COMPORTAREA ÎN TIMP A UNOR BETOANE CU ADAOS DE CENUȘĂ DE TERMOCENTRALĂ SUPUSE LA COROZIUNE PRIN DIZOLVARE-LEVIGARE
THE LONG TERM BEHAVIOUR OF SOME FLY ASH CONCRETE MIXES SUBJECTED TO DISSOLVING - LEVIGATION CORROSION

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The aim of this paper is to present an assessment method for the modification of some essential characteristics of the concrete mixes embedding fly ash subjected to an accelerated corrosion process using softened warm water. In the construction elements exposed to water, the dissolving – levigation corrosion phenomenon occurs by washing the calcium hydroxide from the cement stone, affecting the durability characteristics. A special equipment that enables the acceleration of the processes developed in concrete structure when exposed to softened warm water was designed and constructed to subject the concrete samples to this type of corrosive attack. After subjecting the concrete specimens to softened warm water, several physical and mechanical tests were performed to determine the unit weight, the water absorption, the permeability and the compression strength. A total number of 117 cubic samples were tested for a period of 36 months to observe the behaviour of fly ash concrete mixes subjected to the corrosive attack of softened warm water.

Scopul acestei lucrări a fost prezentarea unei metode utilizate pentru evaluarea modificării unor caracteristici ale betoanelor realizate cu adaos de cenușă de termocentrală, supuse unui proces de coroziune accelerată utilizând apă caldă dedurizată. În elementele de construcție care vin în contact cu apa, fenomenul de coroziune se manifestă prin dizolvarea și levigarea hidroxidului de calciu din piatra de ciment, cu implicații asupra caracteristicilor de durabilitate. În vederea supunerii probelor de beton la acest tip de atac coroziv, s-a proiectat și executat o instalație specială care permite accelerarea proceselor care au loc în structura betonului atunci când este expus acțiunii apei calde dedurizate. În urma supunerii epruvetelor din beton la acțiunea apei calde dedurizate, au fost efectuate câteva încercări fizice și mecanice care au vizat determinarea densității, a absorbției de apă, a permeabilității și a rezistenței la compresiune. Un număr total de 117 probe cubice au fost testate pe parcursul a 36 luni, pentru a caracteriza comportarea betoanelor realizate cu cenușă de termocentrală la acțiunea corozivă a apei calde dedurizate.

Keywords: *concrete, ash admixture, corrosion, dissolving – levigation*

1. Introduction

The dissolving – levigation corrosion process of concrete is encountered in a large number of buildings exposed to softened industrial residual water or to condense water. The dissolving – levigation corrosion process is continuous and accelerated in time, also favouring the destructive effects of other types of corrosion with a damaging effect on the concrete buildings durability. The effects of this type of corrosion need to be analysed in time as they can lead to important structural behaviour modifications.

The surveying process of some buildings under consideration revealed visual structural modifications.

Some concrete mixes characteristics, such as permeability, porosity, mechanical strength, have been determined by tests for a comprehensive understanding of the overall behaviour of structural members and buildings exposed to a long term aggressive attack.

Performing an experimental accelerated dissolving - levigation corrosion process and the correlation of the tests results with the values obtained in-situ, enables the assessment of the produced modifications by mathematical studies for a building life span.

The equipment used for the dissolving – levigation acceleration process, the adverse effects of this process upon some concrete characteristics (density, permeability, mechanical strengths) and the estimation of the structural changes in time are presented in the paper.

The research work carried out in this experimental program reveals the results for the long term behaviour of fly ash concrete mixes subjected to a corrosive environment. The

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dissolving – levigation corrosion occurs in the case of concrete structures which are exposed to softened water [1 - 3]. The in-situ structural changes occur in a relatively long span of time [4, 5], but the equipment used in this study enables the acceleration of the corrosive processes similar to the service conditions, to obtain relevant results in a shorter period of time.

In order to simulate as precisely as possible the real working conditions [6, 7], based on some preliminary studies [5, 8], the long-time behaviour of three types of concrete was analysed. All these concrete mixes were made up with different percentages of fly ash as natural aggregate substitute. The results offered a clear image on the changes occurring in concrete structure with respect to the utilized admixture percentage.

The various types of constructions exposed to rain water, freshwater from lakes or flowing waters during their life time are only a few examples that prove the permanent interaction between the concrete structural members and the aggressive environment [9, 10]. In addition, the large industrial buildings where the softened water, sometimes at high temperatures, comes in contact with the concrete surfaces, are even more affected by the water corrosive attack [10, 11].

The damage produced in time due to the aggressive action of the softened water represents a common consequence of the execution and design errors (inadequate dimensioning and inappropriate utilization of materials), and of the deficient maintenance and exploitation of buildings as well [12, 13]. Even though this type of corrosive attack is not usually the direct cause of the concrete construction degradation, it favours the penetration of other aggressive agents into the concrete structure. Therefore, through a series of complex mechanisms, the concrete covering layer is adversely affected and the steel reinforcement corroded, resulting in important consequences in terms of structural safety and financial costs.

From the previous studies [5, 9] performed on some cooling towers and concrete pipes, different types of damage, such as cracks and spalling of concrete were identified. For this reason, the necessity of a thorough analysis upon the interactions between concrete and the aggressive environment represented by warm softened water was imposed.

The current research work has as objective the experimental assessment of the long term behaviour of some concrete mixes with and without fly ash admixtures subjected to the aggressive action of water. For the laboratory simulation of the dissolving – levigation corrosive attack, an original study method and equipment were designed [14]. They allow to reproduce the working conditions in case of some concrete types used for the construction of the cooling towers structure, heat exchangers etc.

2.Experimental program

The in-situ study of the concrete types affected by the dissolving – levigation corrosive attack, revealed that the occurred structural changes and degradations must be analysed for a longer period of time, at least a decade. The tests, using the specially designed equipment, were carried out for 36 months, the time interval being considered adequate to obtain relevant results. It enabled the assessment of the long-term behaviour of concrete made up with different fly ash admixture proportions.

The testing method utilized in this research work requires the storage of some concrete samples in a steaming device, so that the corrosive attack is achieved by pulverizing the concrete samples with a slightly hard water at high temperature. The samples were subjected to a continuous dissolving – levigation corrosion process. At certain time intervals (3, 6, 9, 12, 18, 24 and 36 months), the density, the water penetration depth and the compressive strength of the concrete samples subjected to corrosion process, were determined. This procedure highlighted the changes produced in the concrete structure and enabled to establish the correlations between the concrete mixes and their behaviour to the accelerated dissolving – levigation corrosion.

2.1.Experimental set up

The equipment (Figure 1.a) is made of a cylindrical steel chamber protected against corrosion by inside priming and painting. The equipment dimensions (1.8 m height and 0.9 m diameter) provide enough room for the samples placing on three grills made of welded mesh [5, 9] (Figure 1.b).

A lateral door permits an easy access to the three grills where the concrete samples are placed. For the purpose of the current experimental program, cubic samples of 150 mm size were prepared. A number of 8 samples were placed on each grill with enough space between them to obtain a uniform atomizing on the sample surface.

The equipment ensures a continuous atomizing on the sample surface with water or vapours depending on the selected temperature. The water is permanently recycled, being collected from the bottom side of the chamber by an aspiration pump and transmitted to the top side of the device by an external circuit made of a rubber hose. Then, the recycled water is again dispersed inside the chamber using a fine atomizing system, all the samples being in contact with water and steam. The water is heated with an electric resistance placed in the water collecting tank. The equipment is provided with a thermostat that ensures the desired temperature setting, in this case 65^{0}C. In the water tank zone there is a

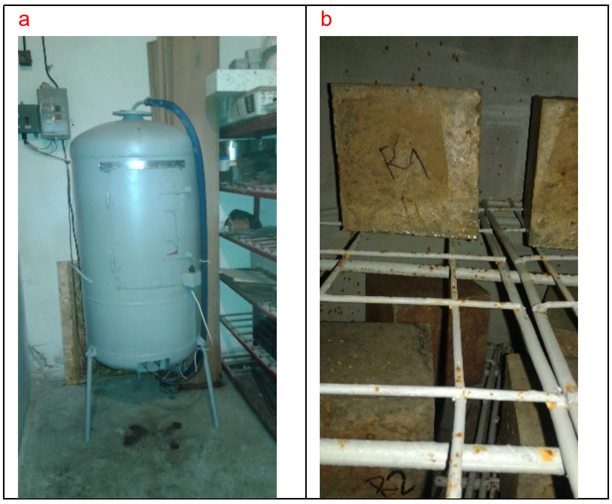

Fig.1 - a. Equipment for the acceleration of dissolving – levigation corrosion process; / *a. Instalație pentru accelerarea procesului de coroziune prin dizolvare – levigare;* b. Concrete sample position inside the equipment/ *b. Poziționarea epruvetelor în interiorul instalației*

temperature sensor operating the thermostat, so that the electrical resistance restarts automatically to constantly maintain the water at the desired temperature.

The operation of the entire equipment is automatically controlled by a control panel thus eliminating the need of the permanent surveillance by an operator and providing the continuous working regime.

The water used in this study is softened water having the same composition with the water used in the cooling towers.

2.2. Materials and concrete mix proportions

The three concrete mixes considered were prepared according to the current European standard provisions [15, 16, 17] and taking into account the quality requirements for the component materials [6, 7].

The following materials were utilised for the concrete mixes analysed within this study:

Cement - the same type of cement, namely CEM I 42.5R, a Portland cement with high initial strength, was used for all the concrete mixes. The main constituents are the Portland clinker (K) (95-100%) and other minor additional components (0-5%) [15, 18].

Natural aggregates (NA) - washed and sorted - were used. The natural aggregates used for the concrete preparation (a total mass of 1982 kg) were subjected to a series of analyses: petrographic analysis, granularity and voids volume, to determine the quality conditions and the main characteristics according to SR EN 12620+A1:2008 [16].

Water – potable water was added to the concrete mixes, according to the requirements of SR EN 1008:2003 [17].

Mineral admixture - fly ash (FA) collected by electrostatic or mechanical precipitators was supplied by Holboca-Iaşi thermal power plant and presented the following characteristics:

- Bulk density – the variation of the FA bulk density with humidity is presented in Figure 2 [14].
- Granularity – the FA grading curve is illustrated in Figure 3 [19].
- The specific surface area – determined using the Blaine air permeability method, has the value equal to S = 1894 cm^2/g [19].

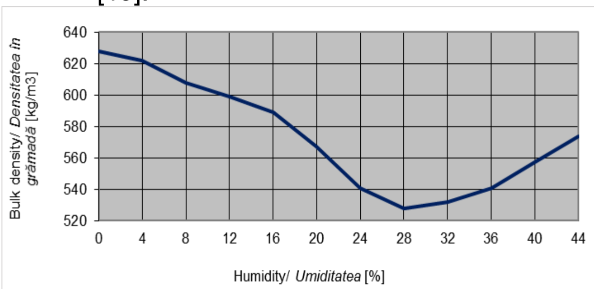

Fig. 2 - Variation of the fly ash bulk density with humidity/ *Variația densității în grămadă a cenușii de termocentrală în raport cu umiditatea*

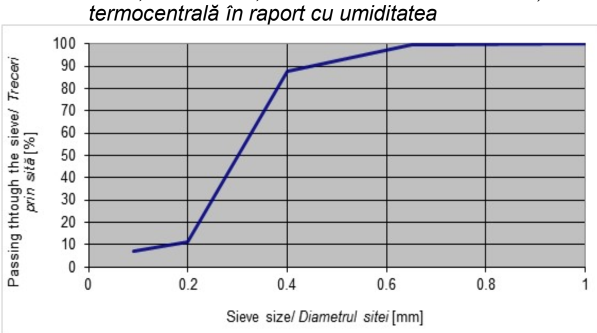

Fig. 3 – Fly ash grading curve / *Curba granulometrică a cenușii de termocentrală*

The concrete mixes are presented in Table 1.

Table 1

Concrete mixes / *Rețete de beton*

Concrete mix/ *Rețeta de beton*	Cement/ *Ciment* [kg/m³]	Water/Cement ratio (W/C)/ *Raport apă/ciment*	Fly ash/ *Cenușă zburătoare* [kg/m³]	Aggregates/ *Agregate* [kg/m³]						
				Sort 0-0.25 mm	Sort 0.25-0.5 mm	Sort 0.5-1 mm	Sort 1-2 mm	Sort 2-4 mm	Sort 4-8 mm	Sort 8-16 mm
A_0	260	0.5	0	160	240	240	201	279	392	470
A_c^5	260	0.5	99	61	240	240	201	279	392	470
A_c^{10}	260	0.5	198	0	202	240	201	279	392	470

Where: A_0 – concrete reference mix;

A_c^5 – concrete mix using 5% of fly ash (FA) as natural aggregate (NA) replacement;

A_c^{10} - concrete mix using 10% of fly ash (FA) as natural aggregate (NA) replacemen

2.3. Concrete specimens casting and testing

The cement, the fly ash and the aggregate amounts were weighted and the water was volumetrically dosed. The granular and powdery materials were introduced one by one in the concrete mixer and a first mixing was performed with a part of the established water volume so that the granular materials surface to be entirely wet. In the second phase, the rest of the water volume has been added and a remixing was performed until the appropriate homogeneity was obtained.

The workability of the concrete mixes, using the slump test, and their density were determined on the concrete fresh state, according to SR EN 12350-2:2009 and to SR EN 12350-3:2009 [20 - 22]. The results are given in Table 2.

Table 2

Fresh concrete characteristics
Caracteristicile betonului proaspăt

Concrete mix/ *Rețeta de beton*	Slump/ *Tasarea* [mm]	Density/ *Densitatea* [kg/m^3]
A_0	120	2392
A_c^5	140	2374
A_c^{10}	130	2358

A number of 117 cubic samples of 150 mm side were prepared. These specimens were preserved in water tanks for 7 days and then in the climatic chamber up to 28 days at 25-30^{o}C temperature and the relative air humidity of 60-65% [23]. A series of samples were considered as reference specimens, while the other ones were introduced into the steaming device to be subjected to the accelerated corrosion process with warm softened water.

3. Experimental results and discussion

Initially, some of the concrete specimens were tested at the age of 28 days. That was considered the reference moment "0" for all the proposed measurements: density, water penetration depth and compressive strength (Figures 4 - 8).

The quantification of the changes that occurred in time due to the accelerated corrosive process was done through the interpretation of the recorded data for density, water penetration depth and compressive strength at various curing ages [24, 25, 26], compared with the results obtained on the reference samples at the "0" moment [27].

In Figure 4 the variation of the concrete density as function of the curing age is represented for each of the mixes considered in Table 1. In case of the reference concrete mix, A_0, a slow decrease of the unit weight for the entire time interval of 36 months, can be observed. Initially, a value of 2380 kg/m^3 was obtained on the reference samples, while at the end of the exposure the corresponding value was equal to 2370 kg/m^3. The density decreases at a quasi-constant rate, at 3, 6, 9, 12, 24 and 36 month intervals. It can be concluded that the calcium hydroxide from the cement dissolved and was removed by levigation.

The fly ash concrete mixes presented lower initial values of the density (2360 kg/m^3 for A_c^5 and 2345 kg/m^3 for A_c^{10}), but a quite similar decreasing behaviour in time, with the reference concrete mix, A_0, was observed. As the fly ash percentage was increased (the case of A_c^{10} concrete mix), the levigation process became more intense. This is a consequence of the modification in cement stone compactness followed by the increase in the contact surface area exposed to the aggressive environment. This change represents the cause of the more pronounced decrease of the density in the porous cement stone produced by the water excess from the fresh concrete mix.

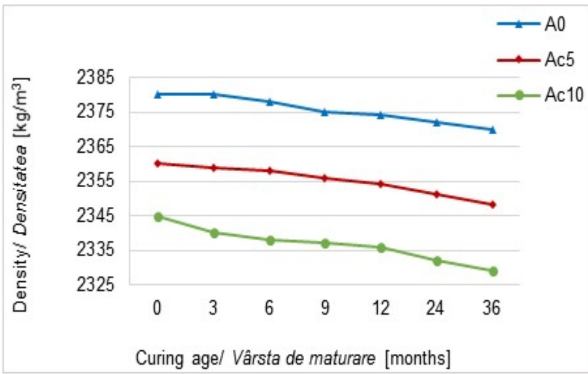

Fig. 4 – Concrete density variation depending on the curing age
Variația densității betonului în funcție de vârsta de maturare.

The most intense levigation process was observed in the case of concrete containing a larger percentage of fly ash (10% replacement of the natural aggregate by FA). The calcium hydroxide dissolving was followed by a noticeable density loss for the 36 month duration. This process begins to decrease after a certain time interval as a consequence of the calcium hydroxide fixing through the chemical compounds of the fly ash [28].

Figure 5 presents the variation of the water penetration depth in time. At the beginning, all the concrete mixes were at the age of 28 days. After that, the reference concrete mix, A_0, was tested at various ages up to the 36th month. The depth of the water penetration in the case of reference concrete specimens, measured at the initial moment, was 103 mm (average value determined on three samples). A slow decrease was observed at the other curing ages, the water penetration

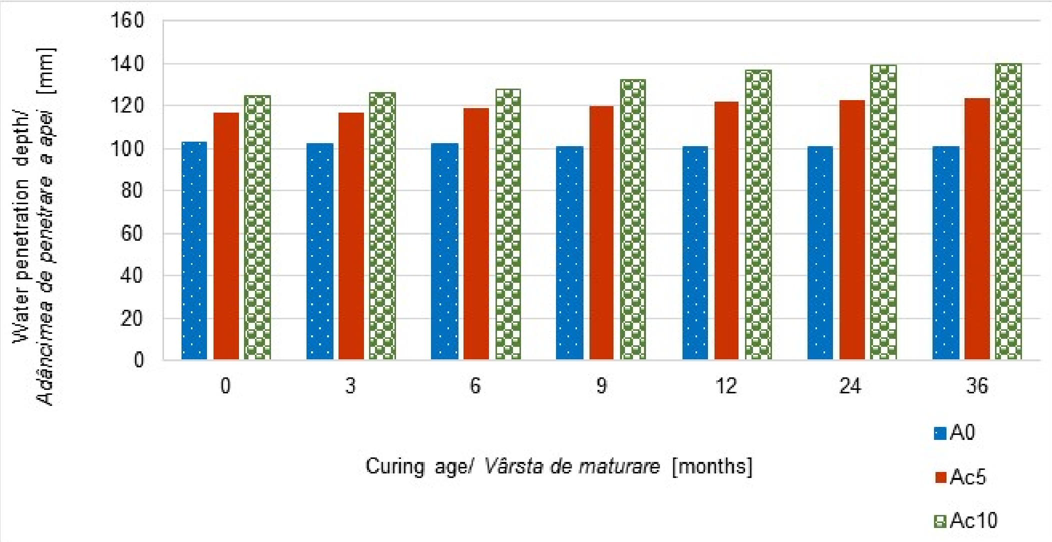

Fig. 5 – Water penetration depth variation versus curing age / *Variația adâncimii de penetrare a apei în funcție de vârsta de maturare*

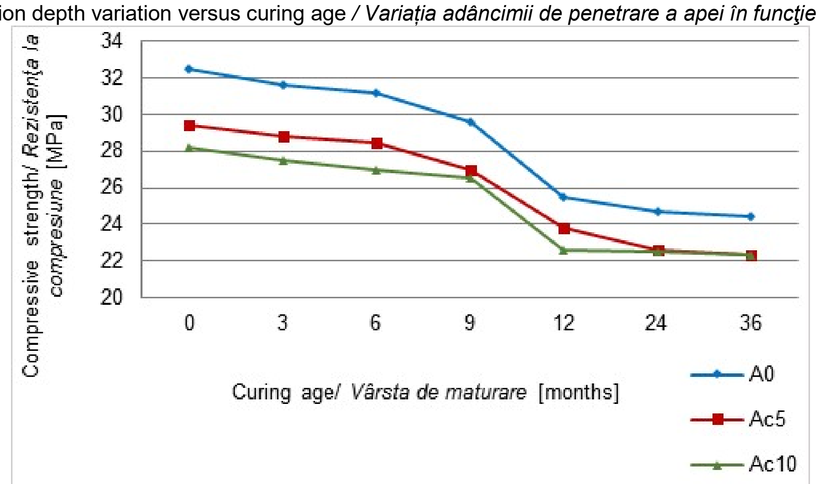

Fig. 6 - Compressive strength variation of the studied concrete mixes/ *Variația rezistenței la compresiune a rețetelor de beton studiate*

depth being settled at the value of 101 mm. This result certifies that the calcium hydroxide was partially dissolved, and the levigation was not significant.

As it concerns the fly ash concrete specimens, an unfavourable behaviour was observed. Even in the case of the specimens that were not subjected to the accelerated corrosion process yet, at the reference moment "0", increased values of the water penetration depth were recorded in case of fly ash concrete mixes, compared to those of the reference concrete, A_0. The initially measured average values were 117 mm for the A_c^5 concrete mix and 125 mm for the A_c^{10} concrete mix.

By analysing the recorded data up to the 36th month, a constant increase of the water penetration depth was observed in the case of fly ash concrete mixes. Moreover, the water penetration depth increased with the increase of the percentage of fine natural aggregate replaced by fly ash. After subjecting the A_c^{10} concrete specimens to the corrosive attack with warm softened water for 36 months, the water penetrated almost the entire depth of the specimens, reaching the maximum value of 140 mm.

Figure 6 shows the variation of the compressive strength of the considered concrete mixes over the entire time interval. At the beginning, the compressive strength values were almost similar, varying from 32.5 MPa in case of A_0 mix to 28.2 MPa in case of A_c^{10} mix, and all three mixes presented the same decreasing tendency in time. After subjecting the specimens to the accelerated corrosive attack for a period of 12 months, a steep decrease of the compressive strength was recorded.

The values of the compressive strength determined on the concrete specimens embedding variable percentages of fly ash as fine natural aggregate substitute, were compared to those of the reference concrete specimens A_0 and the strength decrease is illustrated in Figure 7 and Figure 8.

As the previous two graphs show, the destructive effect of the corrosion is more pronounced in the first part of the testing time interval of 36 months. This is the consequence of the more porous structure of the fly ash concrete

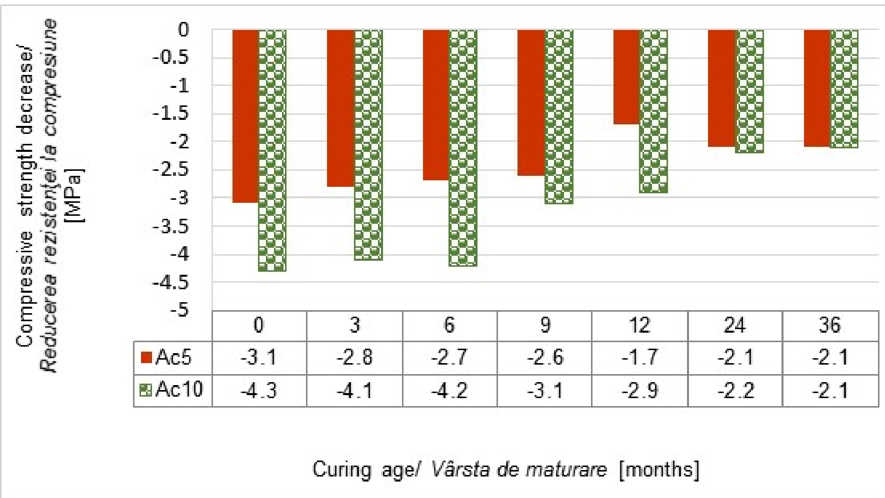

Fig.7 - The compressive strength decrease of the fly ash concrete mixes related to the reference concrete mix */ Reducerea rezistenței la compresiune a betonului cu cenușă de termocentrală raportat la betonul martor*

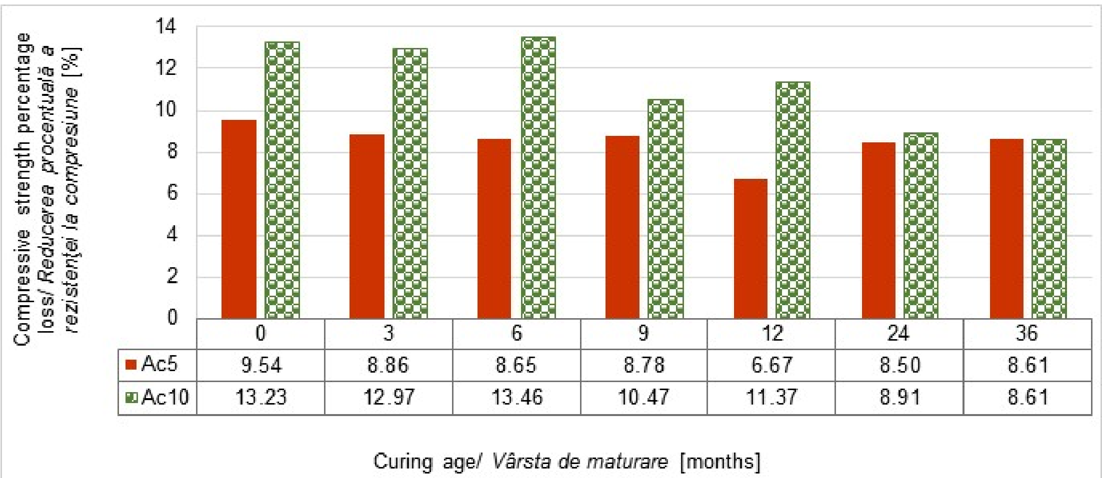

Fig. 8 – The compressive strength percentage loss of the fly ash concrete mixes related to the reference concrete mix */ Reducerea procentuală a rezistenței la compresiune a betonului cu cenușă de termocentrală raportat la betonul martor*

specimens caused by the increased amount of water needed for the mixing process. The specific surface area of the mineral aggregates increases due to the addition of the fine and irregular fly ash granules to the concrete mixes. Moreover, the compactness of the cement stone is reduced and the corrosion effect is amplified, directly influencing the properties of the hardened concrete.

An important adverse effect of the corrosive attack upon the fly ash concrete properties consists in the significant reduction of its compressive strength, related to the reference concrete, especially in the first part of the exposure. Starting with the 24th month of subjecting the concrete specimens to the accelerated corrosion process, the two concrete mixes embedding fly ash, A_c5 and A_c10, presented a quite similar behaviour in terms of the compressive strength. According to the results previously illustrated in Figure 7 and Figure 8, it can be seen that the most significant strength reduction was recorded in the case of A_c10 concrete specimens up to the 12th month, reaching an average percentage of 12%.

4.Conclusions

The experimental program carried out by the authors to analyse the long term behaviour of some concrete mixes with and without fly ash exposed to an accelerated corrosion process due to warm softened water, conducted in a specially designed and constructed installation, leads to the following conclusions:

The density of fly ash concrete mixes has decreased in time in case of both fresh and hardened state as a consequence of the cement stone compactness modification.

The recorded data concerning the water permeability of the concrete mixes reveal increased values of the water penetration depth in case of fly ash concrete mixes, compared to those of the reference concrete. An increasing tendency of this phenomenon with the curing age has been noticed.

The substantial degradation of concrete subjected to dissolving – levigation process occurs after a long term exposure producing a strength decrease, more significant in the case of the concrete mixes with fly ash, especially in the first part of exposure to the corrosive attack.

The corrosive effect by dissolving – levigation could be diminished if water reducing admixtures were utilised for the preparation of concrete mixes embedding fly ash.

At the same time, the use of fly ash in concrete represents a means of integrating a pollutant material with harmful effects on the environment in the construction industry.

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