

BEHAVIOUR OF CONCRETE STRUCTURES UPON THE IMPACT OF UV AND RAIN OF NATURAL ACIDITY

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Abstract

A common basic assumption in civil engineering is that rainwater is chemically neutral ($\text{pH} = 7.0$). However, even under pristine conditions, rainwater is often more acidic due to natural emissions of organic acids. Even natural rain acidity may be very aggressive against natural stones and concrete. A harmful impact of UV radiation on the concrete durability was discussed by the authors for the first time in 2006. The objective of the current research was the characterization of weathering processes occurred in the wet cast concrete subjected to the normal acidic rain and UV radiation, and the evaluation of their possible effect on the reinforced concrete durability. It was revealed that organic acids contained in rain of the natural acidity promote an intense concrete carbonation, even when a permeability of concrete looks to be low.

Keywords: concrete, durability, acidic rain, UV radiation, permeability, carbonation

1. INTRODUCTION

Concrete is a dominant construction material today with an annual worldwide production of over 4.5 billion metric tons (Mehta P. K. and Monteiro J. M., 1992). It is most likely that concrete will continue to have the same importance in the future. Therefore, the modern concrete materials must meet new and higher demands of long life-cycle and high performance, especially in preventing the steel corrosion. Nowadays the steel corrosion is 'problem # 1' faced by the reinforced concrete structures in the world. The main factors affecting the steel corrosion in concrete are chloride ingress and carbonation of concrete (Bentur, 1997)). The mechanisms of steel corrosion in concrete have been in a research focus for the last 20 years. The special lab tests were designed to evaluate the durability of reinforced concrete upon the chloride attack or carbonation. Mostly these tests are based on the cyclic exposure of concrete samples to environments simulating the moist and dry conditions which can strongly affect the rate of carbonation or chloride ingress in concrete.

A common basic assumption in most codes, standards and practices dealing with evaluating the durability of concrete is that rainwater is chemically neutral ($\text{pH} = 7.0$) if there are no any polluted species causing the acidic rain and fog/dew ($2 \leq \text{pH} < 4.5$) (Norvaišienė *et al.*, 2007). However, the recent hydrological and ecological investigations have revealed that rainwater has slightly acidic pH in the different geographical regions (Winkler, 1997; White, 2003; Chandra *et al.*, 2005; Hu *et al.*, 2003; Peña *et al.*, 2002; Levi and Rosenfeld, 1996; Herut *et al.*, 2000; Mahfoud and Beck, 2003). Rainwater in equilibrium with carbon dioxide (CO_2) in air (and with no other species affecting pH) is slightly acidic, with a mean pH of 5.6, while neutral water exhibits a pH of 7.0, Fig 1. However, even under pristine conditions, rainwater is often more acidic due to natural emissions of organic acids, e.g. acetic acid, $\text{CH}_3\text{--COOH}$, oxalic acid, HOOC--COOH , and formic acid CH--OOH (Rogge *et al.*, 1993; Limbeck *et al.*, 2001; Fornaro and Gutz, 2003; Wang, 2007). On the other hand, typical pH values of acid precipitation caused by anthropogenic emissions (gaseous air pollution incl. CO_2 , NO_x , and SO_2) may be in the range of 2.0 – 4.5 (Menz and Seip, 2004). A distribution of rainwater pH in the different geographical regions is shown in Fig 2.

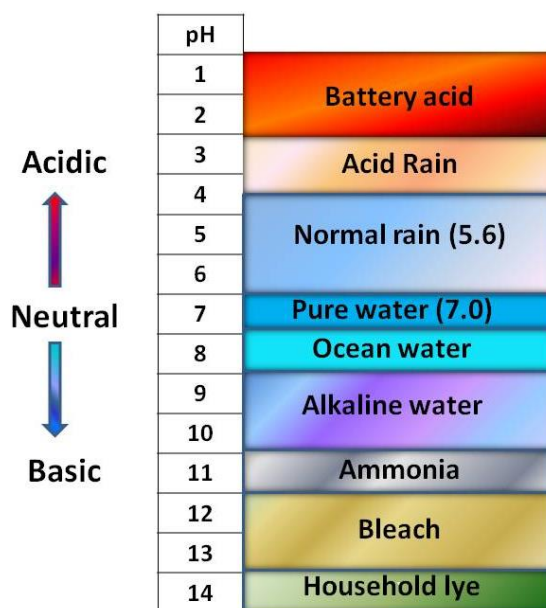


Figure 1: pH of most common water based solutions

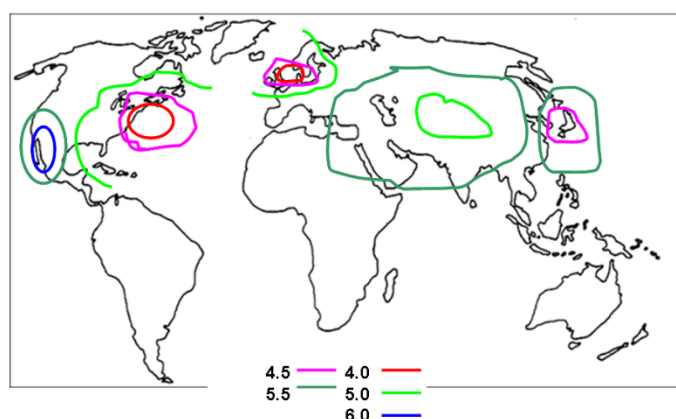


Figure 2: Mean rainwater pH in the world (according to Winkler, 1997)

Acidic attack represents a worrying topic of increasing significance, owing to the spread of damages of concrete structures in over the entire world (Okochi *et al.*, 2000; Zivica and Bajza, 2001). Even natural rain acidity may be very aggressive against natural stones and concrete. Carboxylic acids may be of such a kind, especially those having their molecules substituted by electronegative radicals, like halogens or keto-groups, etc. significantly increasing their acidity. Generally, the great effect of organic acid on dissolution of rocks and minerals is attributed to the presence of hydrogen ions and the formation of cation-complexes. The structural cations, released from minerals as a result of the attack of hydrogen ions, tend to form cation–organic complexes with oxalic acid in which cation–oxygen bonds are more susceptible to hydrolysis and weathering (Chen *et al.*, 2000). This alteration translates into decalcification of the cement paste, and a modification of microstructure manifesting itself by the progressive dissolution of all the crystallized phases and the formation of a probable silica gel enriched with silicon, aluminum and iron in the superficial layer. Thus the altered cement paste has poor mechanical resistance (Bertron, 2004). On the other hand insoluble salts of calcium and aluminium formed by oxalic acid are not aggressive for hydrated cement (Mangabhai, 1990).

It is important to emphasize that oxalic and acetic acids are broadly used as inhibitors of steel corrosion (Wiersma and Subramanian, 2002; Wiersma and Mickalonis, 2008; Giacomelli *et al.*, 2004; Kuznetsov

and Ibatullin, 2002; Invernizzi *et al.*, 2008; Asatryan and Balayan, 1965). The optimal passivation properties of these acids are found at $\text{pH} > 3$ and the temperature less than 50°C (Wiersma and Subramanian, 2002; Wiersma and Mickalonis, 2008; Giacomelli *et al.*, 2004). Of those acids, formic acid, even of the small concentration, might to be a factor causing steel corrosion (Invernizzi, 2008). Generally, the concentration of formic acid in atmosphere depends on the photochemical degradation of formaldehydes originated in the air pollution from electricity-generating fuel combustion plants and industrial boilers (Karademir, 2006). The accumulation of formic acid causes to the changes in organic acids' equilibrium of normal rain, as well as to a dominance of formic acid over oxalic and acetic acids in rainwater. Therefore, such a change might accelerate steel corrosion in the concrete structures placed in the industrial zones with the fuel combustion plants and the industrial boilers.

Furthermore, it should be emphasized that acetic and oxalic acids are effective as corrosion inhibitors only if any inorganic anions are deficient in the environment, i.e.:

- chlorides: the inhibiting properties of acetic acid are considerable if the content of chloride ions in solution is less than 1% in terms of NaCl (Okafor and Nesic, 2007). Whereas, the chloride content in Mediterranean Sea is about 3% in terms of NaCl;
- SO_3^{2-} and NO_3^- : the combination of carboxylic acids and sulfuric or nitric acids, even of low concentration, causes a prompt acceleration of steel corrosion (Invernizzi *et al.*, 2008; Wiersma and Subramanian, 2002). Obviously, sulfuric and nitric anions are available in concrete, especially in the exposed one.

The awareness to the harmful effect of UV radiation on the bio-organic and organic polymeric systems has risen in recent years (Brenner *et al.*, 1998; Wolf *et al.*, 2001; Johnson and McIntyre, 1996). However, the pioneer research made by the author in 2006 has discussed for the first time a harmful impact of UV radiation on concrete durability (Wasserman and Bentur, 2006). Before this research the common opinion was that the UV energy could affect only a solid surface directly exposed to the radiation, whereas the UV rays are incapable to penetrate into the solid material bulk. However, the studies carried out by the space scientists on Mars have revealed that the UV energy caused the chemical activation of aluminosilicate soils at depth of up to 10 cm (Yen *et al.*, 2000; Zent, 2003; Nussinov, 1978). This activation was a result of the following chemical and physical processes:

- UV radiation might cause the photolysis of the atmospheric water and breaking the chemical bonds $-\text{Si}-\text{O}-$ in aluminosilicate matrix, and these destruction processes could lead to the formation of superoxide radicals: H_2O_2 , $\text{O}^{\bullet-}$; $\text{O}_2^{\bullet-}$, $\text{O}_3^{\bullet-}$, precipitating on the soil surface ;
- The formed superoxide radicals are characterized by the highest chemical reactivity and perfect mobility. Following the adsorption on silica molecular centers, the superoxide radicals diffuse into the solid bulk in very short repositioning hops of 2.6×10^{-9} seconds. Additionally, UV radiation catalyzed a penetration of physically trapped oxygen into the material bulk (Nussinov, 1978). Therefore, it was concluded that the silicate lattice accelerates the destructing impact of UV radiation on aluminosilicate matrix;
- The direct UV radiation causes a photochemical transformation of iron phases at surface of aluminosilicate soil. This process is an additional source of the superoxide radicals penetrating into the material bulk. The superoxide radicals oxidize the organic materials contained in the aluminosilicate soils, Fig. 3.

There is a partial similarity of the chemical and mineralogical composition of the cement gel and the aluminosilicate soils. Therefore, one can expect that the described chemical and physical processes might occur in the cement gel upon the impact of UV radiation and in the presence of organic acids in concrete. In addition, transition metals (iron phase) could cause the photo-induced catalytic and photo-assisted chain reactions of the organic radicals (Zepp, 1992; Faust and Zepp, 1993; Zuo, 1995; Sulzberger and Laubscher, 1995; Hennig, 1999; Zhou, 2004) which could be presented in concrete due to the absorption of natural rainwater. Furthermore, it could be supposed that highly acidic hydrogen peroxide, H_2O_2 , formed in the described processes might disassemble calcium hydrosilicate minerals causing the

formation of dissolved colloidal silica, SiO_2 , and calcium ions, Ca^{2+} . This process is similar to geochemical weathering of hydroalumosilicate rocks caused by the natural acids (White, 2003).

SEM observations of concrete exposed to UV radiation showed the microstructural deterioration of dry-cast concrete and the formation of new minerals lacking in the concrete exposed to the lab and the natural acidic environments, (Wasserman and Bentur, 2006).

The combined effect of the natural acidic rain and UV radiation on the concrete durability could be of a predominant importance for the concrete structures in arid and semi-arid areas. However, understanding of the processes occurring in the concrete exposed to the combined effect of UV radiation and natural acidic rain is still lacking.

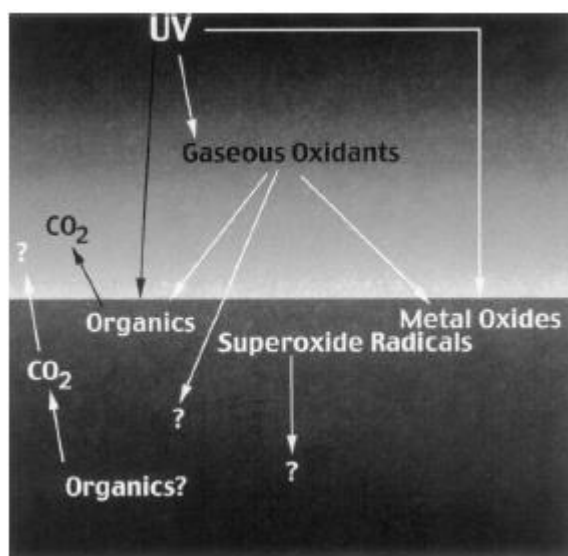


Figure 3: Chemical processes caused by UV radiation in aluminosilicate systems like as soil (Zent, 2003)

2. OBJECTIVE

The objective of the research was the characterization of weathering processes occurring in wet cast concrete subjected to the normal acidic rain and UV radiation, and the evaluation of their possible effect on reinforced concrete durability. The environmental conditions incl. normal rain and UV radiation are typical for the Eastern Mediterranean region. However, these weathering factors have been still neglected by civil engineers in the concrete design. Hence, they may have a crucial importance for an assessment of the long-term durability of the concrete structures.

3. EXPERIMENTAL

3.1 Concrete composition

Three concrete mixes were made of Type CEM I 52.5N Portland cement. The cement content in the concretes was constant, 350 kg per 1 m³. The mixes were prepared with the different water-cement ratios of 0.45, 0.5 and 0.6, with or without commercial carboxylic superplasticizer Glenium 51 added to control workability of the fresh concretes. Water content in concretes was kept as 179 ± 23 kg per 1 m³. The crushed coarse dolomite aggregates were used, as well as the quartz sea sand. The characteristics of the coarse aggregates were as follows:

- *large-size aggregate*: maximal particle size - 19-mm; oven-dried bulk density - 2,730 kg/m³, maximal water absorption – 0.8% (by weight);

- *medium-size aggregate*: maximal particle size – 9.5-mm; oven-dried bulk density - 2,650 kg/m³, maximal water absorption – 1.4% (by weight)

The composition of concretes is summarized in Table 1.

3.2 Sample preparation and curing

Concretes were prepared step-by-step in a drum mixer. The large and medium size aggregates were mixed with 2/3 of the water content during 1 min and hold over 10 minutes afterwards. Cement, sand, the superplasticizer and remain water were added, and the concrete mix was blended for another 3 minutes.

After moulding the concrete samples were kept under polyethylene foil for 24 hours. After demoulding the concrete samples were cured in moist environment at 21°C/100%RH for the next 6 days and matured at the lab environment (21°C/60%RH) till the age of 28 days old.

3.3 Concrete ageing

Few samples continuously kept at lab conditions (20°C/60%RH) were used as the control models.

Other matured concrete samples were exposed to the two-step accelerated weathering simulated the Eastern Mediterranean climate, i.e.:

- “rain” ageing step consisted of exposure of the concrete samples to twelve cycles of “shower” simulating the Mediterranean discontinuous natural rain (Peña et al., 2002, Levi and Rosenfeld, 1996, Herut et al., 2000). Each cycle included “raining” period followed by moist keeping under the polyethylene foil. “Raining” period lasted 72 hours; the “rain” capacity was 45 litre of solution supplied at a rate of 600 ml/hour. The chemical composition of the artificial rain solution is presented in Table 2. After each “raining” period the samples were covered with a polyethylene foil and kept for the next 96 hours at temperature of 20° C. This ageing routine fits a mean annual raining regime in the Eastern Mediterranean (Goldreich, 1995).

Table 1: Composition of concretes

Component, kg per 1 m ³	Water/cement ratio, w/c		
	0.45	0.5	0.6
Portland cement CEM I 52.5N	347	356	352
Water	156	178	202
Large-size aggregate	773	807	771
Medium-size aggregate	378	382	386
Natural sand	722	701	695
Superplasticizer content, % of cement weight	1.2%	1.0%	0%
Air content, litre per 1 m ³	57	23	16
Cone slump, mm	90	204	115
Fresh concrete bulk density, kg/m ³	2,380	2,427	2,407

- « solar » ageing step – exposure of concrete to 90 cycles of UV and IR radiation imitating an impact of solar energy. Each radiation cycle included the direct UV radiation with intensity of 16 – 20 W/m² for 6 hours at a temperature of 60°C and relative humidity of 65% RH, and IR radiation for next 18 hours at temperature of 35°C and relative humidity of 65% RH. The temperature intervals, as well as an intensity of UV radiation were experimentally measured at building facades in Haifa in

summer periods of 2006 - 2008. The measurements proved the literature data that even when the air temperature was 27° - 32°C, the wall substrate becomes easily hot over 60°C (Stephenson, 1963). The high levels of UV radiation in the Eastern Mediterranean were reported elsewhere (Wasserman and Bentur, 2006). In the current research UVA lamps were used with a peak emission at 340 nm enabling the simulation of a sun radiation at the ultra-violet range of 295 to 365 nm (ASTM, 2006). IR radiation was provided with 250W Screwbase Ceramic Infrared Heating Emitter. The constant level of relative humidity was achieved with glycerin solution (ASTM, 2003).

Some of the samples were exposed to only one-step aging, whereas others were subjected to the combined courses of ageing steps, i.e.:

- “winter” course: “rain” ageing step followed by “solar” ageing;
- “summer” course – vice versa.

These itineraries were carried out in order to reveal which one of two weathering mechanisms might cause more destructive effect on concrete durability in arid and semi-arid Mediterranean climate.

3.4 Concrete testing

Concrete tests were carried out with the control and weathered samples.

Compressive strength—100 mm cubes were prepared and tested at ages up to 240 days.

Total absorption—Oven-dry disc specimens were immersed in boiling water for 3 h, cooled down slowly to room temperature, and then dried in an oven to a constant weight. Total absorption was calculated as the weight loss on drying from saturated surface dry conditions to oven dry condition.

Table 2: Chemical composition of the solution imitating the natural acidic rain in the Eastern Mediterranean (Peña et al., 2002, Levi and Rosenfeld, 1996, Herut *et al.*, 2000)

Ions	Content, µeqv/l
Na ⁺	172
K ⁺	9
Ca ²⁺	185
Mg ²⁺	71
SO ₄ ²⁻	114
Cl ⁻	213
HCO ₃ ⁻	119
NO ₃ ⁻	23
Organic acids	Content, µmol/l
Formic acid, HCOOH	11.9
Acetic acid, CH ₃ COOH	11.6
Oxalic acid, H ₂ C ₂ O ₄	3.8
Citric acid, H ₃ C ₆ H ₅ O ₇	1.0
Lactic acid, C ₃ H ₆ O ₃	5.9
pH	5.0

Capillary Absorption—Capillary absorption was determined according to EN 772–11 (CEN, 2004 – 2006), using cylindrical specimens (200 mm diameter and 50 mm height). The specimens were dried at $55 \pm 2^\circ\text{C}$, sealed with bitumen at the top and the cylindrical sides, and then immersed in water to a depth of 5 mm. The weight increase over time was measured, and the capillary absorption coefficient was calculated from the slope of the curve of weight increase vs. square root of time.

Air permeability test - The air permeability was determined using the Torrent test method, (Torrent, 1992), which is based on the measurement of the air flow on a pressurised concrete surface. Air permeability test was done with control samples, samples after one-step aging, and samples after the combined courses of ageing steps. For these tests the specimens were conditioned by drying at 60°C until a constant weight was achieved, in order to neutralize the effect of moisture content.

Accelerated carbonation—Accelerated carbonation was determined by exposure of concrete samples to environment of 5% CO_2 /50%RH/ 30°C and testing the depth of carbonation at predetermined time periods. Carbonation coefficient was calculated from the slope of the curve of carbonation depth vs. square root of time. For these tests the specimens were conditioned by drying at 60°C until a constant weight was achieved, in order to neutralize the effect of moisture content.

4. RESULTS

4.1 Concrete strength

Fig 4 presents the compressive strength of the concretes before and after accelerated weathering. Generally, two mechanisms of weathering almost had no substantial effect on the concrete strength.

However, small enhancing effect was in concretes that were subjected to the “winter” weathering course, i.e. “rain” ageing step followed by “solar” ageing. The differences between strengths of concretes after “winter” and “solar” weathering courses was about 6% for all water/cement ratios.

4.2 Concrete permeability

4.2.1 Water absorption

The results of the total and capillary water absorption are shown in Figs 5 & 6, respectively. The concretes after weathering courses were characterized by lower water absorption, then unweathered control samples. “Summer” weathering course had stronger effect on water absorption than the “winter” one. These effects were more substantial for capillary water absorption. The difference in water absorption of concretes after various weathering courses increases with the decrease in water/cement ratio.

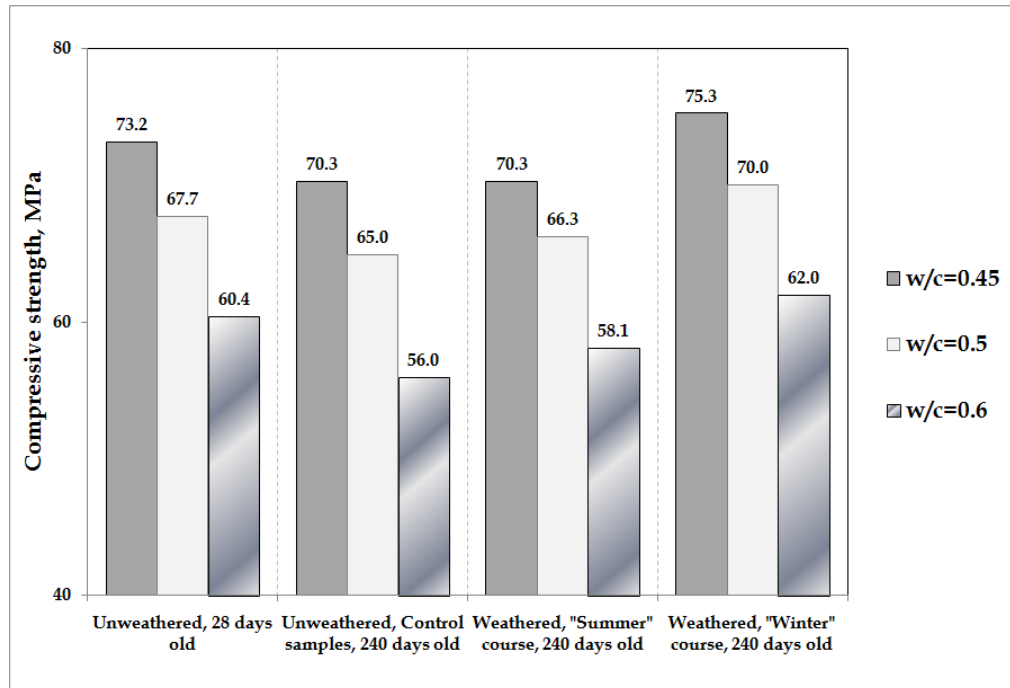


Figure 4: Compressive strength of concretes

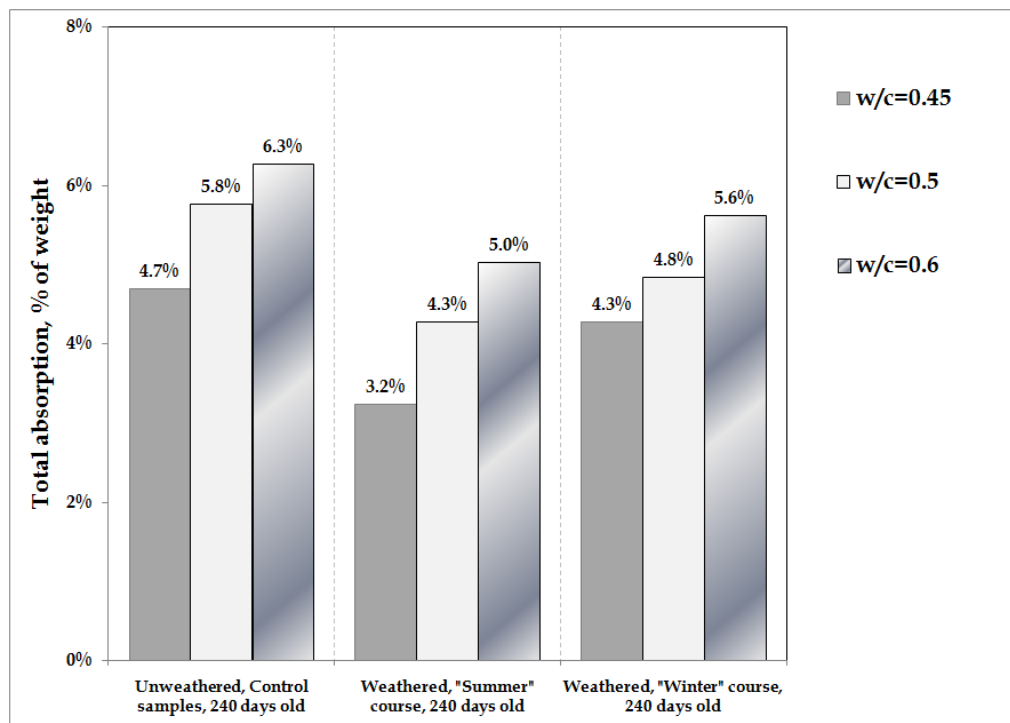


Figure 5: Total absorption of concretes

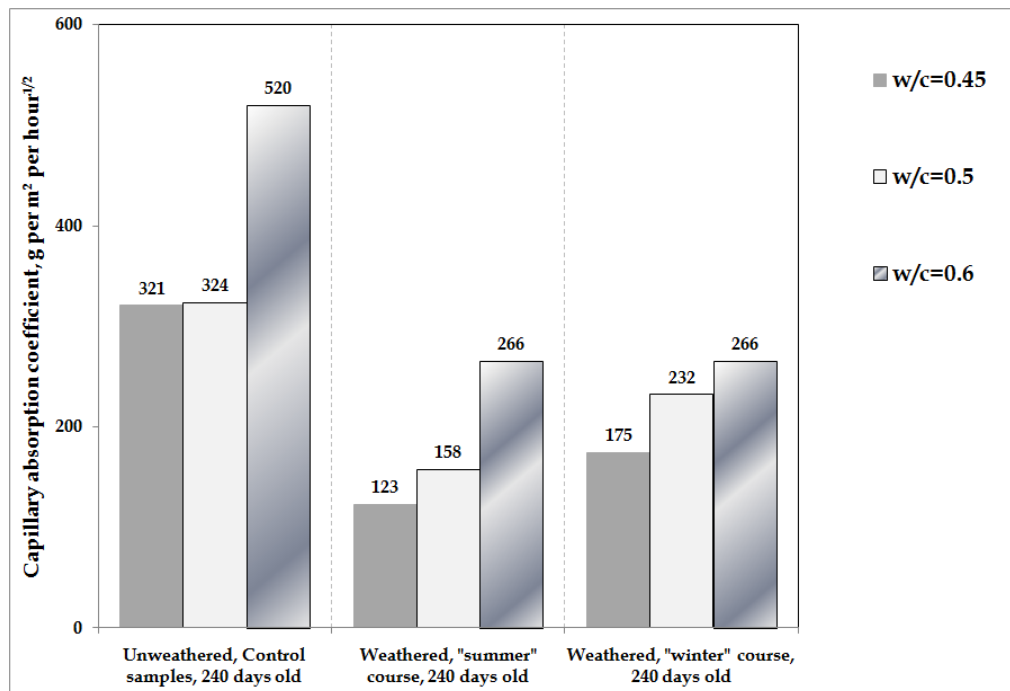


Figure 6: Capillary absorption coefficient of concretes

4.2.2 Air permeability

The results of air permeability test are presented in Fig 7. The trends observed in air permeability of concretes exposed to the combined weathering courses, were similar to the patterns showed by water absorption, i.e.: weathering of concretes led to the decreased air permeability. This trend, however, completely extreme, was also distinctive for one-step "rain" aging. The concretes after this aging were almost air-impermeable. In spite of "rain" aging, the air permeability of concretes after one-step "solar" aging increased by a factor of 3 to 4. Thus, the counter impact of "rain" and "solar" aging on concrete air permeability could be concluded.

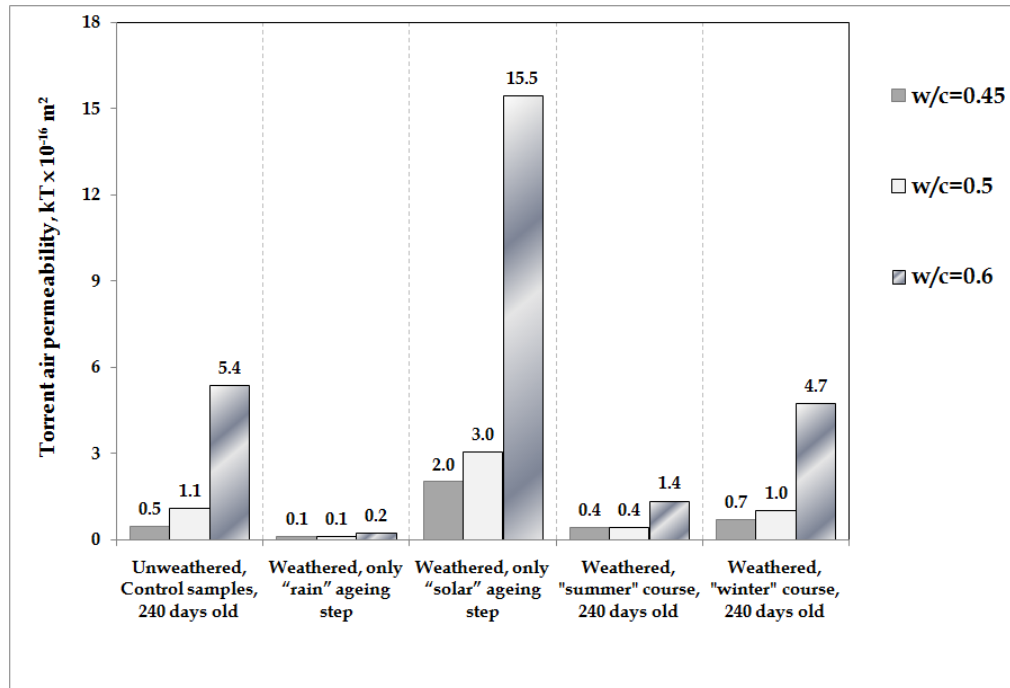


Figure 7: Torrent air permeability of concretes

4.3 Concrete durability

4.3.1. Accelerated carbonation

Tables 3-5 summarize the images captured from the concretes before and after accelerated carbonation. Average depths of low pH band formed in concretes after 56 days of accelerated carbonation are shown in Fig 8. It could be suggested that in spite of the improved permeability characteristics of the weathered concretes, the carbonation process was almost not affected by weathering of any mode. The magenta patterns of high pH observed in weathered samples were more fade coloured and surrounded by degraded pinkish halos. This unexpected phenomena was very obvious in concretes made with water/cement ratios of 0.5 & 0.6 aged by "winter" course weathering.

Table 3: Accelerated carbonation of concretes $w/c = 0.45$

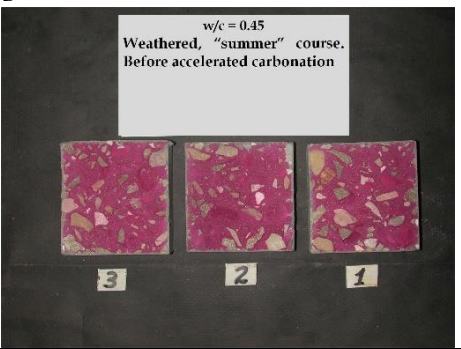
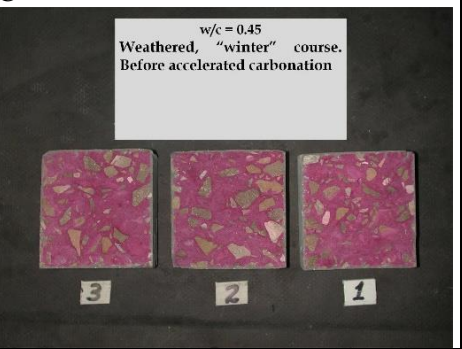
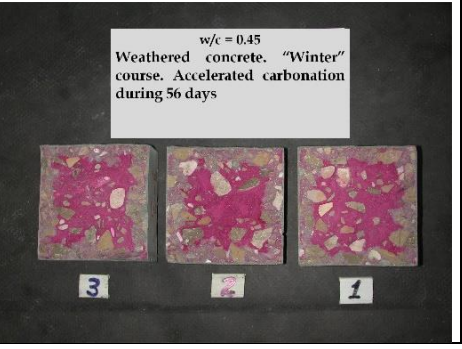
	Unweathered. Control samples	Weathered. "Summer" course	Weathered. "Winter" course
Before carbonation	A  $w/c = 0.45$ Unweathered concrete. Control samples. Before accelerated carbonation	B  $w/c = 0.45$ Weathered, "summer" course. Before accelerated carbonation	C  $w/c = 0.45$ Weathered, "winter" course. Before accelerated carbonation
After carbonation during 56 days	D  $w/c = 0.45$ Unweathered concrete. Control samples. Accelerated carbonation during 56 days	E  $w/c = 0.45$ Weathered concrete. "Summer" course. Accelerated carbonation during 56 days	F  $w/c = 0.45$ Weathered concrete. "Winter" course. Accelerated carbonation during 56 days

Table 4: Accelerated carbonation of concretes $w/c = 0.5$

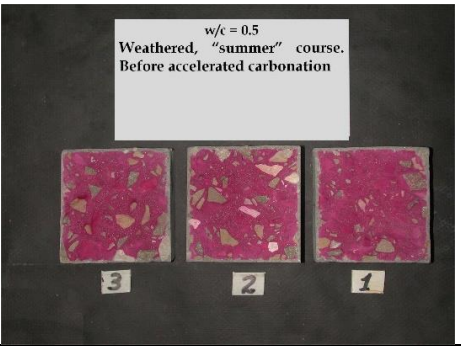
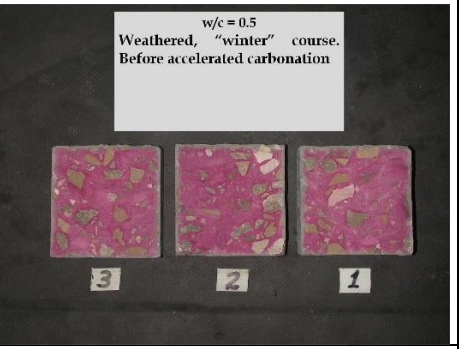
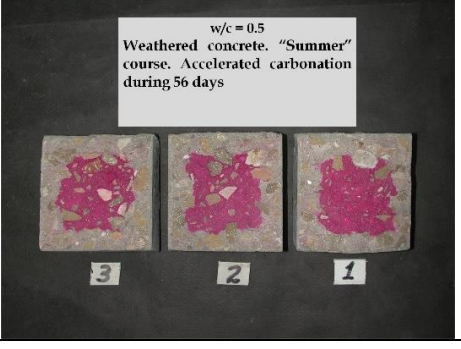
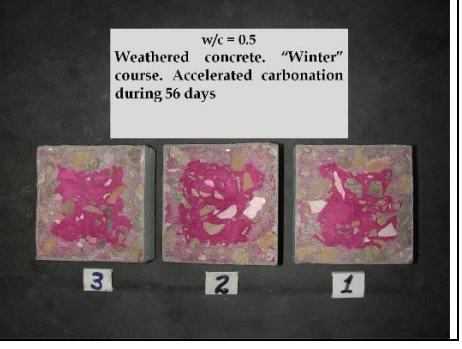
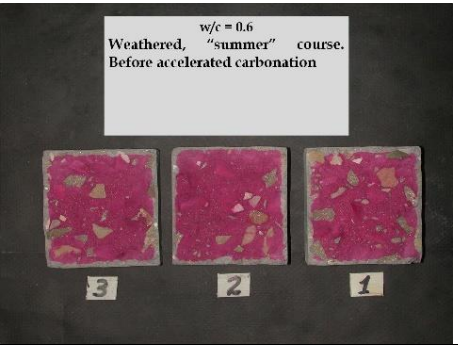
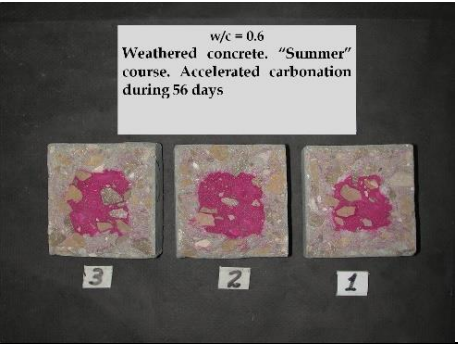
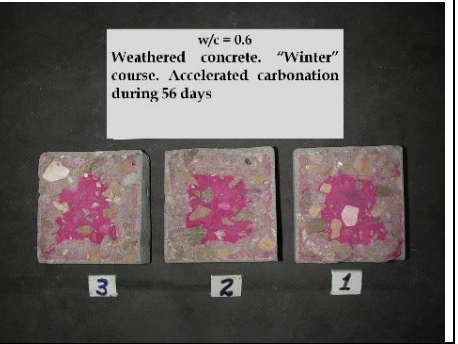
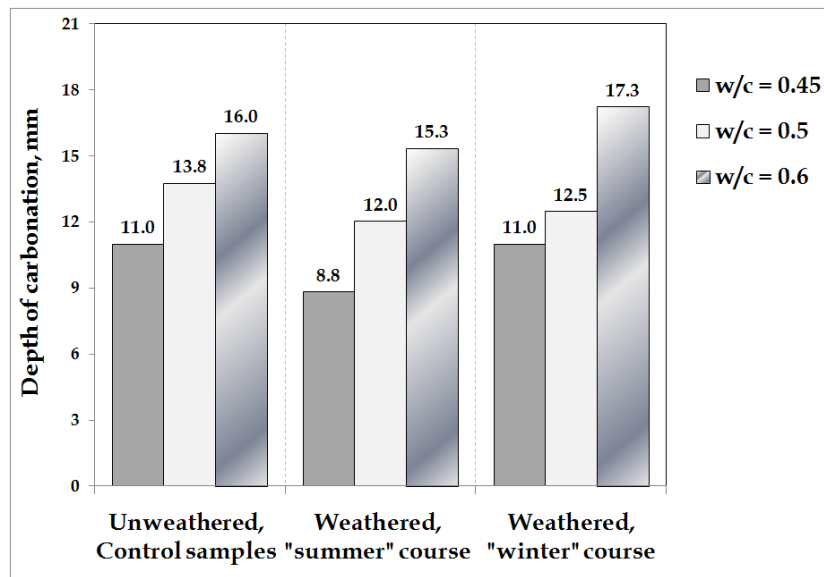
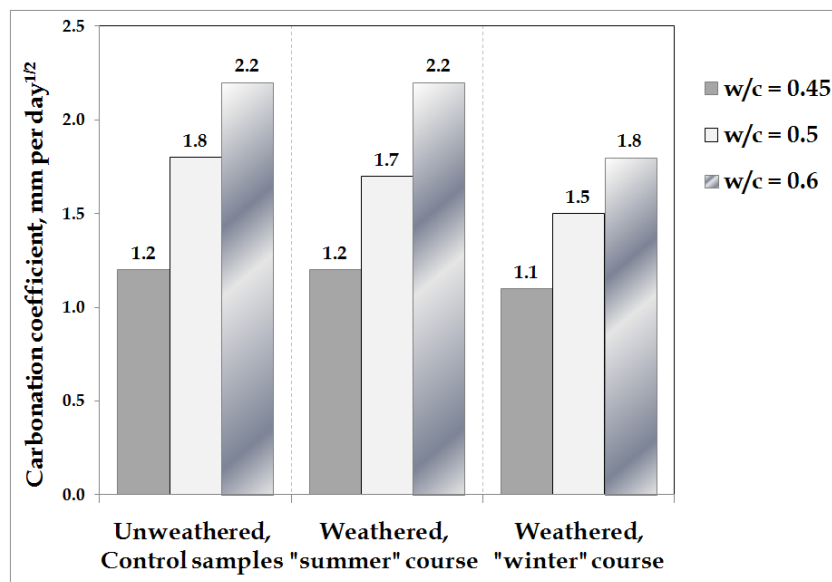
	Unweathered. Control samples	Weathered. "Summer" course	Weathered. "Winter" course
Before carbonation	A  $w/c = 0.5$ Unweathered concrete. Control samples. Before accelerated carbonation	B  $w/c = 0.5$ Weathered, "summer" course. Before accelerated carbonation	C  $w/c = 0.5$ Weathered, "winter" course. Before accelerated carbonation
After carbonation during 56 days	D  $w/c = 0.5$ Unweathered concrete. Control samples. Accelerated carbonation during 56 days	E  $w/c = 0.5$ Weathered concrete. "Summer" course. Accelerated carbonation during 56 days	F  $w/c = 0.5$ Weathered concrete. "Winter" course. Accelerated carbonation during 56 days

Table 5: Accelerated carbonation of concretes $w/c = 0.6$

	Unweathered. Control samples	Weathered. "Summer" course	Weathered. "Winter" course
Before carbonation	A 	B 	C 
After carbonation during 56 days	D 	E 	F 



a)



b)

Figure 8: Accelerated carbonation of concretes: a) depth of low pH band after 56 days of carbonation; b) carbonation coefficient

5. DISCUSSION

The changes occurred in the concretes due to weathering could be concluded as a covercrete alteration. The compressive strength and the total absorption which are the bulk features of concrete, have been almost unaltered by weathering courses. However, the capillary absorption and the air permeability, which are the main covercrete characteristics, indicate concrete microstructural changes. Generally, a decrease of permeability is a positive phenomenon regarding concrete durability. However, this was not the case in the current study. The accelerated carbonation of weathered concretes was substantially higher than might be expected from the permeability characteristics. The carbonation characteristics of the weathered and unweathered concretes were almost equal. However, the weathered concretes were less permeable. Thus, the enhanced carbonation of the weathered concretes could be caused by the internal source of CO₂ needed for the carbonation processes. First of all, CO₂ could be formed in

weathered concretes because of the dissolution of calcium carbonate by acetic and formic acids at surface of coarse and medium-sized aggregates. This process is described by equations presented in Fig 9. Obviously, the rate of this process depends on concentration of acids, temperature, humidity, aggregate surface characteristics, etc.

As was previously mentioned, iron phase contained in cement matrix could cause the photo-induced catalytic and photo-assisted chain reactions of organic acids (Zepp, 1992, Faust and Zepp, 1993, Zuo, 1995, Sulzberger and Laubscher, 1995, Hennig, 1999, Zhou *et al.*, 2004). Thus, these chain reactions might occur in concrete and serve as an additional internal source of CO₂ formed from oxalic and acetic acids absorbed by concrete during weathering courses. These processes could be described by equations presented in Figs 10-11. Obviously, the acids concentration, UV radiation intensity and the content of iron phases in Portland cement seem to be the main factors determining the rate and the intensity of these processes.

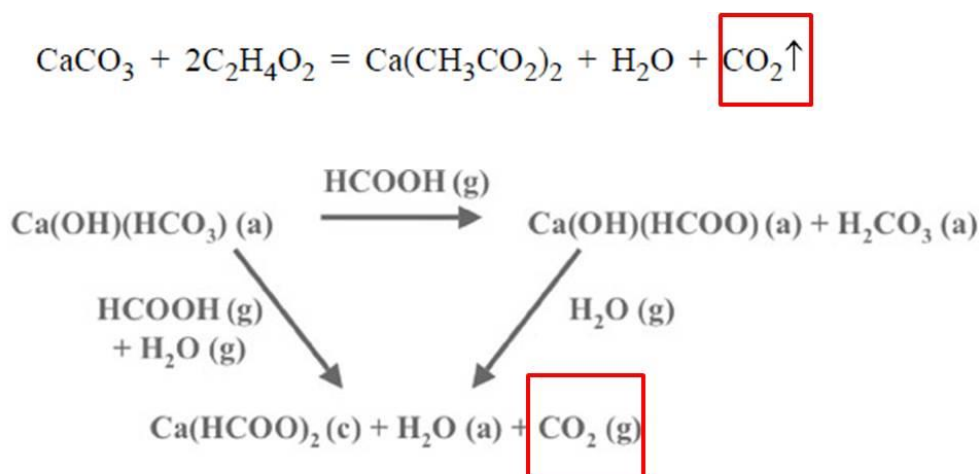


Figure 9: Formation of CO₂ caused by dissolution of calcium carbonate in presence of acidic and formic acids, according to Blinkova and Eliseev, 2005, Al-Hosney *et al.*, 2005)

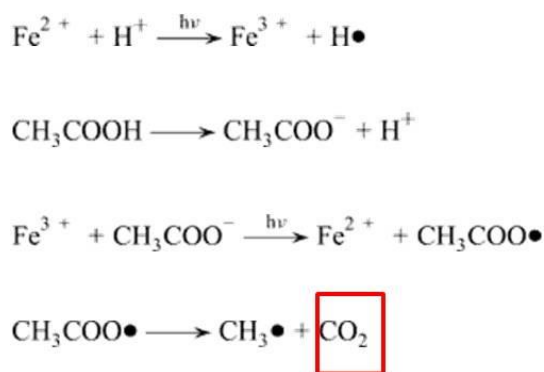


Figure 10: Formation of CO₂ caused by decomposition of acetic acid in presence of iron oxides, according to Yang *et al.*, 2010.

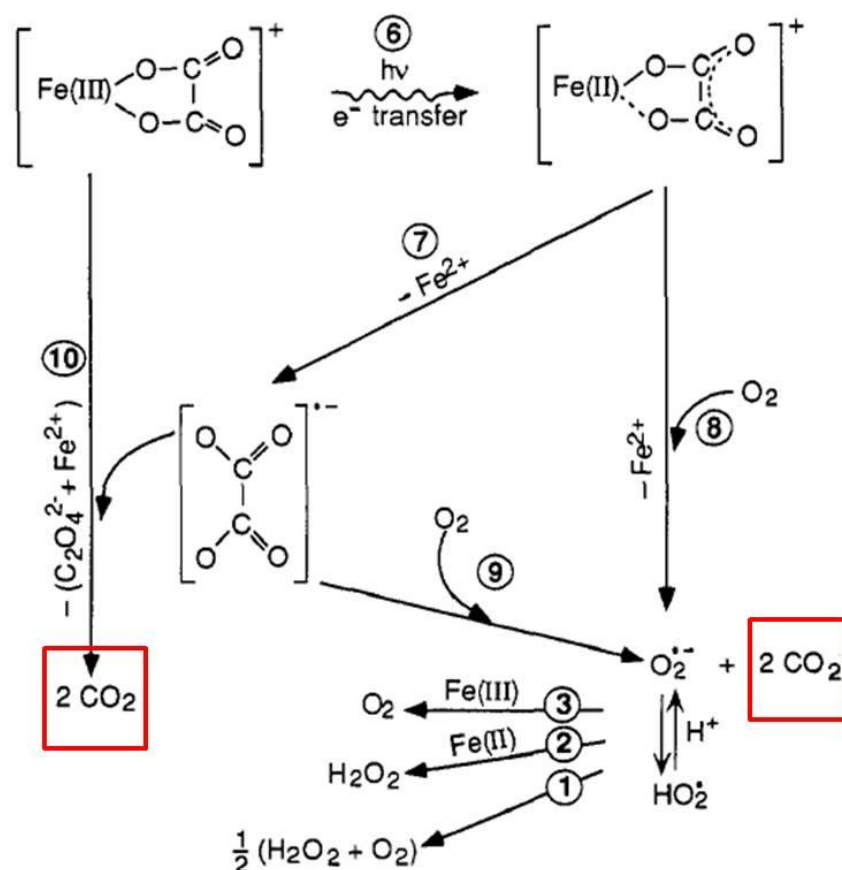


Figure 11: Formation of CO₂ caused by decomposition of iron-oxalic complexes, according to Zuo and Deng, 1997

Therefore, organic acids contained in rain of the natural acidity could be suggested as “delayed action mine” could promote an intense concrete carbonation, even when the permeability of concrete is low. Therefore, the accumulation of organic acids in the concrete in the course of its service life will cause two complementary effects of pH reduction in the covercrete, i.e.:

- A direct decrease of pH caused by neutralization reaction of absorbed organic acids with concretes alkalis. The fade hue of magenta phenolphthalein patterns observed in weathered concretes before an exposure to accelerated carbonation confirms that weathered concretes had the decreased levels of pH in comparison to unweathered control samples, see Table 4 (Fig. 14.1 in ChemEd DL).
- Internal source of CO₂ causing to a more intensive carbonation of concreted. The intensity of this autogenous carbonation will occur all time that the concrete subjected to natural rain and UV impact.

It seems that carbonation characteristics of weathered concrete should be correlated with the quantity, periodicity and composition of local rainfall and UV radiation intensity. The rain of natural acidity could make the concrete almost air impermeable after relatively short exposure, whereas only UV radiation might be a reason why relatively young concretes have high air permeability after few years of service live. However, more systematic research on this issue should be done.

6. CONCLUSIONS

The mild acidic rain containing organic acids caused a drop in permeability characteristics of concrete. However, the organic acids absorbed by concrete seem to be the reason for more intensive carbonation of concrete, inspite of its apparent low permeability.

The rainfalls of mild acidic pH are characteristic for the Eastern Mediterranean. These rainfalls, even relatively scarce and meagre, and the high levels of UV radiation seem to play an important role in the concrete behaviour upon the carbonation conditions.

In Central Europe increasing trend of UV irradiation has been observed during the last three decades and the forecast that the enhanced recent UV values will persist for the next decades, (Reuder *et al.*, 2001). Therefore, the systematic study of concrete behaviour upon UV radiation should be continued to establish well grounded knowledge of concrete behaviour upon combined impact of UV radiation and rain. The main issues of this study should be the interrelation between the concrete composition, the local meteorological conditions and the long-term durability of reinforced concrete.

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ABBREVIATIONS

% - percent sign

°C - degree Centigrade

C₂O₄²⁻ - oxalate anion

C₃H₆O₃ – lactic acid

Ca(CH₃CO₂)₂ – calcium acetate

Ca(HCOO)₂ - calcium formate

Ca²⁺ - calcium cation

CaCO₃ – calcium carbonate

CEM I 52.5N – type of Portland cement

CH₃COO⁻ - acetate anion

CH₃—COOH; C₂H₄O₂ – acetic acid

CH—OOH – formic acid

Cl⁻ - chloride anion

CO₂ – carbon dioxide

e[•], e⁻ - electron

Fe²⁺; Fe(II) - ferrous cation

Fe³⁺; Fe(III) - ferric cation

H• - hydrogen

hν – photon

H⁺ - hydron; hydrogen cation

HCO₃⁻ - Bicarbonate anion

H₂CO₃ – carbonic acid

H₂O – water

H₂O₂ - hydrogen peroxide

H₃C₆H₅O₇ – citric acid

HOOC—COOH - oxalic acid

IR – infra-red

kg – kilogram
kT – Torrent air permeability coefficient
l - litre
m² - square meter
m³ – cubic meter
Mg²⁺ - magnesium cation
ml – millilitre
mm - millimeter
MPa – megapascal
Na⁺ - sodium cation
NaCl – sodium chloride
nm - nanometer
NO₃⁻ - nitric anion
NO_x - a term for the nitrogen oxide air pollutants
O – oxygen
O₂ – oxygen gas
O₃ - ozone
pH – a measure of acidity and alkalinity of solutions
RH – relative humidity
Si – silicon
SO₂ – sulphur dioxide
SO₃²⁻ - sulfuric anion
SO₄²⁻ - sulfate anion
UV – ultra-violet
UVA – ultra-violet radiation type A
W – watt
w/c - water/cement ratio
μeqv – microequivalent
μmol – micromole