (1.5 in) for reinforcement size of No. 19 or smaller (<imperial #6) can be compared with 45 mm required by EN 1992-1-1 (2004). Such example shows that despite all aforementioned differences between two methods, the concrete requirements set forth for concrete would be very similar and most likely would result in a concrete specification with similar if not identical quality.

Prescriptive design methodologies provide similar recommendations in order to achieve a very dense high quality concrete. However, the major flaw of prescriptive apaches is lack of connection between the limiting requirements and main source of degradation mechanisms for each specific type of concrete damage. In contrast, performance-based design approaches despite all challenges related to these methods provides significant benefits to designers by focusing on the specific sources of concrete damages in a project-specific fashion (Swiss Standard SIA 262, 2003). In order to achieve a performance design, rapid, easy, and reliable test methods are needed to assess properties of structural concrete. Future studies are needed to develop a performance-based design approach with reference to different major tunnel segment projects. While this design approach is not discussed in this paper, studies such as Rashidi and Nasri (2012), Sigl *et al.* (2000) and Li *et al.* (2015) provide important new insight into such design method for CSO, subway and sub-sea road tunnels, respectively. Also durability recommendations of national and international tunnel segment guidelines should be analyzed and compared including BSI PAS 8810 (2016), DAUB (2013), AFTES (2005), OVBB (2011), and LTA (2010).

5.0 CONCLUSIONS

Common conventional degradation mechanisms of concrete linings include chloride- and carbonation-induced corrosion, sulfate and acid attacks, alkali-aggregate reactions, and frost attack. All these degradation mechanisms are introduced and mitigation methods are explained. Stray current-induced corrosion as one major unconventional durability concern specific to railway and subway tunnel linings is discussed. Mitigation methods for stray current corrosion including use of FRC segments are discussed and durability of segments under coupling multi-factors of stray current with other conventional degradation mechanisms are explained. Prescriptive approaches for durability design based on major codes and standards are presented and compared. The need for developing a performance-based design approach for tunnel linings is explained. Future studies should include also comparison of current durability recommendations by national and international tunnel guidelines.

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