EFFECT OF FRESHWATER POLLUTION ON THE INTEGRITY OF BRIDGE STRUCTURES IN THE STATE OF GEORGIA

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Abstract. A preliminary assessment was done to investigate the effects of water pollutants on concrete and steel bridges located above surface waters in the state of Georgia. A research investigation was conducted to determine which contaminants, commonly found in the streams of Georgia, could deteriorate and accelerate structural damages in concrete and steel bridge structures, thereby decreasing their designed life span. Water data collected from the GA 305(b)/303(d) list of impaired waters revealed that bridge structures are continuously exposed to contaminants such as nitrate, sulfate, phosphorus, corrosive materials, and organic matter derived pollutants (e.g. humic substances and CO2) that have detrimental effects on the steel and concrete of all bridge structures. Additionally, eutrophic waters have the potential to corrode steel structures and damage concrete piers by increasing or decreasing the pH of surface waters. This study reveals that the most common negative effects on steel and concrete structures include: corrosion of reinforcing steel and other embedded metals, concrete deterioration, cracking, delamination, and spalling. Identifying initial signs of concrete and steel deterioration without compromising the structure is a difficult task. In most cases, a visual inspection was not sufficient to determine early stages of structural damage. Therefore, a more comprehensive analysis involving non-destructive tests was performed. Infrastructures in Georgia were selected and after analysis of the surrounding surface water and recognition of the water contaminant, Non Destructive Tests (NDT) were conducted to detect corrosion in concrete and steel material in the structures exposed to the polluted water. A comparison between the result of different NDT on the areas exposed to polluted streams and areas far from the pollution is presented to highlight the effects of fresh water contaminants on infrastructures.

INTRODUCTION

A durable structure is expected to retain its engineering, chemical, and physical properties for the complete duration of the projects service life. The most critical engineering properties of hardened concrete take account of strength, modulus of elasticity, water tightness, and volume stability. Chemical durability is defined as the resistance against external or internal, surface or bulk reactions that may lead to the exchange of chemical species between the concrete and the environment. This exchange may involve carbonates, sulfates, chlorides, nitrates, and other inorganic and organic species. Concrete is fabricated to have a dense, impermeable, and chemically stable macro- and microstructure. However, environmental exposure to surface or ground water contaminants, atmospheric pollution, humidity fluctuations, industrial waste, and extreme temperatures will lead to concrete deterioration. Concrete will act in response to its environment to produce chemical species that are unstable and whose formation may result in microstructural changes that could harshly compromise the anticipated concrete properties. The chemical nature of the water and soil to which a concrete structure will be exposed should be well known before the concrete is designed for that particular environment (Jan S. et al., 2002).

Georgia's agricultural industry occupies an important role in the state's economy. As a result, fertilizers and livestock contribute to environmental pollution. The problem originates when excessive amounts of fertilizers or animal's manures are used. Unused sulfur, nitrate, and phosphorus will leach into the water courses. Streams with high organic matter (OM) content can potentially trigger the decomposition of carbon dioxide causing the water to become acidic. Environmental exposure to Sulfate, which is frequently found in the streams of Georgia, can deteriorate and accelerate structural damages in concrete and steel bridge structures thereby diminishing their intended life-span (Hedjazi S. et al. 2018). The surface water situated underneath infrastructures in the state of Georgia was examined to determine which contaminants were present. It was discovered that the infrastructure chosen for this study was unceasingly exposed to surface water containing a high concentration of sulfate. The importance of recognizing geographical areas with high sulfate concentrations plus the type and concentration of the accompanying contaminants will be explained in more detail later.

Sulfate attack has substantial consequences on the microstructure and engineering properties of concrete. Sulfate can generate enough pressure to disrupt the cement paste, occasioning loss of cohesion and strength (PCA, 2002). Deterrence of concrete corrosion by any means of deterioration will be contingent on proper use of modern knowledge such as standards and destructive and nondestructive test methods. The Ultrasonic Pulse Velocity (UPV) and the Rebound Hammer (RH) are recognized as the most utilized NDT in determining the compressive strength of concrete. The SonReb methodology correlates the results of UPV and RH to obtain reliable values for compressive strengths. The results will be based on empirical mathematical equations grounded on linear regression models (Costel C. et al., 2017).

SULFATE ATTACK ON CONCRETE

External Sulfate Attack

Sulfate Attack is defined as a succession of chemical reactions between sulfate ions and the components of hardened concrete, mainly the cement paste, initiated by exposure of concrete to sulfates and moisture (Jan S. et al., 2002). Sulfates of sodium, potassium, calcium, or magnesium are occasionally discovered in soil or dissolved groundwater adjacent to reinforced concrete structures. When evaporation takes place the sulfate ions can cluster on the surface and augment the potential for deterioration. The two most acclaimed chemical consequences of sulfate attack on concrete components are the materialization of ettringite and gypsum. The formation of ettringite can result in an increase in solid volume, instigating expansion and cracking. The formation of gypsum can engender softening and loss of concrete strength. The presence of ettringite or gypsum in concrete is not by itself an adequate indication of sulfate attack; evidence of sulfate attack should be verified by petrographic and chemical analysis (ACI, 2008).

Noticeable examples of damage caused by the reaction of concrete components with sulfates include spalling, delamination, macrocracking, and loss of cohesion (Jan S. et al., 2002). Acids react with the calcium hydroxide of the hydrated Portland cement. The chemical reaction produces water-soluble calcium compounds (ACI, 2008). The outcome of such dissolution could bring about the leaching of calcium and hydroxyl ions, consequently decreasing the alkalinity (pH) of the cement paste. Additionally sulfonation of the Calcium ions could possibly form expansive compounds such as ettringite and gypsum (Jan S. et al., 2002).

Delayed ettringite formation (DEF) is the deleterious reformation of ettringite in moist concrete, mortar, or paste after destruction of primary ettringite by high temperature (PCA, 2001). Portland cement concrete does not have good resistance to acids. No hydraulic cement concrete, despite its composition, will withstand being exposed to a solution with a pH of 3 or lower (PCA, 2002). Acids act in response to the calcium hydroxide of the hydrated Portland cement. The chemical reaction forms water-soluble calcium compounds, which are then leached away by aqueous solutions (ACI, 2008).

Figure 1: Bridge Site Columns

Prevention of Sulfate Attack

Environmental conditions can have an immense influence on sulfate attack. The attack is augmented when concrete is exposed to wet/dry cycling. Resistance to sulfates can be accomplished by using a low water-to-cement ratio and a cement with a regulated amount of tricalcium aluminates. As delineated in ASTM C 150, Type II cement contains less than 8% C_3A, and Type V cement contains less than 5%. Cements meeting the ASTM C 1157 requirements of Type MS cement (moderate sulfate resistant) and Type HS cement (high sulfate resistant) can also be used to bestow sulfate resistance, as well as moderate sulfate-resistant cements per ASTM C 595 (PCA, 2002).

NON-DESTRUCTIVE TESTS

Ultrasonic Pulse Velocity

The UPV is a non-destructive test method employed to examine the quality of concrete elements by identifying voids, cracks, honey combs, and compressive strength. The UPV method is described in the American standard, ASTM C597. The device that is used for this method is shown in Figure 2, the Ultrasonic Pulse Velocity Tester (Costel C. et al., 2017). Pulses of Longitudinal stress waves are produced by an electro-acoustical transducer that is in contact with one surface of the concrete. After traversing through the concrete, the pulses are received and converted into electrical energy by a second transducer situated a distance L from the transmitting transducer. The transit time T is measured electronically. The pulse velocity V is calculated by dividing L by T.

Figure 2: Ultrasonic Pulse Velocity Tester

The pulse velocity in steel is up to double that in concrete therefore, the pulse-velocity measured in the vicinity of the reinforcing steel will be higher than in plain concrete of the same composition. If possible, stay away from measurements close to steel parallel to the direction of pulse propagation (ASTM C597, 2016). Based on the values of pulse velocity, important relationships can be articulated with respect to the quality, uniformity, damage extent and to the compressive strength of the inspected concrete element (Costel C. et al., 2017).

UPV Methodology

First, functional check of the equipment and zero-time adjustment. Second, apply an appropriate coupling agent to the transducer faces, the test surface, or both. Third, Press the faces of the transducers firmly against the test surfaces of the concrete until a stable Transit Time (T) is displayed. For best results locate the transducers directly opposite each other. Fourth, determine the straight-line distance (L) between centers of transducer faces. Fifth Calculate the Pulse Velocity (V) by dividing L by T (ASTM C597, 2016). UPV tests assess concrete quality and strength. UPV should be > 3.5 km/s, otherwise the concrete shall be considered poor. However, precise prediction of concrete strength is difficult to obtain. The single variable formula relating compressive strength and UPV that was used in this study is shown below (Brayan et al., 2015) .

$$f_{cu} = 8.88 \exp(0.42V)$$

for CA = 1000 kg/m^3

Rebound Hammer

The rebound hammer method is one of the most utilized nondestructive procedures designed for measuring the surface hardness of concrete elements (Costel C. et al., 2017). This testing method is described in the American standard ASTM C805. A steel hammer impacts a metal plunger with a fixed amount of energy against a concrete surface as can be seen in Figure 3.

Figure 3: Rebound Hammer

Either the distance that the hammer rebounds is measured or the hammer speed before and after impact are measured. The test result is reported as a dimensionless rebound number. This test method delineates variations in concrete quality to estimate the in-place strength (ASTM C805, 2013).

RH Methodology

First, Hold the instrument firmly so that the plunger is perpendicular to the test surface. Second, Record the orientation of the instrument to the nearest 45-degree increment. Third, gradually push the instrument toward the test surface until hammer impacts. Fourth, maintain pressure on the instrument until plunger is locked. Fifth read and record rebound number to the nearest whole number. Take ten readings from each test area. A Relationship between rebound number and concrete strength is provided by the instrument manufacturer via regression curves (ASTM C805, 2013).

RESULTS AND CONCLUSIONS

Water and sediment samples retrieved from the bridge site revealed a sulfate concentration ranging from 8-10 mg/L. Sulfate Attack can result in an increase in solid volume causing expansion, cracking, softening, and loss of concrete strength. In order to quantify the effect that this contaminant has on the structures design life span NDT were conducted. The NDT were conducted on the column's affected and unaffected areas and the compressive strength of each area was determined using both the UPV and the RH methods.

The results from each test method were compared and recorded. Figure 4 is a graphical representation of the different compressive strengths obtained using the RH method of each column. This test method was conducted on the affected and unaffected areas. The average compressive strength for the affected and unaffected areas are 32.4 MPa and 53.4 MPa respectively.

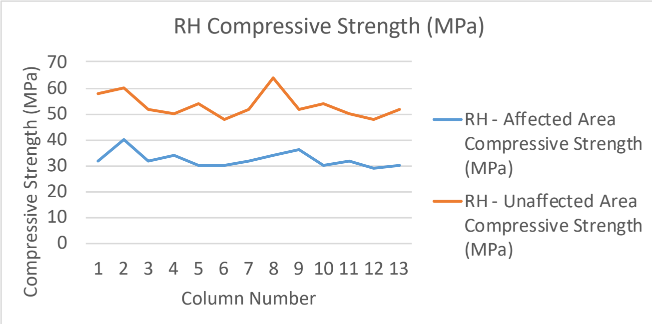

Figure 4: Rebound Hammer Compressive Strength

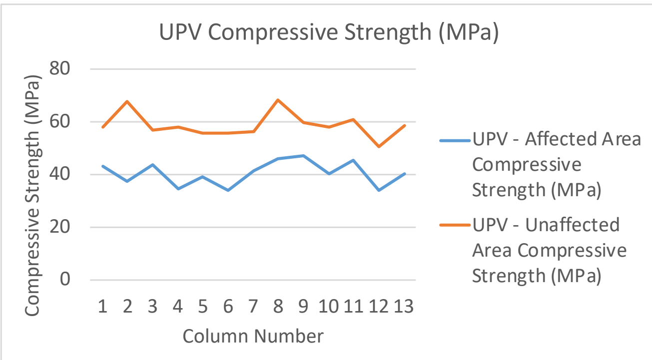

Figure 5: UPV Compressive Strength

Figure 5 is a graphical representation of the different compressive strengths obtained using the UPV method of each column. This test method was conducted on the affected and unaffected areas. The average compressive strength for the affected and unaffected areas are 40.4 MPa and 58.7 MPa respectively.

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Table 1: Influencing Factors for UPV Method (Breysse D., 2012)

Constituent	Property	Influence
Aggregate	Size	Average
	Type	High
Cement	Percentage	Moderate
	Type of Cement	Moderate
Other	Fly ash content	Average
	Water/cement ratio	High
Humidity / Moisture Content		Average
Other Factors	Reinforcements	Moderate
	Age of concrete	Moderate
	Voids, cracks	High

Table 2: UPV – Index for Concrete Quality Assessment (Agunwamba J.C. and Adagba T., 2012).

Concrete Quality	Ultrasonic Pulse Velocity (m/s)
Excellent	Over 4,500
Good	3,500 – 4,500
Doubtful	3,000 – 3,500
Low	2,000 – 3,000
Very low	Under 2,000

Table 3: Influencing Factors for RH method (Breysse D., 2012)

Constituent	Property	Influence
Aggregate	Size	Average
	Type	High
Cement	Percentage	Moderate
	Type of cement	Moderate
Humidity degree / Moisture Content		Average
Contact surface properties	Carbonation degree	High
	Smoothness degree	Average
	Formwork type and curing conditions	Average
Other Factors	Temperature	Moderate
	Voids	High

Table 4: Rebound Number – Concrete Quality Assessment (Costel C. et al., 2017)

Average Rebound Number	Concrete quality
Above 40	Very good concrete
30 – 40	Good concrete
20 – 30	Fair concrete
Below 20	Poor concrete