Investigations on a green concrete obtaining through a partial cement replacement by fly ash

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Abstract. Concrete is a non-ecological material due to very high amounts of virgin materials used for its obtaining, significant energy levels being spent for their extraction and processing. The production of Portland cement is a major factor responsible for greenhouse gas emissions. Substituting a part of the cement by waste with puzzolanic properties, such as the fly ash, will lead to a decreasing of used cement and a consequent reduction of the pollutants generated by its obtaining. The present study aimed to investigate the effects of 10%, 20% and 30% volume replacement of cement by fly ash on the concrete density, compressive and split tensile strengths. The experimental results revealed that fly ash adding had a negative effect on the compressive strength of the obtained concrete, but a positive effect on its density. Replacing up to 20% volume of the cement by fly ash led to improved split tensile strength of the concrete. From the point of view of the fly ash quantity and concrete properties ratio, the obtained concrete with 20% volume of cement replaced by fly ash showed the optimum results.

Key Words: ecological concrete, waste, cementitious/puzzolanic material, mechanical properties.

Introduction. Concrete is the most common material of the building industry, being considered non-ecological due to its obtaining process from exhausting natural resources whose extraction and processing involves significant levels of energy. Among the components of typical concrete, the Portland cement causes, through its manufacture process, significant greenhouse gas emissions and huge amounts of polluted particles (Mehta 2004).

Nowadays, concrete is produced in very high amounts, more than 10 billion tons annually, and it is expected that its demand to increase up to 18 billion tons annually till 2050 (Aprianti 2017). Due to the increasing demand and usage of concrete in the building industry all around the world, there is a growing concern about the environmental effects of the emissions resulting from its manufacturing process, various materials for total/partial substitution of cement and/or aggregates being tested as a part of the interest for more environmentally friendly concrete production. Ecological concrete is most often the result of the use of a waste material as a partial or total substitute for cement, sand and/or aggregates, or that concrete whose production process does not significantly affect the environment. Therefore, using different ashes with cementitious properties as cement replacement materials represents a way for ecological concrete developing.

The fly ash (FA) is generated from coal combustion in thermal power plants. A tonne of pulverized coal can produce about 30 to 40% FA (Sun et al 2003). Large amounts of FA are usually discharged directly into landfills, resulting in substantial land occupation and environmental pollution (Aprianti 2017).

FA particles are generally spherical, in the range of 0.5-100 microns, almost entirely being formed of silicon dioxide. The physical and chemical properties of FA may vary depending on each thermal plant, mainly due to differences in the coal source (Sun et al 2003).

Nowadays, FA is widely used for many research purposes, one of them being as a cementitious material for concrete obtaining. FA has similar features to puzzolanic materials, in terms of SiO_2 (silica) and Al_2O_3 (alumina). Pozzolan is defined as a silicious or silico-alumina material, which possesses itself a small or no cementitious value but, in finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide to form compounds with cementitious properties (Aprianti 2017). FA is an important puzzolanic material that has a number of advantages over ordinary Portland cement. First, the heat of hydration is lower, making ash a popular substitute for cement for mass structures. Concrete with FA can have better strength and properties than conventional concrete. It is widely available, and is generally cheaper than Portland cement. The relatively slow rate of development of FA concrete strength is a disadvantage in applications where early strength is imperative. But in many situations, especially those involving mass concrete structures, such as dams and heavy foundations, which are not loaded at their design values for several months, they work with concrete strength developed at 90 days instead of 28 days. If the normal strength development is critical, additives are available to accelerate the hydration rates of ash concrete mixtures (Meyer 2009).

FA has been consistently used throughout the world to improve concrete properties and to reduce the risks of environmental pollution (Siddique 2003; Tangchirapat et al 2009; Barbuta et al 2014; Salas et al 2016). For example, replacing 15-35% of cement with FA in the concrete mix increases strength, improves sulphate action, reduces permeability, reduces the amount of water required and improves workability (Badur & Chaudhary 2008).

The aim of this scientific paper was to investigate the effects of three volumes replacement of cement by FA on some physical and mechanical parameters of the obtained concrete. This work is important due to the conducting of the experiments in the climatic conditions of Romania, and using local resources, respecting the appropriate standards for the classification of the obtained concrete.

Material and Method

Description of the research. The present research was performed in August 2017 and aimed to investigate the effects of the three volumes (expressed as percentages) of cement replacement by FA, on the density, compressive and splitting tensile strengths of the concrete. It was used FA as a cementitious material to replace 10%, 20% and 30% vol. of the cement quantity from the concrete recipe.

Experimental design. The research involved the development of four types of concrete recipes, as follows:

- RC: a reference concrete manufacturated using a formula for the 25/30 microconcrete class;
- CFA10: a concrete with 10% vol. FA, in which 10% of cement volume of the reference concrete was replaced by FA;
- CFA20: a concrete with 20% vol. FA, in which 20% of cement volume of the reference concrete was replaced by FA;
- CFA30: a concrete with 30% vol. FA, in which 30% of cement volume of the reference concrete was replaced by FA.

The components used for the RC manufacturing were:

- Portland cement CEM II/A-LL 42.5R, with granulated blast furnace slag and limestone, produced in Romania;
- two sorts of river aggregates: sand (0-4 mm diameter) and gravel (sort 4-8 mm);
- water for a water/cement ratio of 0.43;
- additives: a policarboxilateter based superplasticizer (Sika Plast 140) used to reduce the water/cement ratio and to improve the concrete workability, and a rhodanid based accelerator (Sika BE5), to enhance the cement hydration process.

The RC recipe was calculated with a water/cement ratio of 0.50, but using the superplasticizer additive, was obtained an easy workable concrete with 0.43 ratio.

To analyze the effect of FA on the concrete properties, the cement was partially replaced by FA in 10%, 20% and 30% vol., respectively. The source of the used FA was Holboca Thermal Power Plant, Iasi County, Romania.

The developed concrete was poured in 150 mm cube molds for compressive strength test and in cylinder molds with 100 mm diameter and 200 mm length for splitting tensile test. Each test was made on three samples, at 28 days and according to the Romanian Standards (SR EN 12390-7/AC:2006; SR EN 12390-3:2009/AC:2011; SR EN 12350-6:2010; SR EN 12390-6:2010).

Data manipulation and analysis

A. The determination of apparent density of fresh and hardened concrete. The determination of apparent density consists in the establishing of the mass of a fresh concrete sample and reporting it to the volume of the sample in compacted state, according to SR EN 12350-6:2010. For this parameter, the same type of cylindrical metallic container was used as for casting the test specimens on which the mechanical strength were tested.

Procedure:

- the mass (m_1) of the empty vessel was determined;
- the fresh concrete was introduced into the bowl and compact it with vibration;
- the excess concrete was removed using the metal ruler;
- the mass (m_2) of the vessel filled with concrete was determined.

The apparent density of the fresh concrete was calculated using the following formula:

$$\rho = \frac{m_2 - m_1}{V} \left[\frac{kg}{m^3}\right] \quad \textit{(equation 1)}$$

where: m_1 - mass of the empty vessel [kg]; m_2 - container mass filled with concrete [kg]; V - vessel volume [m^3].

The density of the hardened concrete was determined according to SR EN 12390-7/AC:2006, using the following formula:

$$\rho = \frac{m_s}{V_s} \left[\frac{kg}{m^3}\right] \quad \textit{(equation 2)}$$

where: m_s - sample mass [kg], V_s - sample volume [m^3].

The investigated parameter of density was appreciated by computing the arithmetic mean of three determinations.

B. Mechanical tests on hardened concrete. After the preparation, casting and preservation of the concrete compositions for 28 days, the mechanical characteristics determined were the compressive strength and the splitting tensile strength. These two mechanical characteristics were determined by short-term tests, the compressive strength being considered the main quality criterion for concrete.

B1. The determination of compressive strength. Cubes testing was performed on mono-axial compression, with a hydraulic concrete press which carries a uniformly distributed load on the surface of the specimen according to SR EN 12390-3:2009/AC:2011. The cubes were loaded perpendicular to the direction of concrete casting. The average of three attempts was determined for the compressive strength appreciation.

The compressive strength value was determined considering the following formula:

$$f_c = \frac{F_{max}}{A_C} \left[\frac{N}{mm^2}\right] \quad \textit{(equation 3)}$$

where: F - the maximum force, in [N]; Ac - the compressed area perpendicular to the loading direction, in [mm^2].

B2. The determination of splitting tensile strength. The determination of splitting tensile strength was performed on cylinders with a diameter of 100 mm and a length of 200 mm. This test consisted of compressing a specimen after two diametrically opposed generators.

The splitting tensile strength *(f_{td})* was calculated using the following formula:

$$f_{td} = \frac{2F_b}{\pi bh} \left[\frac{N}{mm^2}\right] \quad \textit{(equation 4)}$$

where: F_b - breaking force, in [N]; π - the value of pi number; b - the average width of the breaking cross-section, in [mm]; h - the average height of the breaking cross-section, in [mm].

The tests were carried out in accordance with SR EN 12390-6:2010. For testing, a hydraulic press was used, recording the value of the breaking force. The force was applied perpendicularly to the direction of the material casting, continuously and uniformly until breakage. The results of the three samples for each test were averaged and than interpreted.

Results and Discussion

The concrete density. The evolution of the concrete density during the curing period of 28 days is represented in Figure 1. It can be observed that the slope degree is different for every concrete variant. The smothest one is that of CFA10 which means that it had the smallest water quantity lost by evaporation. In condition of the same water/cementitious materials ratio, CFA20 had the biggest slope of density evolution, especially in the first 7 days of curing.

The final concrete density, after 28 days of curing, is represented in Figure 2. The density of the developed recipes slightly decreased as the cement was replaced by FA, but in smaller rates as the FA quantity increased. Over the 20% vol. replacement, FA has an increasingly smaller effect on concrete density.

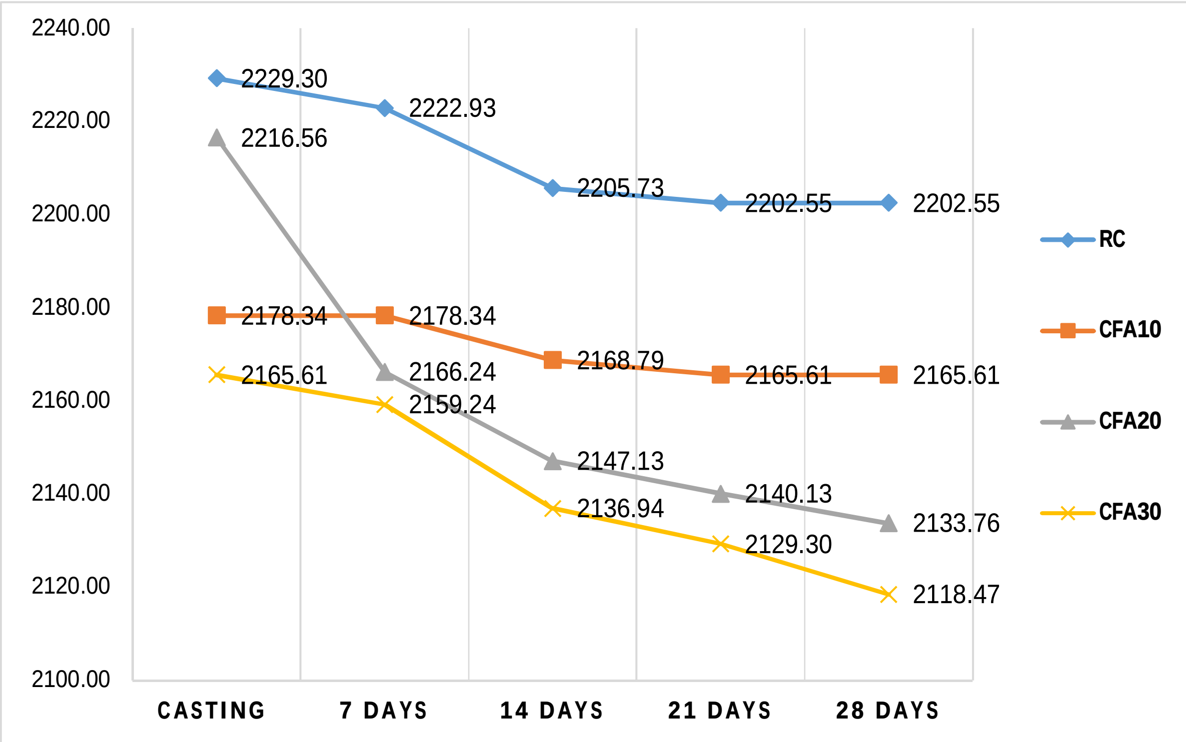

Figure 1. The evolution of the concrete density during the curing period of 28 days [kg m^{-3}].

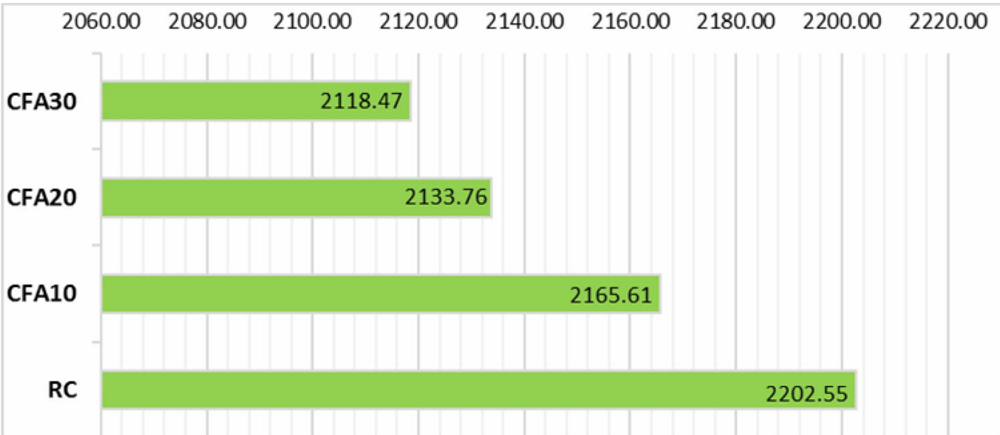

Figure 2. The concrete density at 28days [kg m^{-3}].

The concrete compressive strength. The compressive strength values for the four types of concrete recipes are compared in Figure 3. As the FA quantity increased, the concrete compressive strength decreased. For a 10% vol. of cement replacement by FA, the obtained concrete recorded a smaller value of its compressive strength (by 8%) compared to the measured compressive strength of RC; for a 20% vol. replacement, the decreasing was by 10%, while 30% vol. of FA of cement led to a compressive strength decreasing by almost 17%. So, even the cement replacement with FA was made in equal rates, the effects on the compressive strength of the obtained concrete was not in the same proportions. However, the compressive strength decreasing of the concrete with FA additions can be due to a high amount of carbon in the FA composition (a high amount of carbon in its content is due to the incomplete burning of the coal in the thermal plant).

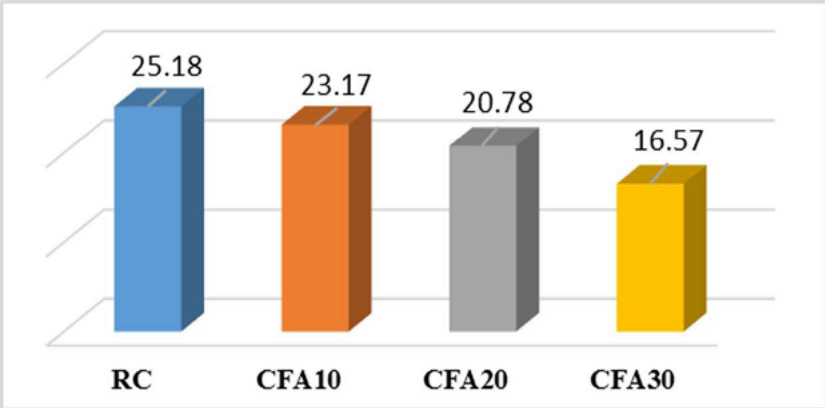

Figure 3. The compressive strength of the concrete [N mm^{-2}].

The concrete splitting tensile strength. The splitting tensile strength of the investigated concretes is compared in Figure 4. For up to 20% FA replacement of cement it was observed an enhanced splitting tensile strength of the investigated concrete, by up to 16%. An addition of over 20% FA results in a decreased splitting tensile strength with almost 27% compared to that determined for RC.

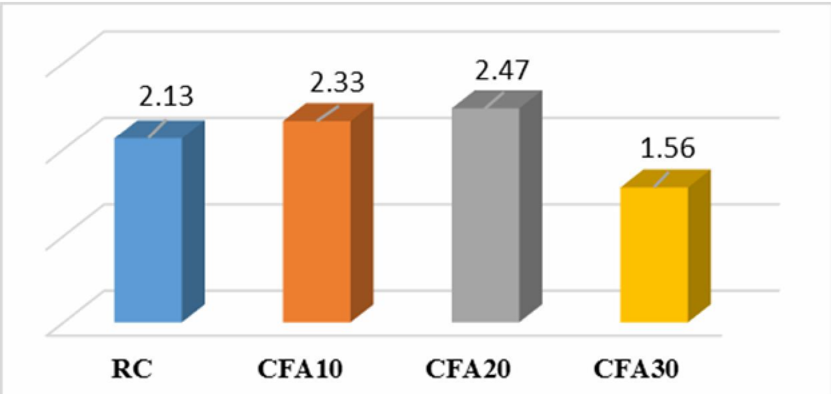

Figure 4. Split tensile strength of the concrete [N mm^{-2}].

The idea of FA using in the concrete composition as a depollution technique of the areas used for its storage is known and successfully applied worldwide by various research centers. However, each research is particular by the composition and amount of FA used, additives, as well as the size of the aggregates. Therefore, discussions and comparisons are deficient from this point of view. For example, Serbanoiu et al (2017) prepared some variants of FA concrete with 10, 15, 20, 30 and 40% FA as cement replacement. There was used the same type of cement and the samples were kept also in air as in the case of present research. The differences were the maximum size of aggregates (16 mm), water/cement and water/cement+FA ratio (0.48) and the using of a superplasticizer only as additive, without the accelerator. The results revealed also smaller values for mechanical strengths, as the present study. Among the variants of FA concrete, the best results were obtained by that with 10% of FA for compressive strength. Regarding the split tensile strength, the concretes with 10% and 15% of FA had the higher results. Muhit et al (2013) studied the effect of 5, 10, 15, 20, 25 and 30% of FA on high performance concrete. They used almost the same water/cement and water/cement+FA ratio as in the present research (0.42) but a maximum size of aggregates of 18 mm and a superplasticizer additive with a set retarding effect. The results revealed higher compressive strength for all FA concretes, especially for that with 10% of FA. Regarding the split tensile strength, higher values were obtained by the concretes with 5, 10, 15 and 15% of FA, and that with 10% of FA had the best result.

Conclusions. The present research aimed to develop a green concrete, with a cement partially replacing by FA in 10%, 20% and 30%vol. The effects of FA addition on the mechanical properties of the obtained concrete were investigated respecting the methodology and the law-in-force. The FA source was Holboca Thermal Power Plant, Iasi County, Romania, its using having a double benefit: its consumption from the areas used for its storage and the obtaining of a concrete with a better density and an improved split tensile strength (in the conditions of up to 20% volume of cement replaced by the FA). From the point of view of FA quantity and concrete properties ratio, the concrete with 20% vol. of FA showed the optimum results.

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