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Evaluation of Chloride Ion Penetration in Reinforced Concrete Using Rapid Chloride Penetration Test

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Abstract

Chloride ion penetration is one of the major causes of deterioration in reinforced concrete structures. When chloride ions enter through the concrete cover and reach the steel reinforcement, they can damage the protective passive layer around the steel and initiate corrosion. This corrosion further leads to cracking, spalling, loss of bond strength, reduction in steel area, and decrease in the service life of concrete structures. The Rapid Chloride Penetration Test is widely used to evaluate the resistance of concrete against chloride ion penetration by measuring the electrical charge passed through a concrete specimen. The present study focuses on understanding the effect of chloride ion penetration on reinforced concrete and the role of RCPT in assessing concrete durability. The study highlights that lower RCPT values indicate better resistance to chloride ingress and improved durability performance. Therefore, RCPT can be considered an important method for durability-based evaluation of reinforced concrete structures exposed to chloride environments.

Keywords

Chloride ion penetration, Reinforced concrete, Rapid Chloride Penetration Test, RCPT, Corrosion, Durability, Service life, Concrete permeability.

Introduction

Reinforced concrete is widely used in buildings, bridges, marine structures, parking structures, industrial floors, and other civil engineering works because of its strength, durability, and structural efficiency. However, concrete structures exposed to chloride environments often face serious durability problems. Chloride ions may enter concrete through pores, cracks, and capillary channels. When these ions reach the steel reinforcement, they can break the passive protective layer formed around the steel and start corrosion. This process is dangerous because the early stage of chloride attack may not show visible damage, while internal corrosion may already be taking place.

The corrosion caused by chloride penetration affects both the durability and structural performance of reinforced concrete. Corrosion products occupy more volume than the original steel and create internal pressure around the reinforcement. This pressure causes cracking, spalling, bond loss, and reduction in the effective cross-sectional area of steel. As a result, the load-bearing capacity and service life of the structure may decrease. Chloride-induced deterioration is especially common in marine environments, bridge decks, foundations in saline soil, and structures exposed to de-icing salts.

To assess the resistance of concrete against chloride ingress, the Rapid Chloride Penetration Test is commonly used. RCPT measures the total electrical charge passed through a concrete specimen under an applied voltage. A lower charge passed value indicates lower chloride penetrability and better durability performance. Although RCPT does not directly measure natural chloride diffusion, it provides a rapid and useful method for comparing the durability of different concrete mixes. Therefore, the evaluation of chloride ion penetration using RCPT is important for improving durability-based concrete design and service-life prediction of reinforced concrete structures.

Objectives of the Study

1. To study the effect of chloride ion penetration on reinforced concrete structures.
2. To understand the role of chloride ions in corrosion of steel reinforcement.
3. To examine the use of Rapid Chloride Penetration Test for evaluating concrete durability.
4. To assess how chloride penetration affects cracking, spalling, strength loss, and service life of concrete structures.

Effect of Chloride Ion Penetration on Reinforced Concrete

Chloride ion penetration has a serious effect on reinforced concrete because it directly attacks the durability mechanism that protects embedded steel. In normal concrete, steel reinforcement remains protected due to the highly alkaline environment of the cement paste. This alkaline condition forms a passive protective layer around the steel surface and prevents active corrosion. However, when chloride ions penetrate through the concrete cover and reach the reinforcement, they can destroy this passive film and start corrosion. Therefore, chloride ingress is considered one of the main causes of premature deterioration in reinforced concrete structures, especially in marine areas, bridge decks, parking structures, industrial zones, and structures exposed to de-icing salts (Angst et al., 2009; Neville, 2011).

The effect of chloride penetration is not limited to chemical corrosion only. It gradually affects the physical, mechanical, and structural performance of concrete. At first, chloride ions move through the pores and cracks of concrete. After reaching the reinforcement, they initiate corrosion if oxygen and moisture are present. As corrosion continues, rust products form around the steel. These rust products occupy a larger volume than the original steel and create internal pressure in the surrounding concrete. This pressure leads to cracking, spalling, bond loss, reduction in steel area, and weakening of the structure (Chen & Poon, 2018; de la Fuente et al., 2016).

The damage caused by chloride ion penetration is often progressive. In the early stage, there may be no visible sign of deterioration, although chloride ions may already be accumulating near the steel reinforcement. Later, rust staining, surface cracks, delamination, and spalling may appear. If the problem remains untreated, the structural capacity of reinforced concrete members can decline significantly. This makes chloride-induced deterioration a major concern for durability design, inspection, repair planning, and service-life prediction of reinforced concrete structures (Thomas & Bamforth, 2010).

Corrosion of Steel Reinforcement

Corrosion of steel reinforcement is the most harmful consequence of chloride ion penetration in reinforced concrete. In sound concrete, the pore solution is highly alkaline due to the presence of calcium hydroxide and other hydration products. This alkaline environment generally protects the steel by forming a passive oxide film on its surface. The passive film acts as a barrier and prevents corrosion under normal conditions. However, when chloride ions reach the steel surface in sufficient concentration, they break down this passive layer and create conditions for active corrosion (Angst et al., 2009). The corrosion process requires three main conditions: chloride ions, moisture, and oxygen. Chloride ions initiate the breakdown of the passive film, moisture acts as an electrolyte, and oxygen supports the electrochemical corrosion reaction. Once corrosion begins, anodic and cathodic areas form on the steel surface. At the anodic area, iron dissolves into the pore solution, while at the cathodic area, oxygen reduction takes place. These reactions produce corrosion products, commonly known as rust, around the steel reinforcement (Neville, 2011).

Chloride-induced corrosion is particularly dangerous because it may occur locally in the form of pitting corrosion. Pitting corrosion causes deep localized attack on the steel surface rather than uniform loss of steel. This type of corrosion can reduce the cross-sectional area of reinforcement at specific points and may seriously weaken the steel even when the overall amount of corrosion appears limited. Because pitting is difficult to detect in early stages, it increases the risk of hidden structural damage (Angst et al., 2009). The corrosion of reinforcement also affects the bond between concrete and steel. Reinforced concrete depends on strong bond action for load transfer between concrete and steel. When corrosion products form around the steel, they disturb the steel-concrete interface and reduce bond strength. Loss of bond may affect flexural performance, crack control, anchorage, and overall load-carrying capacity of reinforced concrete members (Chen & Poon, 2018).

The rate of corrosion depends on several factors, including chloride concentration, availability of oxygen, moisture content, concrete resistivity, cover thickness, temperature, and quality of concrete. Dense concrete with low permeability can delay the arrival of chloride ions at the reinforcement level. In contrast, porous concrete, poor curing, high water-cement ratio, and cracks accelerate chloride movement and increase the risk of reinforcement corrosion (Ling & Poon, 2015; Wong & Buenfeld, 2018).

Thus, corrosion of steel reinforcement caused by chloride penetration is a major durability problem because it begins internally and becomes visible only after considerable damage has occurred. Once corrosion starts, it can reduce steel area, weaken bond strength, increase internal pressure, and initiate cracking. Therefore, preventing chloride ion penetration is essential for maintaining the long-term safety and durability of reinforced concrete structures.

Cracking, Spalling, and Loss of Strength

Cracking is one of the earliest visible signs of chloride-induced deterioration in reinforced concrete. When steel reinforcement corrodes, the corrosion products occupy a larger volume than the original steel. This volume expansion creates tensile stress in the surrounding concrete. Since concrete is weak in tension, the internal pressure caused by rust formation eventually leads to cracking along the reinforcement direction. These cracks allow more water, oxygen, and chloride ions to enter the concrete, which further accelerates corrosion (de la Fuente et al., 2016). Once cracking begins, the protective capacity of the concrete cover is reduced. The concrete cover acts as the first barrier against aggressive agents. If this cover cracks, chloride-bearing water can reach the reinforcement more easily. Therefore, cracking creates a feedback cycle: chloride ions cause corrosion, corrosion causes cracking, and cracking allows more chloride ingress. This cycle can rapidly increase the rate of deterioration in reinforced concrete members (Chen & Poon, 2018).

Spalling occurs when the cracked concrete cover separates or breaks away from the surface. This usually happens when corrosion pressure becomes high enough to detach the cover concrete from the reinforcement. Spalling exposes the steel directly to the environment, making corrosion much faster. In severe cases, large portions of the concrete cover may fall off, creating safety risks and reducing the aesthetic and functional quality of the structure (Neville, 2011). Loss of strength may occur in different ways. First, corrosion reduces the cross-sectional area of steel reinforcement, which lowers its tensile capacity. Second, cracking and spalling reduce the effective concrete section and weaken compression zones in structural members. Third, corrosion damages the bond between steel and concrete, reducing composite action. Fourth, continuous chloride ingress may increase permeability and make the concrete more vulnerable to other forms of deterioration such as carbonation, sulphate attack, and freeze-thaw damage (Chen & Poon, 2018; Thomas & Bamforth, 2010).

The mechanical effect of chloride-induced damage is especially important in beams, slabs, columns, bridge decks, and marine structures. In flexural members, corrosion of tensile reinforcement may reduce bending resistance and increase deflection. In columns, corrosion of longitudinal bars and stirrups may reduce load capacity and confinement. In slabs and bridge decks, chloride-induced cracking may reduce durability and increase maintenance requirements. Therefore, chloride penetration affects both durability and structural performance (de la Fuente et al., 2016).

Cracks also influence test results related to chloride penetration. Concrete specimens with cracks generally show higher permeability and higher chloride ingress than uncracked specimens. Even small cracks can become direct channels for chloride-bearing solution. Therefore, crack control is an important part of durability design. Proper mix design, adequate curing, controlled shrinkage, sufficient cover, quality workmanship, and appropriate reinforcement detailing can help reduce cracking and improve chloride resistance (Ling & Poon, 2015; Sarkar & Gupta, 2017), chloride ion penetration causes cracking, spalling, and strength loss mainly through reinforcement corrosion and expansion of rust products. These physical damages reduce concrete cover protection, increase permeability, weaken bond strength, and lower structural capacity. If not controlled, chloride-induced cracking and spalling may lead to serious deterioration and costly repairs.

Reduction in Service Life of Concrete Structures

Service life refers to the period during which a concrete structure performs its intended function safely and satisfactorily with acceptable maintenance. Chloride ion penetration reduces the service life of reinforced concrete by shortening the time before corrosion initiation and accelerating deterioration after corrosion begins. For chloride-exposed structures, service life is commonly divided into two stages: corrosion initiation period and corrosion propagation period (Tuutti, 1982; Thomas & Bamforth, 2010).

The corrosion initiation period is the time required for chloride ions to penetrate the concrete cover and reach the reinforcement in sufficient concentration to break down the passive layer. This period depends on chloride exposure level, cover thickness, concrete permeability, water-cement ratio, curing condition, use of supplementary cementitious materials, and presence of cracks. A dense and well-cured concrete cover can significantly extend the initiation period, while porous or cracked concrete shortens it (Angst et al., 2009; Wong & Buenfeld, 2018).

The corrosion propagation period begins after depassivation of steel. During this stage, corrosion products accumulate around reinforcement, leading to cracking, spalling, bond deterioration, and reduction of steel area. The duration of this stage depends on the corrosion rate, availability of moisture and oxygen, temperature, concrete resistivity, and structural loading condition. If corrosion progresses rapidly, visible damage and structural weakening may occur much earlier than the designed service life (de la Fuente et al., 2016).

Reduction in service life has both technical and economic consequences. Technically, the structure may no longer satisfy strength, safety, durability, or serviceability requirements. Economically, chloride-induced deterioration increases inspection, repair, rehabilitation, and maintenance costs. In infrastructure such as bridges, ports, parking structures, and marine facilities, repair work may also cause traffic disruption, operational delays, and additional public expenses (Neville, 2011).

The service life of concrete structures can be improved by reducing chloride ingress. This can be achieved through low water-cement ratio, adequate cement content, proper compaction, effective curing, use of supplementary cementitious materials, adequate cover thickness, crack control, surface coatings, corrosion inhibitors, and corrosion-resistant reinforcement. Materials such as fly ash, silica fume, slag, and metakaolin can reduce chloride permeability by refining the pore structure and improving the density of the cement matrix (Ghods & Razaqpur, 2014; Ling & Poon, 2015; Sarkar & Gupta, 2017).

RCPT is useful in service-life-related studies because it provides a rapid indication of concrete resistance to chloride ion penetration. Lower RCPT values generally indicate better durability performance and slower chloride ingress. However, service-life prediction should not depend only on RCPT because the test is influenced by electrical conductivity, moisture condition, temperature, and binder type. For more reliable prediction, RCPT results may be combined with diffusion tests, permeability data, cover thickness, exposure conditions, and mathematical modelling (ASTM International, 2019; Wong & Buenfeld, 2018).

The reduction in service life due to chloride ion penetration shows the need for proper durability-based design. Traditional design based only on compressive strength is not sufficient for chloride-exposed environments. A concrete mix may achieve high strength but still show poor durability if it has high permeability or poor resistance to chloride penetration. Therefore, durability parameters such as RCPT, chloride diffusion coefficient, electrical resistivity, permeability, and corrosion initiation time should be considered for long-term performance assessment (Thomas & Bamforth, 2010), chloride ion penetration reduces the service life of reinforced concrete by initiating corrosion, accelerating cracking and spalling, weakening steel-concrete bond, reducing reinforcement area, and increasing maintenance demand. Understanding this process is essential for designing durable RCC structures and for developing service-life prediction models for chloride-exposed environments.

Rapid Chloride Penetration Test

The Rapid Chloride Penetration Test, commonly known as RCPT, is one of the most widely used laboratory methods for assessing the resistance of concrete to chloride ion penetration. Chloride penetration is a major durability concern in reinforced concrete because chloride ions can reach the embedded steel reinforcement and initiate corrosion. Therefore, a reliable and rapid method is needed to evaluate how easily ions can pass through concrete. RCPT provides an indirect indication of chloride penetrability by measuring the total electrical charge passed through a concrete specimen under an applied voltage (ASTM International, 2019). RCPT is important because durability assessment cannot depend only on compressive strength. A concrete mix may show high strength but may still be vulnerable to chloride ingress if it has high permeability or interconnected pores. Since chloride-induced corrosion is one of the main causes of premature deterioration in reinforced concrete structures, tests such as RCPT are useful for comparing different concrete mixes, binder systems, curing conditions, and protection methods (Neville, 2011; Thomas & Bamforth, 2010).

The test is particularly useful for concrete exposed to marine environments, bridge decks, parking structures, industrial floors, foundations in saline soil, and structures exposed to de-icing salts. In these environments, chloride ions may accumulate on the concrete surface and gradually penetrate through the pore solution. RCPT helps to estimate the concrete's resistance to such ionic movement and supports durability-based mix selection (de la Fuente et al., 2016). However, RCPT should be understood as an accelerated electrical test rather than a direct measurement of natural chloride diffusion. The charge passed during the test depends not only on chloride movement but also on the electrical conductivity of the pore solution, moisture condition, temperature, specimen age, and type of supplementary cementitious materials used. Therefore, RCPT results should be interpreted carefully, especially when comparing concretes with different binder compositions (Wong & Buenfeld, 2018).

Concept of RCPT

The basic concept of RCPT is to evaluate the ability of concrete to resist ionic movement through its pore structure. Since chloride ions move through the interconnected pores of concrete, a more porous and permeable concrete allows easier ion transport. On the other hand, dense concrete with low water-cement ratio, proper curing, and supplementary cementitious materials generally restricts ion movement. RCPT uses electrical charge as an indicator of this transport behavior (ASTM International, 2019). In RCPT, a concrete disc specimen is placed between two cells. One side usually contains sodium chloride solution, while the other side contains sodium hydroxide solution. A direct electrical potential is applied across the specimen for a fixed duration, commonly six hours. During this period, ions move through the concrete under the influence of the applied voltage. The total charge passed, measured in coulombs, is recorded. Lower charge passed indicates lower penetrability, while higher charge passed indicates greater ionic movement and higher chloride penetrability (ASTM International, 2019).

The concept of RCPT is based on the relationship between concrete permeability, pore connectivity, and electrical conductivity. If the concrete has a dense microstructure with disconnected pores, less current will pass through it. If the concrete has large and interconnected pores, more current will pass. Therefore, RCPT indirectly reflects the quality of concrete's internal pore system (Ling & Poon, 2015). The RCPT result is usually interpreted according to the total charge passed. Concrete with very high charge passed is considered highly penetrable, while concrete with very low charge passed is considered highly resistant to chloride ion penetration. This classification helps researchers and engineers compare the durability performance of different mixes. For example, concrete containing silica fume, fly ash, slag, or metakaolin often shows lower charge passed because these materials refine the pore structure and reduce ion transport (Ghods & Razaqpur, 2014; Sarkar & Gupta, 2017).

The concept is also useful in studying the influence of water-cement ratio. A high water-cement ratio usually increases capillary porosity and produces more connected pore channels. This increases charge passed in RCPT and indicates higher chloride penetrability. In contrast, a lower water-cement ratio reduces permeability and improves resistance to chloride movement (Zhang et al., 2016). Thus, RCPT is based on the idea that the electrical response of concrete can provide a rapid indication of its resistance to chloride ion penetration. Although it does not measure field chloride diffusion directly, it is useful for comparative evaluation of concrete durability when test conditions are properly controlled.

Working Principle of RCPT

The working principle of RCPT is based on the movement of ions through a concrete specimen under an applied electrical potential. In natural exposure conditions, chloride ions mainly move through concrete by diffusion, absorption, and permeation. In RCPT, this movement is accelerated by applying an external voltage across the concrete specimen. The amount of electrical charge passed during the test is used as an indicator of the concrete's resistance to ionic movement (ASTM International, 2019). A cylindrical concrete specimen is first prepared and cured according to the testing requirement. A slice of the specimen is then cut, generally in the form of a disc. Before testing, the specimen is commonly vacuum-saturated to fill its pores with water. This is done because ionic movement requires a continuous liquid phase inside the pore network. After saturation, the concrete disc is sealed around its sides and placed between two test cells (ASTM International, 2019).

One cell is filled with sodium chloride solution, and the other cell is filled with sodium hydroxide solution. A direct current voltage is applied across the specimen. Under this electrical field, negatively charged chloride ions move toward the positive side, while other ions in the pore solution also contribute to the electrical current. The current is recorded at regular intervals during the test period. The total charge passed is calculated by integrating the current over time and is expressed in coulombs (Thomas & Bamforth, 2010). If the concrete has a highly connected pore structure, ions move more easily through it, and the current remains high. This results in a higher total charge passed. If the concrete has a dense and refined pore structure, ion movement is restricted, and the total charge passed is lower. Therefore, the working principle connects electrical current flow with the ease of ionic transport through concrete (Ling & Poon, 2015).

The test is rapid because it accelerates ion movement using electrical potential. Natural chloride diffusion may take months or years to assess properly under field conditions. RCPT provides comparative results within a short period, usually six hours. This makes it practical for laboratory studies, quality control, material comparison, and durability-based concrete mix evaluation (ASTM International, 2019). However, the working principle also has limitations. The test measures total ionic conductivity rather than only chloride diffusion. This means that all ions present in the pore solution may contribute to the measured current. Concrete containing certain mineral admixtures may show lower charge passed partly because these materials reduce pore solution conductivity, not only because they reduce chloride diffusion. Similarly, temperature rise during the test may increase current flow and affect the result (Wong & Buenfeld, 2018).

Moisture condition is another important factor. If the specimen is not properly saturated, current flow may be reduced, giving misleading results. On the other hand, differences in curing age and hydration level can also affect pore structure and conductivity. Therefore, proper specimen preparation, curing, saturation, temperature control, and testing procedure are essential for reliable RCPT results (Thomas & Bamforth, 2010), the working principle of RCPT is based on applying electrical voltage across a saturated concrete specimen and measuring the charge passed through it. A lower charge passed value indicates better resistance to ion movement and lower chloride penetrability. The test is useful, rapid, and widely accepted, but its results must be interpreted with awareness of its dependence on moisture condition, temperature, pore solution chemistry, and binder type.

Conclusion

The study concludes that chloride ion penetration is a major durability problem in reinforced concrete structures. When chloride ions pass through concrete pores and cracks and reach the steel reinforcement, they damage the passive protective layer of steel and initiate corrosion. This corrosion produces rust, which expands inside the concrete and causes cracking, spalling, bond loss, reduction in steel area, and gradual loss of structural strength. Therefore, chloride penetration directly reduces the service life and safety of reinforced concrete structures, especially in marine areas, bridge decks, parking structures, industrial zones, and saline environments.

References

Amin, M. T. E., Sarker, P. K., Shaikh, F. U. A., & Hosan, A. (2025). Chloride permeability and chloride-induced corrosion of concrete containing lithium slag as a supplementary cementitious material. *Construction and Building Materials, 471*, 140629. https://doi.org/10.1016/j.conbuildmat.2025.140629

Castel, A., Nguyen, Q. D., Law, D., Kim, T., Samson, G., Cyr, M., Provis, J. L., & Li, W. (2025). Recommendation of RILEM TC 283-CAM: Performance-based assessment of alkali-activated concrete durability using the 10 V rapid chloride permeability test. *Materials and Structures, 58*, 219. https://doi.org/10.1617/s11527-025-02738-2

Dashti, P., Moodi, F., Ramezanianpour, A. A., & Banar, R. (2025). Finite element analysis of chloride ion penetration and service life prediction in concrete with supplementary cementitious materials. *Scientific Reports, 15*, 30023. https://doi.org/10.1038/s41598-025-15925-6

Mousavinezhad, S., Nozari, S., & Newtson, C. M. (2025). Classifying concrete permeability using rapid chloride permeability and surface resistivity tests: Benefits, limitations, and predictive models: A state-of-the-art review. *Buildings, 15*(23), 4216. https://doi.org/10.3390/buildings15234216

Ali, M., Shams, M. A., Bheel, N., Almaliki, A. H., Mahmoud, A. S., Dodo, Y. A., & Benjeddou, O. (2024). A review on chloride induced corrosion in reinforced concrete structures: Lab and in situ investigation. *RSC Advances, 14*, 37252–37271. https://doi.org/10.1039/D4RA05506C

Gao, P., Song, Y., Wang, J., Yang, Z., Wang, K., & Yuan, Y. (2024). Prediction model for the chloride ion permeability resistance of recycled aggregate concrete based on machine learning. *Buildings, 14*(11), 3608. https://doi.org/10.3390/buildings14113608

Hasan, T. M., Allena, S., & Gilbert, L. (2024). Rapid chloride penetration test: An evaluation of corrosion resistance in ultra-high performance concrete. *Journal of Building Engineering, 82*, 108317. https://doi.org/10.1016/j.jobe.2023.108317

Li, L., Su, L., Guo, B., Cai, R., Wang, X., & Zhang, T. (2024). Prediction and prevention of concrete chloride penetration: Machine learning and MICP techniques. *Frontiers in Materials, 11*, 1445547. https://doi.org/10.3389/fmats.2024.1445547

Liao, J., Wang, Y., Sun, X., & Wang, Y. (2024). Chloride penetration of surface-coated concrete: Review and outlook. *Materials, 17*(16), 4121. https://doi.org/10.3390/ma17164121

Wang, Y., Liao, J., & Zhang, B. (2024). A review of chloride penetration of recycled concrete with enhancement treatment and service life prediction. *Materials, 17*(6), 1349. https://doi.org/10.3390/ma17061349