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The Erosion of Reinforced Concrete Walls by the Flow of Rainwater

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Abstract: The action of rainwater on reinforced concrete walls has led to an erosion phenomenon. The erosion is very apparent when the walls are inclined. This phenomenon is studied on a real site characterized by different architectural forms. The site dates back to the seventies; it was designed by the architect, modeler of concrete, Oscar Nie Meyer. On this site, the erosion has damaged the cover of the reinforcements and reduced its depth. In this research work, a method of quantification of the erosion is developed. Using this method, the amount of mass loss by erosion was measured on imprints taken from the site. The results are expressed by the rate of mass loss by erosion; they are associated to the height and the inclination of the walls. Moreover, laboratory analysis was carried out on samples taken from the site. From this study, it is recommended to consider the erosion, in any building code, to determine the cover thickness.

Keywords: concrete, erosion, rainwater, flow, walls, prints, mass loss.

Abbreviations

GPR	Ground penetrating radar
H	Height of the wall
M_{eros}	The mass loss
M_{tot}	The mass of the measuring base
R_{eros}	The rate of erosion
SEM	Scanning Electron Microscopy
2θ	2 theta
X	Width of the plate
XRD	X-ray Diffraction
Z	Erosion depth
σ	Compressive strength
V	Ultrasounds velocity
RILEM	Réunion Internationale des Laboratoires et Experts des Matériaux

1. Introduction

In the literature the wall erosion of buildings throw the flow of rainwater has not been much studied. The rare works found in the literature focus rather on the effects of water jets and those of the water flow of rivers and basins. It is often associated with the impact of the hard particles and the water pressure on the surfaces. It arouses the interest of the ACI in the document (ACI 210 1993).

The phenomenon studied in our case is particular; there are no great flows of water but of rain falling and flowing on buildings walls. Degradation is very apparent; the concrete cover of the reinforcement is greatly reduced. In some areas the steel bars are apparent.

There is, thus, a mass loss which indicates a phenomenon of erosion. Our objective is to measure the rate of the mass loss and also to identify the nature of the phenomenon, whether it is a pure mechanical effect or combined with a chemical effect (solvent). In literature, Momber (1998), worked on the mechanical effects of water jet on several types of materials for industrial applications such as machining, drilling, cutting and hydro demolition. For this author, cement composites are quasi brittle materials. In Momber et al. (1995) and Momber (2001) he analyzed the erosion mechanism by the parameters of fracture mechanics in the sense of pre-existing cracks propagated under the effect of the water jet. In this case the compression strength is not sufficient to describe erosion but the fracture depends greatly on the size of the aggregates used. At high pressure water jet exceeding 30 times the tensile strength of the material, Momber et al. (1995) deduced that the interface paste aggregates has a significant impact on erosion, it is the origin of the micro-cracks, leading to erosion. Other researchers like (Liu et al. 2006) and (Liu et al. 2012) had studied the effect of the flow of river water on concrete surfaces, in Liu et al. (2006) erosion of concrete is presented as an abrasion phenomenon that can be corrected by the addition of silica fume and fibers. The same author in (2012) has simulated the flow of river water by a jet of water containing sand combining the water-jet impact load and sand particle shear/friction. He found that the rate of erosion

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is related to the amount of grain moved by the flow of water and to the angle of the water jet to the impact surface. The authors agree that the interface between hardened cement paste and aggregate play the main role in the fracture process by erosion. Aala Rashad et al. (2014) have studied the abrasion of industrial floors and have found a direct relation between the abrasion resistance and the compression strength; they have concluded that the silicate fume improves such abrasion resistance.

2. Site Description

The research work concerns the site of our university. All the structural elements are built with reinforced concrete with brutal surfaces without any protection this was the time of the concrete brutalism. The exposure duration of the studied buildings is 40 years which corresponds to their age. In the site there are 26 identical buildings (the amphitheaters) with more than 100 identical walls (Figs. 1 and 2). Some of them are protected and others are exposed to the rain. The phenomenon of erosion is repeated with the same appearance on all the structural elements.

The erosion appears also on other types of structural elements, such as the elements walls/columns (Fig. 3). There are seven buildings of this kind having 60 columns each. These elements are straight on first 5 m and inclined at the bottom. They have been subjected to the flow of rainwater on one side and protected on the other side (Fig. 4). The measurements were conducted on walls with a protected side (protected concrete) and another exposed to rain (eroded concrete) (Fig. 2). By this choice, the study concerns the same concrete that is poured at the same moment. Thus, it is the same element of the structure with and without erosion.

Fig. 1 Inclined wall intensely eroded.

Fig. 2 The right side protected part, the left side exposed part.

Fig. 3 Repeated wall elements partially eroded.

3. Measurement of the Material Lost by the Erosion

3.1 Experimental Procedure

The adopted experimental procedure is used to measure the material lost by erosion. The measurements are performed on imprints taken from the real wall panel (Kharchi

Fig. 4 The right side protected part, the left side exposed part of the straight wall.

Fig. 5 Plate of the imprint against the wall.

Fig. 6 The imprint taken from the wall.

and Hadja 2014). The protected part (from the rainwater) and the eroded part of the wall are analyzed at the same time.

For the elements such as the type of photos 1 and 4, the imprints are taken on both sides. The right side is the situation before erosion and the left is the situation after erosion.

On the site, heavily eroded elements have visible traces of carbonation, resulting in as reinforcement corrosion and concrete spalling. In the present approach, particular attention was given to select only the elements damaged by water flow to avoid overlapping with several causes of damage.

3.2 The Imprints

A silicone paste mixed with plaster was spread over a stable plate (20×10 cm^2). It was then plated against a part of the reinforced concrete wall during 2 min. Once removed, the imprint appears on the plate. The relief of the past expresses clearly the mass that is lost by erosion (Figs. 5 and 6). This experimental process was improved after several attempts of measurements. Using plates of 60×40 cm^2 and adhesive silicone alone, the imprint did not appear on all the plate and the silicone became deformed. After several attempts, the plates were reduced to 20×10 cm^2 and the paste to a of silicone-plaster mixture. The plaster was added to the silicone paste to reduce its deformability.

3.3 Depths of Erosion

The depth of the mass taken away by the erosion is measured directly on the imprint with a displacement gauge. Measures are taken on several points crossing the studied surface according to two perpendicular axes with a step between 1.5 and 2 cm. (Figs. 7 and 8). The term "erosion depth" is used herein to indicate the thickness of the material taken away by erosion.

3.4 Experimental Results

By the visual observation of imprints and surfaces of the walls, it appears that the effect of the erosion is not uniform.

Fig. 7 Measuring device.

In the less eroded parts, it is rather the cement matrix and the small aggregate particles and sand which are lost. On the contrary, in the most eroded areas, the coarse aggregates are taken away. It can be deduced that the water flow extracts at first the hardened cement paste. Over time larger grains are taken away because there is no more past to seal them.

3.4.1 Profiles of Erosion

The erosion profile represents the variation of the erosion depth (thickness of the material taken away) along the axis OX. The operation is repeated in several positions of the axis OY. The axes OX and OY are those considered in (Fig. 8). The following profiles (Figs. 9 and 10) are drawn from the same plate (imprint).

In order to ensure the repeatability of the procedure, two imprints taken in the same place are compared. The profiles drawn from the two imprints are rather close as shown on Fig. 11.

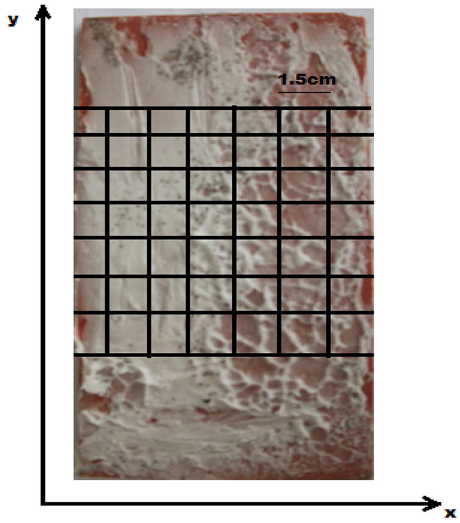

Fig. 8 Imprint with virtual lines.

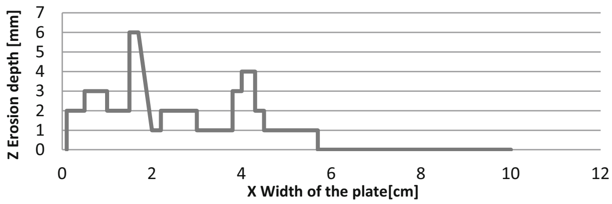

Fig. 9 Profile of erosion obtained from imprint on typical wall.

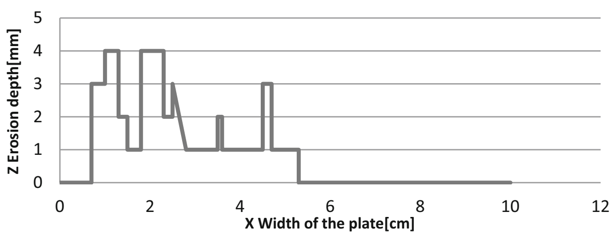

Fig. 10 Profile of erosion-average of five walls.

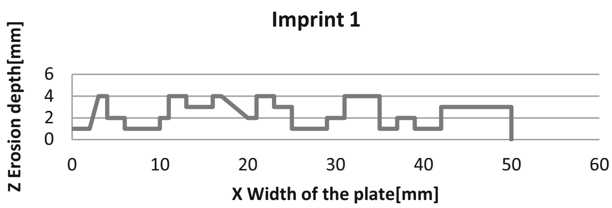

Fig. 11 Two imprints taken on the same surface.

3.4.2 The Material Lost by Erosion and the Rate of Erosion

The surface under the curve (width (x)/depth (z)) corresponds to the mass loss by erosion by unit of height. On the basis of an area of 5 cm in length and 1 cm in width, the previous profiles give successively the following quantities of lost material 127 and 110 mm^3. By defining the quantity of the mass loss is noted: M_{eros}, the rate of erosion noted R_{eros}, can be calculated by reporting M_{eros} to a unit mass corresponding to a depth of 1 cm that is M_{tot}.

$$R_{eros} = \frac{M_{eros}}{M_{tot}} \tag{1}$$

where M_{tot} is the total mass of the area considered (5 cm long 1 cm depth), which is $50 \times 10 \times 10 = 5000$ (mm^3). The choice of the depth value which is 1 cm corresponds to the minimum cover to the reinforcement as considered by most design codes. For the structural elements considered in the present study (walls/columns), the initial concrete cover to the reinforcements is 5 cm as measured at the protected part of the column using two devices of electromagnetic measurements (rebar detector and a GPR). The rate of erosion R_{eros}, thus defined, will vary between the values 1 and 0. The value 1 corresponds to the total loss of the material where the reinforcements are completely uncovered. The value 0 corresponds to an undamaged concrete.

$$0 \leq R_{eros} \leq 1 \tag{2}$$

Meros and Reros values presented in Table 1 were obtained in the x-direction of the imprint. They correspond to the position 1 of Fig. 4 (at $h = 6$ m).

3.4.3 Variation of the Rate of Erosion on the Height of the Wall

The previous testing procedure is repeated at various heights of the wall (1–6 m) with a step of 1 m. The results are reported on the following curves (Figs. 12 and 13). The first one presents the results obtained on the typical wall and the second one presents the average calculated on five walls.

The points 6–3 m are on the straight part of the wall, where the rate of erosion varies very little with the height. The major change occurs from the point 2 m downward; the maximum (70 and 80%) is reached at 1 m. These points are close to the base and correspond to the inclined portion of the wall. It is clear from this result, that the inclination of structural element promotes erosion. The flow of rainwater causes shock waves at the curvature. The pressure is high compared to that in the straight sides of the wall, so the impact force generated in the curved part is very important. It is a singular point which holds potentially the rainwater.

4. Analysis of the Erosion Phenomenon

In order to identify the phenomenon of degradation and separate the chemical and dissolving effect from the mechanical effect, the rainwater is analyzed after passing over the wall. The results (Table 2) indicate that this water is hard and strongly ionized. A part of the damage was due to the action of the dissolving effect of rainwater. Moreover, the observation of the degraded surfaces by the naked eye (Fig. 14) and by using the microscope, shows the detachment of grains of various sizes. The observation of the analyzed rainwater shows the presence of particles.

The results involve two types of processes: a chemical one and a mechanical one, their effects are cumulative. In each

Table 1 Mass loss and erosion rate.

Abscissa (cm)	3	4	5	6	7	8	9
M_{eros} (mm^3)	1790	1270	1510	1100	700	930	870
R_{eros} (%)	35.8	25.4	30.2	22.0	14.0	18.6	17.4

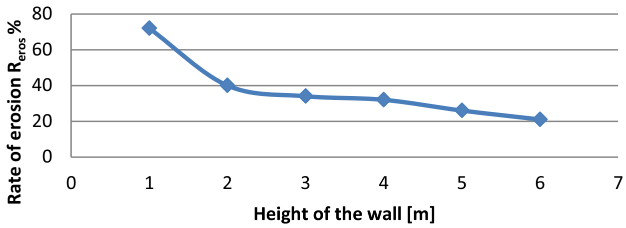

Fig. 12 Typical curve for one wall.

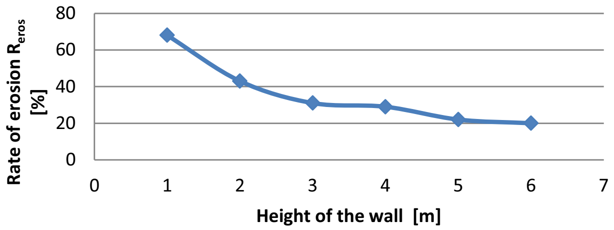

Fig. 13 Average curve for five walls.

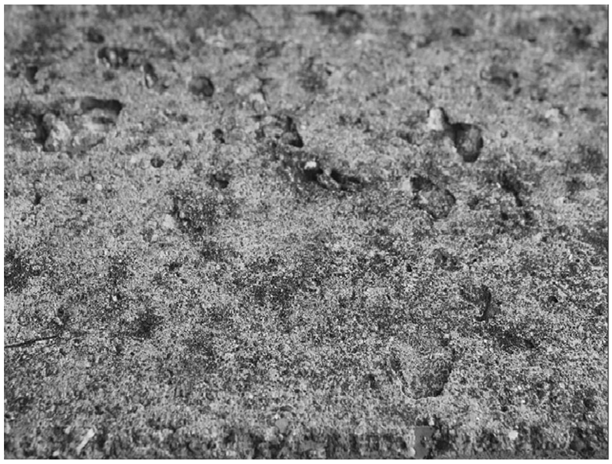

Fig. 14 The detachment of grain of various sizes on the exposed concrete surface.

case, rainwater plays a major role and is the basis of the erosion of walls. The mechanical aspect is also supported by the XRD analysis (Figs. 15 and 16).

The mechanical effect is the consequence of the grain **e**xtraction by dissolution and also by the beating of rain drops on concrete surface. The concrete is weakened by the solvent effect as appears in the mineralogical analyses.

The X-ray diffraction applied on concrete debris collected in the two studied areas: protected (Fig. 15) and exposed (Fig. 16), indicates that there is a reduction of quartz peak about 26 % in the exposed area compared to the protected area.

Observations were carried out using the technique of scanning electron microscope (SEM) on concrete sections. The first one corresponds to the eroded part (Fig. 17) and the second one corresponds to the protected part (Fig. 18).

The image corresponding to the eroded area presents a rough aspect with distributed form in relief as well as the presence of the whitish spots of the lime due to the precipitation of carbonates on the surface of concrete. The image of the protected area presents an aspect slightly worn under the effect of its exposure to weak attacks (wind).

4.1 Impact of the Carbonation Phenomenon

Concrete cores were taken to determine the carbonation depth of the two studied areas of concrete. The phenolphthalein indicates 2.5 and 2.1 cm carbonation depths respectively for the protected and exposed parts (Figs. 19 and 20).

Carbonation is more advanced in the case of protected areas than areas exposed to rainwater. This can be explained by the fact that the carbonation is slowed down by the saturation with water during the pluvial periods. When there is production of calcite, it is on the surface and hence

Table 2 Comparison between the rainwater collected at the bottom of the wall (drained rainwater) and rainwater collected in a reservoir (ordinary rainwater).

Ions	Drained rainwater (mg/l)	Ordinary rainwater (mg/l)
Calcium	24.048	10
Magnesium	16.771	0
Chloride	24.746	8.241
Sulfates	23.84	7.154
Nitrates	7.9	1.803
Ammonium	0.13	0.153

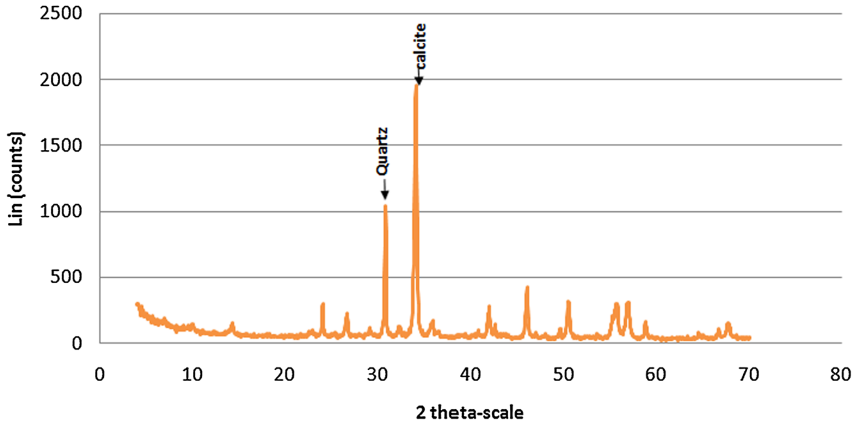

Fig. 15 XRD spectrum-protected area.

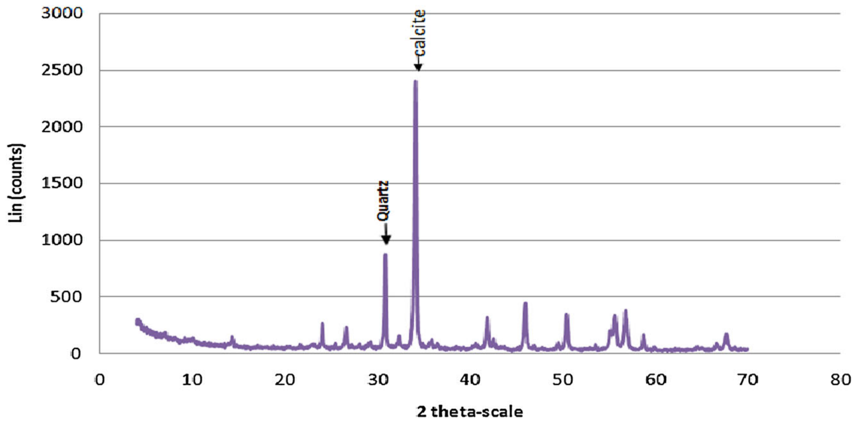

Fig. 16 XRD spectrum-eroded (exposed) area.

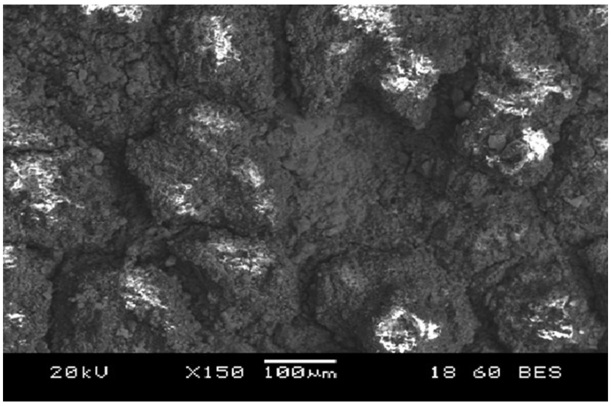

Fig. 17 Image (SEM) of the eroded concrete area.

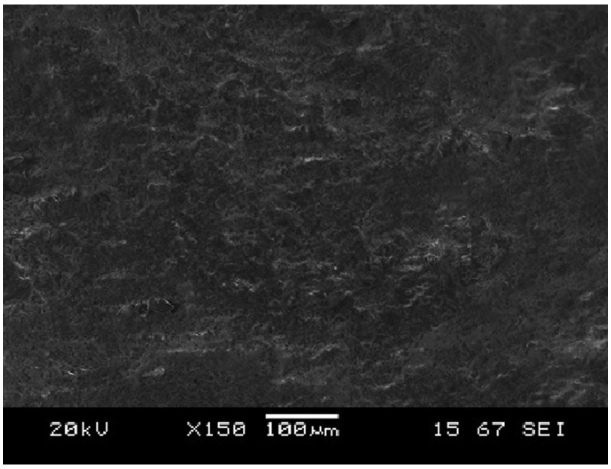

Fig. 18 Image (SEM) of the protected concrete area.

vulnerable to the effect of erosion. The roughness due to erosion also favoured the growth of micro-organisms (algae). Darlington (1981) and (Dubosc 2000) consider the roughness as an important factor in the colonization of concrete walls by the micro-organisms. The filamentous algae consume some mineral precipitants on the concrete surface like calcite.

4.2 Impact on Strengths

In order to study the effect of the erosion of walls by the flow of the rainwater on the mechanical strengths, the compressive strength was measured on the concrete corresponding to the two sides of the wall, the protected part and the exposed part using two methods. The first method is the destructive test; the compressive strength is measured by crushing cylindrical-concrete cores (Fig. 21) in a compression testing machine (Fig. 22). The second method is non-destructive testing by the determination of the rebound hammer (Fig. 23) and the measurement of the ultrasound velocity (Fig. 24 and Table 3)."

Fig. 19 The carbonation depth corresponding to the protected face.

Fig. 20 The carbonation depth corresponding to the exposed and eroded face.

Fig. 21 Core drilling concrete.

Fig. 22 Crushing core concrete.

Fig. 23 Determination of the rebound.

Fig. 24 Estimation of the ultrasound velocity.

Table 3 Mechanical characteristics obtained in the exposed and protected parts of the wall.

Area	Compressive strength σ (MPa)		Ultrasound velocity (m/s)
	Crushing of concrete core	The average value of the rebound	
Exposed	33.6	43	3120
Protected	44	48	3140

The compressive strength obtained in the exposed face by crushing of the concrete core is lower than that of the protected part of concrete. This is due to two reasons:

Firstly, the depth of carbonation in the protected area is higher than the depth obtained in the exposed part of concrete. The protected part being more carbonated (see Sect. 4.1), more calcite is formed which increases the density of the concrete material and hence gives higher strengths. According to Breccolotti et al. (2013) and Jong Yun et al. (2016) and others, the variation of the microstructure of the carbonated concrete decreases the porosity which leads to the augmentation of concrete strength. In this sense Pham and William (2014) indicates that the carbonation decreases, in particular, the volume of the micropores (radius <2 nm).

Secondly, in the case of the exposed concrete, the layer of the calcite has been drained away by the erosion and hence does not lead to an increase in the density of the material. This explains the lower strengths of the eroded concrete. The results of ultrasound indicate a concrete with a low compressive strength (≤10 MPa according to Rilem) because le measurement was applied only on the surface.

5. Conclusion

Erosion by rainwater is observed on a real site built entirely of reinforced concrete. This natural phenomenon is repeated on several structural elements of the same type.

The erosion has damaged the cover of the reinforcements and reduced its depth. A method of quantification of mass lost by erosion was developed. The experimental procedure is based on imprints taken from the structural element in the site.

Erosion is expressed by mass loss as a function of the height and the inclinaison of structural elements. At the scale of the studied walls, mass loss by erosion is more affected by the inclination than by the height. In 40 years of exposure, erosion can remove up to 70 % of the concrete cover. This phenomenon is slow but very detrimental to the sustainability of buildings.

Other laboratory measurements such as SEM observations, XRD and chemical analysis of rainwater, lead to conclude that the erosion by rainwater is due to two cumulative processes, a chemical one (solvent) and a mechanical one.

The carbonation depth and the mechanical strengths were also measured. They indicate that the erosion removes the calcite produced by carbonation, leading to a decrease in the mechanical strengths, and leaves the reinforcing steel without concrete cover and hence free to corrode.

From the present study, it is suggested to take into consideration the erosion phenomenon in any building design code in order to determine the adequate concrete cover to the reinforcement.

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