Erion Luga[1]

CONCRETE DURABILITY IN RC STRUCTURES

Abstract: Nowadays most of the structures surrounding our urban environment are made of reinforced concrete (RC). As civil engineers beside the strength of concrete, we must be conscious about the problems rising from the lack of concrete durability. Concrete suffers from different causes of deterioration, which are seen in the form of cracks, spalling, loss of strength, etc. On the other hand, permeability of concrete is the main factor affecting the durability of concrete. The durability of RC structures depends also on several processes threatening its performance such as: physical processes, chemical processes and biological processes. In order to build safe structures we need to be aware of the durability problems of RC structures and take the necessary measures.

Key words: Reinforced Concrete, Durability

[1] Academic title,Institution name and address, and e-mail

THE IMPORTANCE OF CONCRETE DURABILITY IN RC STRUCTURES

Concrete is nowadays the most widely used material in the construction industry. Most of the structures surrounding our urban environment are made of reinforced concrete. In many countries the ratio of concrete consumption to steel consumption exceeds ten to one and the total world consumption of concrete in one year is estimated at three billion tons. Man consumes no material except water in such tremendous quantities [1].

Figure 1 – Giant prestressed concrete slab, Portuguese National Pavilion, Lisbon

DURABILITY OF CONCRETE

As civil engineers we are mostly concerned about the mechanical behavior of concrete and reinforced concrete. We must be conscious about the problems rising from the lack of concrete durability. Concrete suffers from different causes of deterioration. The effect of these causes may result in loss of strength, in the form of different types of cracks, spalling or surface wear, etc.

On the other hand, permeability of concrete is the main factor affecting the durability of concrete. That is why the necessary mesasures should be taken in consideration to decrease to minimum levels the concrete permeability. The main factors influencing the durability of concrete is its impermeability to the ingress of: oxygen, water, carbon dioxide, chlorides, sulphates, etc.

The durability of concrete is very important, because concrete should be capable to withstand the conditions for which it has been designed throughout the life of the structure.

Loss of concrete durability can be caused by external agents arising from the environment or by internal agents within concrete. The durability of RC structures depends also on several processes threatening its performance such as: physical processes, chemical processes and biological processes. In order to build safe structures we need to be aware of the durability problems of RC structures and take the necessary measures.

1.1. Cracks in Concrete

When the tensile stresses to which concrete may be subjected to exeeds the maximum tensile strength of concrete, it cracks. The increase of these tensile stresses may be caused from different factors, but the most of tham are related to the internal volume changes.

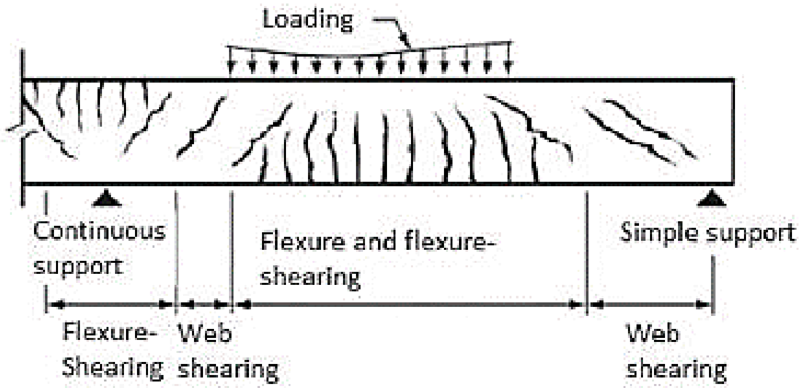


Figure 2 – RC beam under bending [2]

1.1.1.Types of Cracks in RC structures

Concrete changes slightly in volume for various reasons, the most common causes are fluctuations in moisture content and temperature. Restraint to volume changes, especially contraction, can cause cracking. Cracks can occur in hardened or unhardened concrete and may be caused by some of the conditions such as:Plastic Shrinkage cracking, Plastic Settlement cracking, Structural cracking, Rust cracking, Thermally-induced cracking, etc

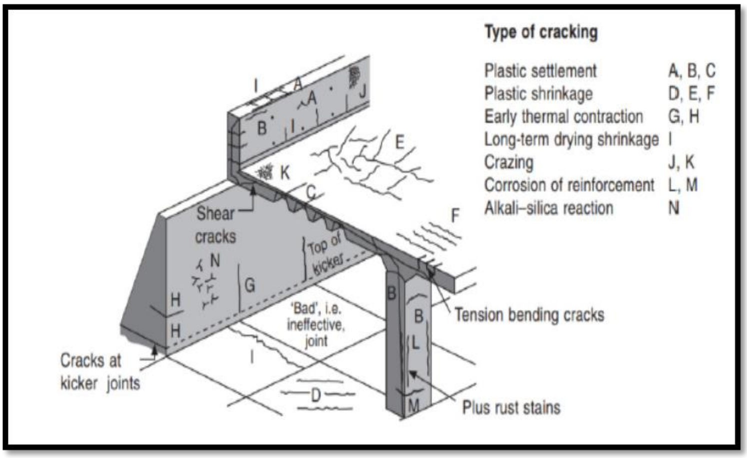


Figure 3 – RC beam under bending [3]

Fast evaporation of water from the surface of freshly placed concrete, makes the surface of concrete shrink. Due to the restraint provided by the concrete below the drying surface layer, tensile stresses develop in the weak reagion, stiffening plastic concrete, resulting in shallow cracks of varying depth. These cracks are often fairly wide at the surface. Plastic shrinkage cracks can be prevented by taking measures to prevent rapid water loss from the concrete surface. Fog nozzles, plastic sheeting, windbreaks, and sunshades can all be used to prevent excessive evaporation

Because almost all concrete is mixed with more water than is needed to hydrate the cement, much of the remaining water evaporates, causing the concrete to shrink. Restraint to shrinkage, provided by the subgrade, reinforcement, or another part of the structure, causes tensile stresses to develop in the hardened concrete. Restraint to drying shrinkage is the most common cause of concrete cracking. In many applications, drying shrinkage cracking is inevitable. Therefore, control joints are placed in concrete to predetermine the location of drying shrinkage cracks. Drying shrinkage can be limited by keeping the water content of concrete as low as possible and maximizing the coarse aggregate content [4].

On the other hand cracks are formed after placing and compaction of concrete. If concrete continues to settle over reinforcement bars, ducts, steps in formwork, etc.

Cracks occur only when there is a high amount of bleeding and settlement, directly over formwork tie bolts, in narrow columns and walls, at change of depth of section

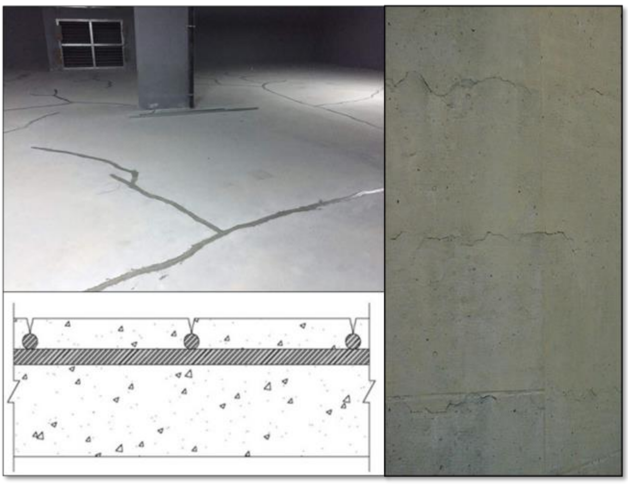


Figure 3 – Cracks formed in unhardened concrete

Properly designed and constructed concrete members are usually strong enough to support the loads for which they are intended. But overloading can occur for a variety of reasons: a change in use of a structure without proper structural upgrades, unintentional overloading, and other unusual circumstances. Earthquake damage is a classic example of the overloading of concrete structures. Overload damage can occur during construction when concrete has not yet reached design strength. Early removal of formwork or the storage of heavy materials or operation of equipment on and around the structure can result in the overloading of certain concrete members. A common error occurs when precast members are not properly supported during transport and erection. Errors in post-tensioned construction, such as improperly timed or sequenced strand release, can also cause overload cracking. Damage caused by impact is another form of overload. A common form of impact overload occurs at slab edges of joints on vehicular traffic surfaces . Even in properly designed reinforced concrete, load-induced tensile stresses can occur. This point is readily acknowledged and accepted in concrete design. Current design procedures use reinforcing steel to not only carry tensile loads, but to obtain both an adequate distribution of cracks and a reasonable limit on crack width [4].

1.2. Permeability of Concrete

Permeability of concrete can be defined as the property that governs the rate of flow of a fluid into a porous solid. It is also related to the amount of water migration through concrete when the water is under pressure, and the ability of concrete to resist penetration of any substance, be it a liquid, gas, or chloride ion. Designers of dams and other large hydraulic structures needed to know the rate at which water passed through concrete that was subjected to relatively high hydraulic pressures [5].

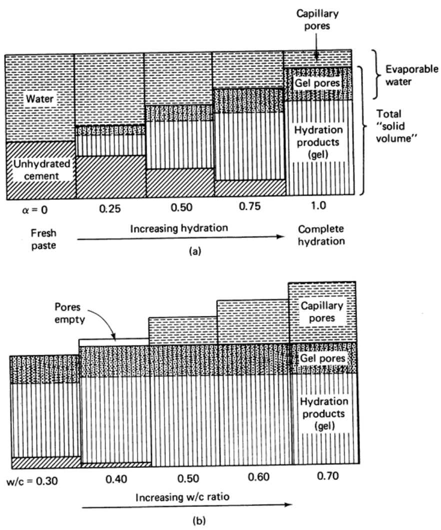


Figure 4 – Porosity of cement paste during hydration

Water is generally involved in every form of deterioration and, with porous solids the ease of penetration of water into the solid usually determines its rate of deterioration [1].

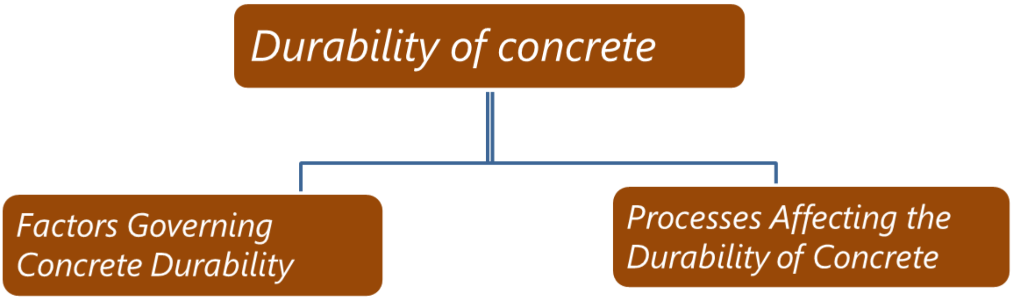


Figure 5 – Scheme for the causes of durability loss

1.3. Factors Governing Concrete Durability

Some of the factors that govern the durability of RC structures can be listed as: Concrete mix design, Structural design, Reinforcement detailing, Concrete cover, Curing of concrete, Supervision, Quality of materials.

1.4. Processes *Affecting the Durability of Concrete*

The behavior of concrete depends on several processes such as: Physical processes, Chemical processes, Biological processes.

1.4.1.Physical *Causes of Concrete Deterioration*

Physical Causes of Concrete Deterioration can be listed as follows: Abrasion/Erosion, Cavitation, Freeze-thaw deterioration, Deicer Scaling, High temperatures, Aggregate expansion

1.4.1.1. *Deterioration from abrasion/erosion*

When a material is repeatedly struck by particles from a harder body and the surface of concrete is unable to resist wear caused by rubbing and friction abrasion damage occurs: outer paste of concrete wears, fine and coarse aggregate are exposed, abrasion and impact will cause additional degradation that is related to aggregate-to-paste bond strength and hardness of the aggregate. The most damaging forms of abrasion occur on vehicular traffic surfaces, bridge piles, surfaces in contact with waves etc.

Figure 6 – Erosion of concrete from sea waves

Figure 7– Concrete deteriorated from erosion

Factors influencing abrasion resistance

Some of the main factors affecting the abrasion resistance of concrete are: Compressive strength; Properties of the aggregates; Nature of the finishing coat; Presence of areas which have been patched up; Condition of the surface.

Figure 8– Segregation and patched concrete

Deterioration from Cavitation

Formation of bubbles or cavities in a liquid.The cavities form where the local pressure drops to a value that will cause the water to vaporize at the prevailing fluid temperature. Cavitation damage is produced when the vapor cavities collapse, causing very high instantaneous pressures that impact on the concrete surfaces, causing pitting, noise, and vibration [4].

Figure 9– Spillway concrete deteriorated from cavitation

Freeze-thaw Deterioration

At temperatures below 0°C cement does not hydrate. On the other hand as it freezes water expands about 9% and produces pressure in the capillaries and pores of concrete. Exceeding the tensile strength of the concrete, the cavity will dilate and rupture. Successive freeze-thaw cycles and disruption of paste and aggregate can cause significant expansion and cracking, scaling, and deterioration [4].

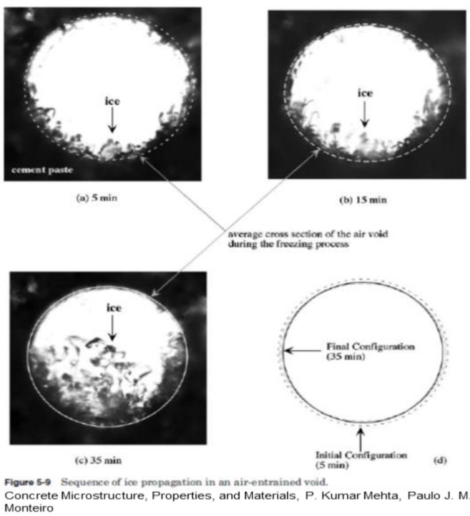


Figure 10– Water freezing inside the concrete pores

In order to prevent freeze-thaw deterioration of concrete, air entraining agent is used. Entrained air voids act as empty chambers in the paste for the freezing and migrating water to enter, thus relieving the pressure in the capillaries and pores and preventing damage to the concrete. Low permeability concrete also performs better when exposed to freeze-thaw cycles.

Deicer Scaling

Deicing chemicals, such as sodium chloride, can aggravate freeze-thaw deterioration. Osmotic and hydraulic pressures in excess of the normal hydraulic pressures produced when water in concrete freezes. Salt absorbs moisture, it keeps the concrete more saturated, increasing the potential for freeze-thaw deterioration.

Aggregate Expansion

Some aggregates absorb too much water, expand and increase hydraulic pressure during the freezing of water. Also aggregates such as CaO expend about 2.5-3 times in the presence of moisture. Concrete disintegrates if these are in high quantity. If it is near the surface of the concrete, it can cause a pop out [4].

Figure 11– Aggregate expansion in concrete

High Temperature

The behavior of concrete at high temperatures is influenced by several factors such as: rate of temperature rise and the aggregate type and stability, moisture level etc. Fast temperature changes can cause cracking and spalling due to thermal shock, and aggregate expansion can also produce distress within the concrete. High temperatures also affect the compressive strength and stiffness of concrete. Above 100º C, the cement paste begins to dehydrate (loses chemically combined water of hydration), which gradually weakens the paste and paste-aggregate bond. The effect of high temperatures on concrete is destructive, reinforcement rods resist at temperatures of up to 500°C, while concrete may resist up to 650°C. The thicker the concrete, the longer it takes for the reinforcement rods to reach their failure temperature of 500°C

1.4.2. Chemical Causes of Concrete Deterioration

The chemical causes of concrete deterioration can be listed as: acid attack, sulphate attack, alkali-silica reaction, carbonation, corrosion, leaching etc.

Acid Attack

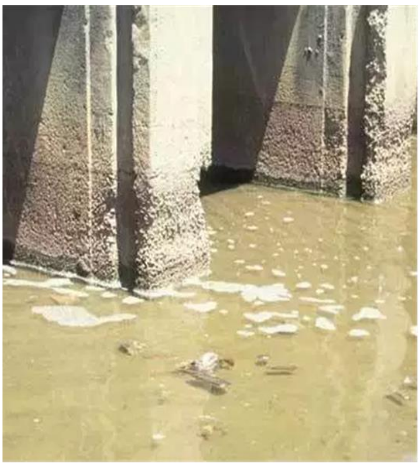
Portland cement concrete is not resistant to acids or solutions with a pH of 3 or lower. It may resist to some weak acids if the exposure is occasional. Acids react with the calcium hydroxide of the hydrated Portland cement. It forms water-soluble calcium compounds, which are then leached away by aqueous solutions

Portland Cement Association, Types and Causes of Concrete Deterioration

Figure 12– Acid attack of concrete

Sulphate Attack

Sulfates of sodium, potassium, calcium, or magnesium are sometimes found in soil or dissolved in groundwater. These salts react with aluminate compounds, calcium and hydroxyl of hardened Portland cement forming ettringite and gypsum. In the presence of sufficient water, these reactions of delayed ettringite formation cause expansion of concrete leading to irregular cracking. The cracking of concrete provides further access to penetrating substances and to progressive deterioration



civilblog.org

Figure 13– Sulphate attack of concrete

Alkali Silica Reaction

Alkalis such as Na_2O and K_2O coming from Portland cement react with reactive silica containing aggregates. Free alkalis present in cement dissolve in the mixing water and form caustic solutions, which attack the reactive silica in the aggregate. As a product of this reaction an alkali silica gel is formed. This gels swell in the presence of moisture, and exerts pressure on the concrete which may lead to formation of cracks and deterioration of concrete.

$$\text{Alkalies} + \text{Reactive Silica} \rightarrow \text{Gel Reaction Product}$$

$$\text{Gel Reaction Product} + \text{Moisture} \rightarrow \text{Expansion}$$

Figure 14– Alkali-silica reaction in concrete

Carbonation

Concrete is a highly basic environment because of the a strong base such as $Ca(OH)_2$ in its internal strcuture. The pH of the fresh cement paste is at least 12.5. When $Ca(OH)_2$ in concrete reacts with CO_2 coming from air or from water enter it produces $CaCO_3$ and water, thus decreasing the $Ca(OH)_2$ in concrete resulting in the decrease of the pH. The pH of a fully carbonated paste is about 7.

When $Ca(OH)_2$ is removed from the paste hydrated CSH will liberate CaO which will also carbonate. The rate of carbonation depends on porosity & moisture content of the concrete.

Figure 15– Measuring of carbonation depth with Phenolphthalein solution

Corrosion

Corrosion of reinforcing steel is one of the main causes of deterioration in reinforced concrete structures. Steel is thermodynamically unstable under normal atmospheric conditions because its natural state is in the form of iron oxides. As a result it tends to release energy and revert back to its natural state. As steel corrodes it produces rust, which occupies a greater volume than steel. Corrosion of the reinforcement in RC structures is classified as: atmospheric corrosion, chloride ion on corrosion, galvanic corrosion and electrochemical corrosion.

Figure 16– Corrosion in reinforced concrete

Leaching

The internal strcuture of concrete is rich of calcium hydroxide $Ca(OH)_2$ which does not have any notable effect on the strength of concrete, but it fills some of the concrete pores and keeps concrete pH above 12.5. When concrete is saturated with water the calcium hydroxide $Ca(OH)_2$ and other soluble salts are dissolved and transported out of concrete, thus increasing the porosity and decreasing the pH of concrete. This process is called Leaching.

Figure 17– Leaching of lime in concrete

1.4.3.Biological Causes of Concrete Deterioration

The metabolic activity of microorganisms causes liberation of many acids as well as hydrogen sulfide and other corrosive reagents into environment. Algae, Fungi, Bacteria, etc are some of the biological threats causing the deterioration of concrete.

Marine Environment

Sea water is a mix of different aggresive environments, because seawaters contain about 3.5% soluble salts and their pH varies from 7.5 to 8.4. On the other hand concrete in marine environment is effected from the combined effects of chemical, physical and biological processes such as: sulfate attack, leaching of lime (calcium hydroxide), alkali-aggregate expansion, salt crystallization, alternate wetting and drying, freezing and thawing, corrosion of embedded reinforcing or pre-stressing steel, eosion and abrasion from waves etc.

Figure 18– Concrete in sea water

The parts of reinforced concrete structures built in marine environment can be classified into three zones regarding the contitions of environment affecting its durability. The first one is the Submerged Zone, which is the lower part, continuously covered by seawater. The second one is the midle part, called Splash Zone, which is subject to continuous wetting and drying. Whereas the third one is the upper part, called Atmospheric Zone, subjected to occasional seawater sprays. The most endengered part is the Splash zone.

Severity of environment

As a general classification exposure conditions can be classified as: Mild/Negligible or Low, Moderate, Severe,Very severe.Whereas EN 206-1 classifies the exposure conditions in more

6 Chemical attack		
Where concrete is exposed to chemical attack from natural soils and ground water as given in table 2, the exposure shall be classified as given below. The classification of sea water depends on the geographical location, therefore the classification valid in the place of use of the concrete applies. NOTE A special study may be needed to establish the relevant exposure condition where there is: - limits outside of table 2; - other aggressive chemicals; - chemically polluted ground or water; - high water velocity in combination with the chemicals in table 2.		
XA1	Slightly aggressive chemical environment according to table 2	
XA2	Moderately aggressive chemical environment according to table 2	
XA3	Highly aggressive chemical environment according to table 2	

3 Corrosion induced by chlorides other than from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts, from sources other than from sea water, the exposure shall be classified as follows: NOTE Concerning moisture conditions see also section 2 of this table.		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements Car park slabs
4 Corrosion induced by chlorides from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water, the exposure shall be classified as follows:		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5 Freeze/thaw attack with or without de-icing agents		
Where concrete is exposed to significant attack by freeze/thaw cycles whilst wet, the exposure shall be classified as follows:		
XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agent	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	Road and bridge decks exposed to de-icing agents Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zones of marine structures exposed to freezing
Class designation	Description of the environment	Informative examples where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: All exposures except where there is freeze/thaw, abrasion or chemical attack For concrete with reinforcement or embedded metal: Very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation		
Where concrete containing reinforcement or other embedded metal is exposed to air and moisture, the exposure shall be classified as follows: NOTE The moisture condition relates to that in the concrete cover to reinforcement or other embedded metal, but in many cases, conditions in the concrete cover can be taken as reflecting that in the surrounding environment. In these cases classification of the surrounding environment may be adequate. This may not be the case if there is a barrier between the concrete and its environment.		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

Figure 19– Concrete exposure condition according to EN 206-1

2. QUESTIONS

1. Which of the following definitions explains better the Durability of Concrete?

Durability of Concrete refers to:

a) The capability of concrete to withstanding the conditions for which it has been designed throughout the life of the structure.
b) The maximum load that concrete can withstand.
c) The innovative technologies used for concrete production.
d) The advantages of concrete as construction materials.

2. Which part of RC structures built in sea water is exposed to a more aggressive environment?

a) The Submerged zone, which is always below the water level.
b) The Splash zone, which is subjected to continuous wetting and drying.
c) The Atmospheric zone, which is not in direct contact with water.

3. Which of the following is not true regarding the effect of carbonation in RC structures?

a) Compressive strength of carbonated concrete increases in comparison with non-carbonate concrete.
b) Increase of carbonation depth, increases the corrosion level of the embedded steel rebars.
c) Carbonation of concrete is related to the sulfate attack.

4. Which of the following levels is part of General environment severity:

a) Mild
b) Moderate
c) Sever
d) all of them?

5. The process of dissolving and transporting substances out of concrete is called

a) Leaching
b) Hydration
c) Deterioration
d) Seepage

6. In order to improve the freeze-thaw resistance of concrete we use:

a) Air-entraining agent.
b) Plasticizers
c) Formwork
d) Salty water

3. REFERENCES

[1] Mehta, Kumar and Monteiro, Paulo. *Concrete: microstructure, properties, and materials*. McGraw-Hill Publishing, 2006.

[2] Souza Junior, O. A., and Oliveira DRC. "Influence of the cable´ s layout on the shearing resistance of prestressed concrete beams." Revista IBRACON de Estruturas e Materiais 9.5 (2016): 765-795.

[3] Day, Richard, and John Clarke. "Plastic and thermal cracking." Advanced Concrete Technology (2003).

[4] Portland Cement Association. Types and Causes of Concrete Deterioration

[5] Islam, GM Sadiqul, and Sristi Das Gupta. "Evaluating plastic shrinkage and permeability of polypropylene fiber reinforced concrete." International Journal of Sustainable Built Environment 5.2 (2016): 345-354.

[6] Last name, First name or Initials year. Title of article. *Title of Journal* (series number if necessary) volume number (issue number if necessary): page numbers.