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# CORROSION'S DIAGNOSIS OF THE REINFORCED CONCRETE ELEMENTS BY USING NON-DESTRUCTIVE TESTING METHODS

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***Abstract:*** *The corrosion of the steel bars embedded in reinforced concrete elements is a process that significantly reduces the lifetime of the structure. Non-destructive testing and evaluation methods has a particularly important role to determine the degradation level of a reinforced concrete element. Non-destructive evaluation means locating, describing and evaluating the corrosion process, determining the shape and position of the reinforcements, and the characteristics of the construction material. This paper presents the main non-destructive testing methods used to identify the reinforcement corrosion process in reinforced concrete elements.*

***Key words:*** *non-destructive testing method; reinforced concrete; corrosion;*

## 1. Introduction

Corrosion of reinforcements represents the main factor causing significant degradation on reinforced concrete elements. After the initiation of corrosion, the rust products (iron oxides and hydroxides) lead to a progressive degradation of the concrete coating layer.

As a consequence, repair costs are a major part of current expenses. Quality control, maintenance, and planning to repair the degradations present in reinforced concrete elements require non-destructive investigation techniques that detect corrosion in early stages [3].

For the purpose of accurately assessing the degradations encountered, the effectiveness of the quality control depends on the proper choice of the control method. A classification of these methods can be illustrated as follows:

- partially destructive methods - cause local surface degradation. It is achieved by mechanical, chemical or thermal means.

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- non-destructive methods - allow numerical or other data to be obtained on defects, deterioration or deformations. It is done by methods that do not cause degradation on the studied element.

Non-destructive investigation techniques are used to detect, record, and analyse early stage degradations and their subsequent assessment.

Investigation of the corrosion process of the reinforcement can be accomplished by the following methods:

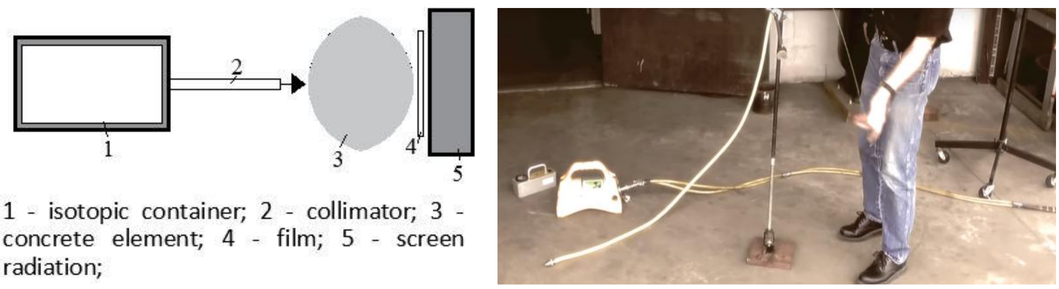
- radiographic method;
- radiometric method;
- radioscopic method;
- method of the magnetic field’s determination;
- the method of the electrical resistivity’s determination;
- ultrasound method;
- wireless NDT testing method;
- galvanostatic pulse measurement;
- linear polarization resistance method;

## 2. Reinforcement Corrosion Non-Destructive Investigation Methods

### 2.1. Radiographic method

The radiographic method uses gamma radiation and consists in highlighting the difference between the densities of some materials using a photosensitive film (Figure 1) [16].

Radiographic control is based on the irradiance of concrete elements with radioactive isotope, which provide, by recording the variation in the resulting intensity distribution (on radiographic sensitive plates - X-ray films or on fluorescent screens whose sensitivity is appropriate to the radiation used), areas of shadow and light [9].




a. b.

Fig. 1. *Radiographic method a. schematic representation; b. practice situation*

The method can be applied to reinforced concrete elements with a thickness of maximum 500 mm.

The radiographic method is more qualitative than other non-destructive methods due to its accuracy.

A distinctive feature of this method is represented by the fact that it provides photographic precision of the interior details of reinforced concrete elements. At the same time, it is a laborious technique because it involves developing the film (made in a specialized laboratory) and then analysing the obtained images.

**2.2. Radiometric method**

The principle of the method consist in the flow of gamma radiation diminishes its intensity when passing through a material (concrete). This phenomenon is quantified by measuring the rate of counting the attenuated beam impulses [7].
For thick elements made of reinforced concrete, the gamma ray penetration power is greater than the X-rays, being inversely proportional to the wavelength.

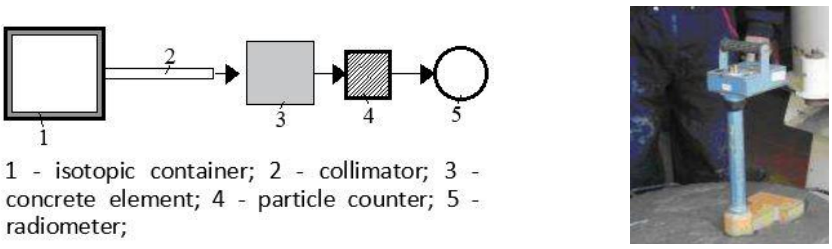
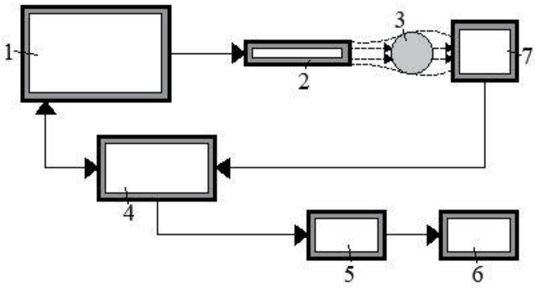



Fig. 2. *Radiometric method (a. schematic representation; b. practice situation)*

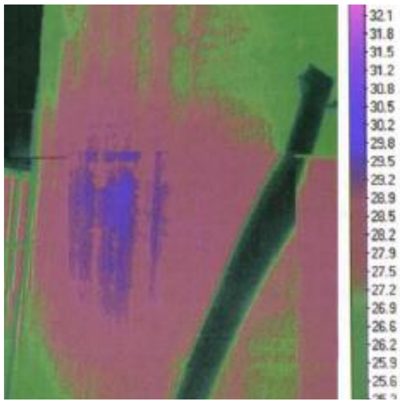
In the exemplified scheme (figure 2) [17], the apparatus comprises a source of radioactive isotopes in a lead container, which emit a beam of gamma radiation to the reinforced concrete element through a collimator.
At the other end of the element, a Geiger-Müller counter is placed in a lead container connected to a measuring instrument (radiometer). Depending on the variation in particle counting speed, the position of the reinforcements embedded in the concrete can be detected.

**2.3. Radioscopic method**

Determination by this method consists in measuring, preparation and drawing a thermal map of the reinforced concrete element analysed using high-energy X or gamma radiation. The radiation flux penetrates the concrete, and by transforming it into an electrical signal with a detector, the resulting images are displayed on a monitor [2].



1 - X radiation source; 2 - collimator; 3 - concrete element; 4 - CPU; 5 - TV monitor; 6 - recorder; 7 - receiver;




*a.* *b.*

Fig. 3. *Radioscopic method (a. schematic representation; b. practice situation)*

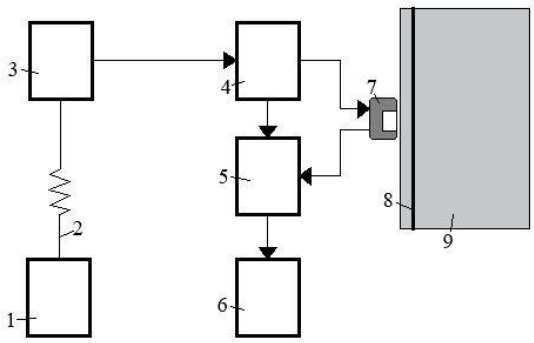
Using this method (figure 3) [3], corroded and non-corroded areas can be detected as a result of thermal diffusion differences. The captured images can be displayed graphically, and by thermography the structural anisotropy of the analysed reinforced concrete element is highlighted [3].

### 2.4. Method of using magnetic field

The magnetic field method is used to determine the thickness of the concrete cover layer and diameter of the steel reinforcement.

This method is based on the modification of the magnetic flux and the current induced by a probe due to the presence of concrete in the concrete when the primary of the probe is crossed by alternative current [11].

With this method (figure 4) [2], concrete reinforcements can be detected up to a maximum depth of 250 mm.



1 - battery power; 2 - switch; 3 - oscillator AC; 4 - out of phase; 5 - rectifier; 6 - galvanometer; 7 - touch probe; 8 - reinforcement; 9 - concrete.

*a.* *b.*

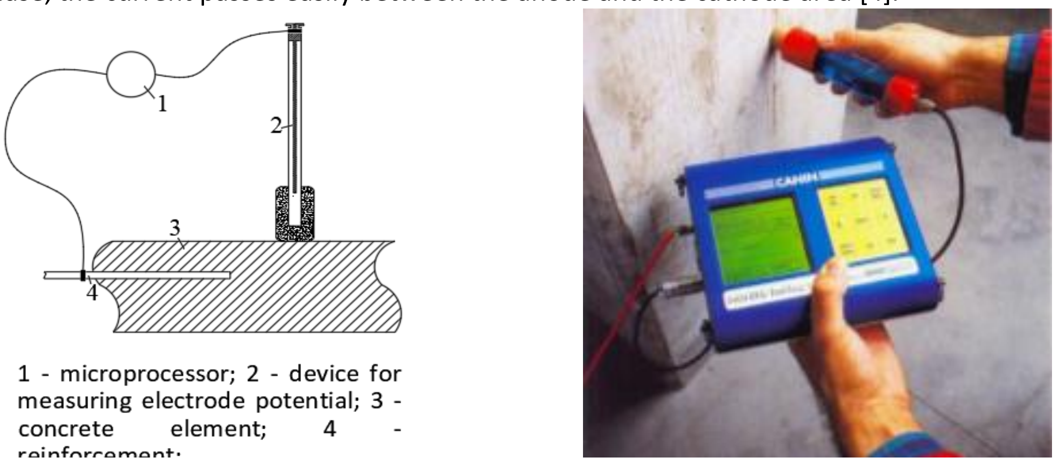
Fig. 4. *Pachometer operating scheme (a. schematic representation; b. practice situation)*

The measuring tool used to diagnose reinforced concrete elements is called a pachometer. It is an instrument that can determine the position of the armed forces and may signalise their presence in concrete with a precision of the order of millimetres [8].

### 2.5. Method of determining the electrical resistivity

Measuring changes in the electrical resistivity of a metal sample is a method that can be applied for non-destructive monitoring of reinforcement corrosion in concrete. The principle of this method is based on the fundamental theory of the relation of change of electrical resistance to the cross-sectional dimension of each conductor [1].

In terms of determining the corrosion process initiated, the electrical resistivity of the reinforced concrete elements is an important parameter. In concrete with a high resistivity, the corrosion process is slow compared to low resistivity concretes. In this case, the current passes easily between the anode and the cathode area [4].




a. b.

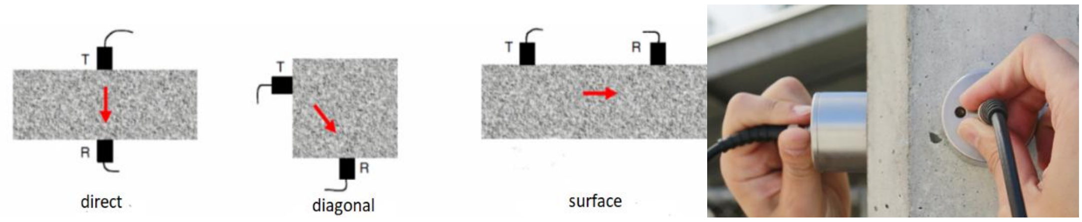
Fig. 5. *Electrical resistivity measuring (a. schematic representation; b. practice situation)*

The electrical resistivity method (Figure 5) [3] is based on the determination of the electrode potential existing between the reinforcement and a reference electrode (copper sulphate) located on the surface of the concrete. Measurements are made by means of scanning devices that determine corroded areas on the test surface. Due to the penetration of chlorine ions in concrete, the electrical potential is determined.

Electrical resistivity depends on the quality of the concrete and the exposure conditions (humidity, temperature, etc). Resistivity measurement is an additional useful measure to help identify the problematic areas.

### 2.6. Ultrasonic pulse method

The ultrasonic method is a non-destructive test based on measuring the propagation velocity of ultrasonic pulses in concrete between two transducers (transmitter and receiver) to detect the presence of internal defects (cracks) [6]. Depending on the location of the transducers on the concrete surface, the following test techniques (figure 6) [18], can be distinguished: direct transmission technique, diagonal transmission technique and surface transmission technique.




*(a. schematic representation; b. practice situation)*

Fig. 6. *Ultrasonic transmission techniques*

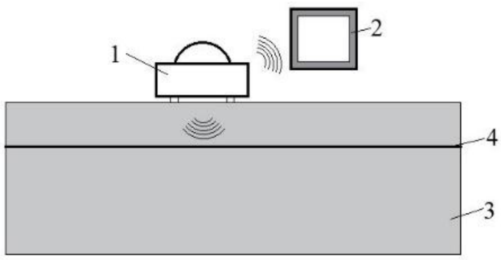
This method allows to establish the areas with degradations (cracks), the determinations taking place over a relatively short period of time.

The use of the ultrasonic pulse method is indicated in the following situations [8]:

- control of the quality of the concrete, especially when it is poured into massive elements or exhibits apparent or hidden defects;
- tracking of concrete reinforcement, particularly in the initial phases of this process, when significant changes in propagation velocity occur;
- determination of structural degradation of concrete during aggressive stresses (physical or chemical) or actions;
- determining of the compaction degree of concrete in the work;
- the test of elements where there is a possibility of a systematic difference between the quality of the concrete in the surface layer and in depth.

## 2.7. Wireless NDT Corrosion Detection Method

This non-destructive testing method measures the electrical response of the reinforcement inside the concrete without having a physical connection with it, representing a rapid procedure to measure the corrosion rate in the reinforced concrete elements [13].




1 - measurement instrument; 2 - receiver;
3 - concrete; 4 - reinforcement;

*a.*

*b.*

Fig. 7. *Wireless NDT method (a. schematic representation; b. practice situation)*

The apparatus presents high precision sensors to measure the electrical resistivity of concrete, the half-cell potential, ambient temperature and relative humidity, and it benefits from a wireless capability to transmit data to a tablet, where data can be stored, analyzed and visualized (figure 7) [13].

Moreover, the tablet app offers a powerful post-processing tool and an easy way to share the results with other team members.

This technique can be also used for the following applications:
- detection of corrosion in the reinforcement;
- measurement of corrosion rate in concrete structures;
- measurement of real in-situ electrical resistivity of concrete;
- evaluation of corrosion potential of rebar in concrete;
- rehabilitation and repair of concrete structures

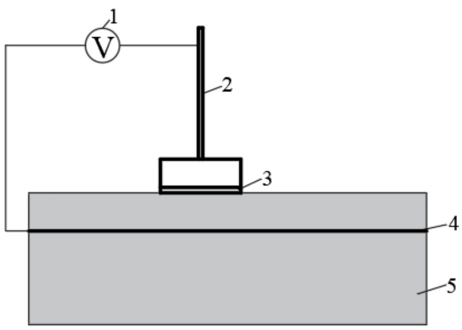
The main advantage of this technique is to provide much faster results than conventional test methods. The measuring tool allows for early detection of potential degradation and the necessary repairs before the corrosion process is amplified.

Compared with other non-destructive techniques used nowadays (for example, galvanostatic pulse technique or linear polarization resistance method), the NDT method helps to achieve more accurate results and reduced costs. It also provides detailed information on the concrete quality and the corrosion level of the reinforcement.

### 2.8. Galvanostatic Pulse Measurement (GPM)

In general, the galvanostatic pulse method is characterized by impressing a small amplitude, short interval anodic current pulse, applied galvanostatically with the help of an external counter electrode over the concrete surface and analyzing the resultant change in potential of the steel reinforcement [10].

The GPM corrosion evaluation (Figure 8) [14] is based on the measurement of the current required to change the potential difference between the reinforcement and a standard reference electrode. The current is a result flow of electrons from the anodic and cathodic sides in concrete.




1 - voltmeter; 2 - reference electrode; 3 - conductive foam; 4 - reinforcement; 5 - concrete;

*a.*

*b.*

Fig. 8. *GPM method (a. schematic representation; b. practice situation)*

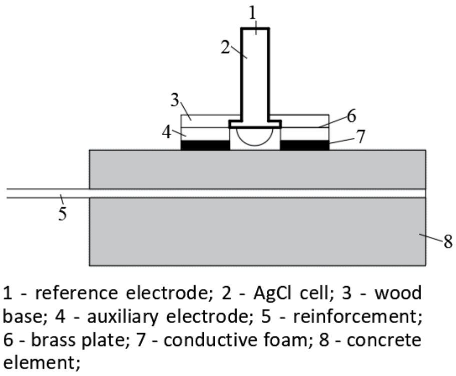
The anodic side is a corroding rebar where there is surplus of electrons on the base metal as a result of releasing metal ions into an electrolytically conducting liquid. Those excess electrons flow to a cathodic side, concrete with oxidizing agents in the liquid, inducing a corrosion current between the two sides [14].

Knowing the current and voltage allows an inspector to determine the polarization resistance, which is related to the rate of corrosion.

### 2.9. Linear Polarization Resistance (LPR) method

The LPR technique is a method for evaluating instantaneous rate of rebar corrosion. The technique is noninvasive but requires a localized damage to the concrete cover to enable an electrical connection to be made to the reinforcing steel [15].

The principle of LPR (Figure 9) [15] is based on disturbing the corrosion equilibrium on the surface of steel reinforcing bars by introducing a small perturbative electrical signal using a surface counter electrode.

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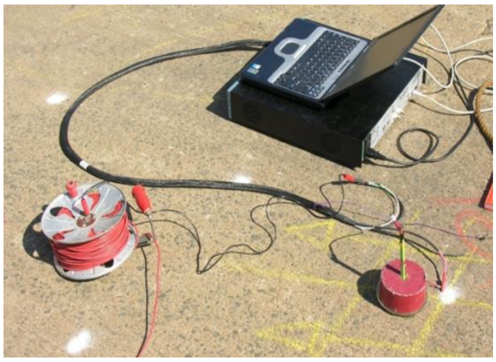


*b.*

Fig. 9. *LPR method (a. schematic representation; b. practice situation)*

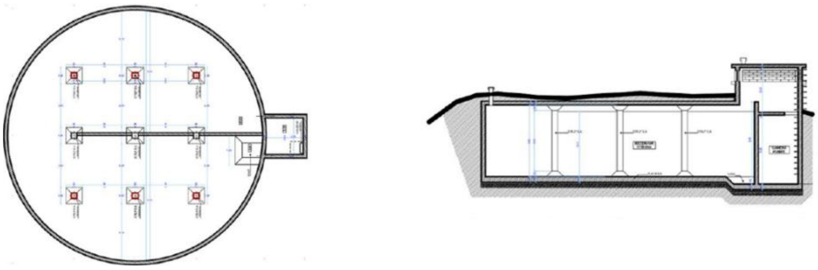
When the passive oxide film that protects the steel is broken by an unfavorable environment in the concrete, the potential difference produces a current within a micro electrolytic cell. At the anode of this cell, iron atoms transform to ferrous ions, move into the surrounding concrete, and leave their free electrons on the steel bar. When the corrosion continues, these free electrons accumulate and give the rebar negative charge [5, 6].

Monitoring the relationship between electrochemical potential and current generated between electrically charged electrodes under the test allows the calculation of the corrosion rate.

### 3. Case study

The analysed construction is a cylindrical reinforced concrete water tank located in Vișan village, Iaşi county, and it was built during the 1980s (Figure 10). The water tank has a circular shape, in horizontal plane, having an inner diameter of 13.40 m and a useful height of 3.80 m being covered with earth.

Within the objective under consideration, there is a pump room and a room for access to the tank. Due to the long exploitation and possible execution errors, the exploitation environment favoured the decaying and evolution of the corrosion process of the reinforcement.



*a. Top-view section;* *b. Transversal section*

Fig. 10. *The built*

Following the visual analysis of the objective, the main degradations are based on exploitation causes or caused by various interventions.

These were manifested by reducing the cross-section of the steel and expulsion of the concrete cover layer from the circular wall (Figure 11). Following the quantitative analysis and direct observations, it was found that the reinforcements are degraded by 20% and in some cases by 60%.

Fig. 11. *Degraded reinforced concrete wall*

At the same time, for the determination of the concrete class affected by the corrosion process, tests were carried out at the wall of the water tank (Figure 12), using non-destructive methods: the superficial hardness method (sclerometer) [16] and the combined non-destructive method [6].

Fig. 12. *Sclerometer testing on water tank wall*

The superficial hardness method using sclerometer is based on the measurement of the recoil index after the impact with the concrete surface.

The combined non-destructive method has an equal efficiency in determining concrete strength regardless of the concrete class under consideration. The test apparatus is composed of:

- the instrument for measuring the pulse propagation velocity in concrete;
- apparatus for measuring the superficial hardness of the concrete by means of the recoil index (sclerometer).

The results of the water tank wall tests using the superficial hardness method (Table 1), respectively the combined non-destructive method (Table 2) was processed according to the following tables:

*Superficial hardness method* Table 1

| No. | $R_{ci}$ [N/mm$^2$] | $f_{m(n),is}$ [N/mm$^2$] |
|---|---|---|
| 1. | 22.80 | 21.70 |
| 2. | 22.20 | |
| 3. | 23.40 | |
| 4. | 21.20 | |
| 5. | 21.70 | |
| 6. | 22.90 | |
| 7. | 20.40 | |
| 8. | 19.30 | |
| 9. | 21.10 | |

$f_{m(n),is}$= 21.70 [ N/mm$^2$] ;

$f_{is,\ min}$= 19.30 [ N/mm$^2$] ;

The characteristic compressive strength of in-situ test area is the smallest of the following values:

$$\min\begin{cases} f_{ck,\ is}=f_{m(n),is}-k_1\cdot s \\ f_{ck,is}=f_{is,min}+4 \end{cases} = \begin{cases} 18.20\ [\ N/mm^2] \\ 23.30\ [\ N/mm^2] \end{cases}$$

*Non-destructive combined method* Table 2

| No. | $R_{ci}$ [N/mm$^2$] | $f_{m(n),is}$ [N/mm$^2$] |
|---|---|---|
| 1. | 20.90 | 21.10 |
| 2. | 21.10 | |
| 3. | 21.20 | |
| 4. | 21.40 | |
| 5. | 20.90 | |
| 6. | 21.40 | |
| 7. | 21.00 | |
| 8. | 21.00 | |
| 9. | 21.10 | |

$f_{m(n),is}$= 21.10 [ N/mm$^2$] ;
$f_{is,\,min}$= 20.90 [ N/mm$^2$] ;

The characteristic compressive strength of in-situ test area is the smallest of the following values:

$$\min\begin{cases} f_{ck,\,is}=f_{m(n),is}-k_1\cdot s \\ f_{ck,is}=f_{is,min}+4 \end{cases} = \begin{cases} 17.60\ [\mathrm{N/mm^2}] \\ 24.90\ [\mathrm{N/mm^2}] \end{cases}$$

where:
- $f_{ck,is}$ – the in-situ characteristic compressive strength;
- $f_{is,\,min}$ – the minimum in-situ compressive strength;
- $f_{m(n),\,is}$ – the average of the in-situ characteristic compressive strength after n tests;
- $k_1$ – coefficient depending of number of tests;
- s – standard deviation.

According to NP 137-2014, Table 6.1., the compressive strength values corresponding for class C16/20 is $f_{ck,is,cube}$=17 [ N/mm$^2$].

The in-situ characteristic compressive strength value using superficial hardness method is $f_{ck,is}$=18.20 [ N/mm$^2$], and for non-destructive combined method is $f_{ck,is}$=17.60 [ N/mm$^2$] thus classifying in the class C16/20.

## 4. Conclusions

Non-destructive testing methods used to diagnose the corrosion process on reinforced concrete elements have certain advantages and disadvantages.

Generally, to obtain high accuracy measurements is recommended to use at least two combined methods.

With the help of the non-destructive investigation methods, a precise assessment of the degradations resulting from the corrosion process and the proposal of intervention solutions for both reinforcements and degraded concrete are sought.

These interventions aim to restore building in service and to increase the nominal values for the durability characteristics to ensure proper exploitation conditions.

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