EVALUATING CONCRETE STRENGTH: A STUDY ON THE IMPACT OF FLY ASH AND CALCINED CLAY

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Abstract

Materials with a certain binding capacity have been decisive in the development and evolution of construction. This evolution has led to Portland cement and reinforced concrete being the most widely used materials in the construction industry. On the other hand, the cement industry is one of the main sources of CO2 emissions. Consequently there is a need for alternative binders with cementing capabilities, which do not harm the environment and can also bring benefits, such as fly ash and calcined clay. These materials can be used as mineral additives in the preparation of Portland cement, as additives in grinding or in the mixture of two or more fine materials that partially replace Portland cement. In this paper, the compressive strength of the mortars prepared with fly ash and calcined clay, coming from deposits of Albania, were tested after 2,7 and 28 days and the results were compared with that of OPC concrete (CEM I 42.5 R).

***Key words**: Alternative binders, Clinker, Fly ash, Calcined clay, Compressive strength, Ordinary Portland Cement.*

Përmbledhje

Materialet me një kapacitet të caktuar lidhës kanë qenë vendimtare në zhvillimin dhe evolucionin e ndërtimit. Ky evolucion ka bërë që çimentoja Portland dhe betoni i armuar të jenë materialet më të përdorura në industrinë e ndërtimit. Nga ana tjetër, industria e çimentos është një nga burimet kryesore të emetimeve globale të C02. Rrjedhimisht lind nevoja për lidhës alternativë me aftësi çimentuese, të cilët reduktojnë ndotjen mjedisore dhe mund të sjellin përfitime në vetitë fiziko-mekanike të çimentos, të tilla si hiri *fluturues dhe argjila e kalcinuar. Këto materiale mund të përdoren si additive minerale në përgatitjen e çimentos Portland, si aditivë në bluarje ose në përzierjen e dy ose më shumë materialeve të imta që zëvendësojnë pjesërisht çimenton Portland. Në këtë punim u testua qëndrueshmëria në shtypje 2, 7 dhe 28 ditore e mostrave të përgatitura me hi fluturues dhe argjilë të kalcinuar, të marra nga depozitime të ndryshme në Shqipëri. Rezultatet u krahasuan me mostrat e betonit me çimento Portland OPC (CEM I 42.5 R).*

Fjalë kyçe: *Lidhësa alternativë, Klinker, Hi fluturues, Argjilë e kalcinuar, Rezistencë në shtypje, Çimento Portland e zakonshme.*

Introduction

The cement industry is one of the main sources of CO_2 emissions. It is estimated that CO_2 emissions into the atmosphere reach a value of 1 ton of CO_2 per ton of clinker, so Portland cement contributes to about 5% of global CO_2 production (Cassgnabere *et al.*, 2009). For this reason, researches are carried out to find alternative materials with cementing capabilities, which do not harm the environment due to their origin and that when used carefully, can bring benefits (Malhotra *et al.*, 1996). There are some industrial wastes, which can be used as cementitious materials. There are also other cementitious materials of natural origin (like volcanic ash), which can be used in the concrete mix. Today, over 80% of supplementary cementitious materials used to reduce the clinker factor in cement are: limestone, fly ash, wood ash, fumed silica, furnace slag (from the metallurgical industry), metakaolin (from calcined clay) and shale (Day & K.W, 2006) These materials can be used as mineral additives in the preparation of Portland cement, as additives in grinding or in the mixture of two or more fine materials that partially replace Portland cement. Below, some of these supplementary cementitious materials will be treated separately (Kosmatka & S.H, 2004).

Figure 1. Supplementary cementitious materials.

A cementitious byproduct is a secondary material derived from an industrial production process that possesses conglomerative characteristics after a certain treatment (Malhotra *et al.*, 1996).

These materials, which are considered as waste, may possess or have a certain adhesion capacity and may be useful or marketable when they find application in other industrial sectors, for example, as partial replacement materials in Portland cement, as is the case fly ash. There is currently a high interest in the application of this material in the production of cement to reduce the amount of CO_2 released into the atmosphere.

The physical and mechanical properties are very important and determine the suitability of concrete for use. The main characteristic of concrete, which is affected by the use of cementitious materials of natural origin, is resistance to compression. Under different mixtures, conditions, origin, or atmosphere, the use of a certain amount of these materials is allowed without significantly affecting the mechanical properties of concrete (Cassgnabere *et al.*, 2009; Ashtiani *et al.*, 2013; Bagheri 2013). The main objective is to review the situation on the trends of concrete compressive strength.

One of the future development options is to increase the use of industrial by-products (Huntzinger & Eatmon, 2009) such as municipal solid waste ash. If the waste has binding properties, then the use of Portland cement clinker can be reduced, which is beneficial to the environment due to reducing $C0_2$ gas emissions (Bauchard, 1978; Collins & R.J., 1978; Organization for Economic Cooperation and Development Road Research Group, 1977). Incinerator ash often consists of fine fly ash, and bottom ash, which is usually a denser material that remains in the incinerator after combustion. The bottom ash is mainly composed of amorphous silica, alumina (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO) and is similar to slag, which is used as a substitute in cement (Ferraris et al., 2009). Also, this mineralogical content is analogous to the mineral mixture used in Portland cement. Other components, such as chlorides, alkalis, trace metals can change the hydration properties, mechanical strength and reactivity of cement products (Cioffi *et al.*, 2011; Ginés *et al.*, 2009). Ash cement contains about 10% more C_3S than ordinary cement, which is the phase mainly responsible for the development of resistance and heat generation during the first 28 days of hydration.

The higher C_3S content results in more heat in the first days, faster setting time, and in a concrete with higher compressive strength in the first days compared to Portland cement. The mechanical properties are favored when the percentage of ash replacement is within certain limits (Taylor, 2004). Beyond them, the resistances in compression and bending decrease gradually with the increase of the ash content (Shih *et al.,* 2003).The only type of material which is available in the quantities needed to meet the demand is clay and its combination with limestone allows replacement of up to 50% of clinker, having the same mechanical properties as well as improving the stability of concrete (Scrivener, 2004).

The reactivity of the calcined clay depends on the kaolin content in it (Fernandez *et al.,* 2011). A kaolin content of about 40% in a mixture of LC_3-50 (50% clinker, 30% calcined clay, 15% limestone, 5% gypsum) is sufficient to give mechanical properties comparable to those of ordinary Portland cement (Alujas *et al.,* 2015; Avet *et al.,* 2016). In terms of investment and production cost, the latter is similar to the cost of Portland cement (Gettu *et al.,* 2019). Technologically, it has been proven that it is able toeconomicaly produce cement with a quality comparable to that of Portland cement (Joseph *et al.,* 2016).

Materials and methods

This section describes the experimental study of the elemental composition and compressive strength of ash and calcined clay samples. The main purpose is to determine the compressive strength of the samples formed with the above-mentioned materials and their comparison with ordinary Portland cement. Several samples were taken for analysis and the sampling site is as follows:

- The ash samples were taken in the municipal solid waste incinerator, in the city of Elbasan, Albania.
- The clay samples were taken in the clay quarry near the Cement Factory in Fushe-Kruja, Albania.

The XRF analysis of the samples

The samples taken for analysis were respectively fly ash, bottom ash, taken in the municipal solid waste incinerator, in Elbasan, Albania and calcined clay, from the quarry near Fushe-Kruja Cement Factory, Albania, fig.2. The XRF analysis procedure for these materials was carried out in the apparatus illustrated in figure 3. The principle of this procedure is to create curves for different applications with raw materials of different chemical composition, in order to create curves of dependence between the concentration of the oxide of interest and the number of voltage drops/second (kcps - kilocounts per second) coming from the sample.

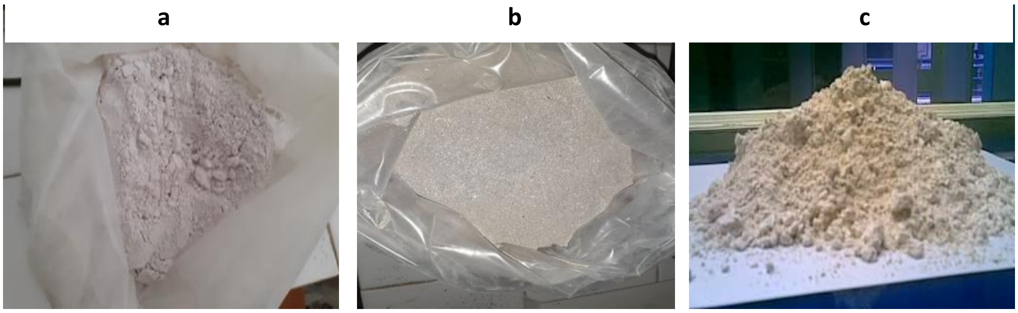

Figure 2. Sample illustration taken for analysis a). Fly ash, b). Bottom ash, c). Calcined clay.

Figure 3. XRF apparatus (SDD detector).

Clay calcination procedure, prism formation and compressive strength analysis

For the clay calcination procedure, a sample weighing 5 kg is selected according to the sample selection procedure in the ECF laboratory.It is then dried for 12 hours in a thermostat at a temperature of 110 °C. After drying, it is ground in a laboratory mill. 20 g of ground clay are taken and placed for 1 hour in the MUFFEL for calcination at 800 °C.

Briefly, the procedure for the formation of prisms and the analysis of compressive strength is described below. The samples consist of 450 ± 2 g of cement, 1350 ± 5 g of sand and 225 ± 1 g of water.

Initially the cement is mixed with water and then sand is added. The prisms are 40 mm x 40 mm x 160 mm in size and are stored in water baths at (20.0 ± 1) °C (European Norm, EN 196-1:2016). The prism must be placed in the press (class 1,50-250 KN according to EN 7500-1 (International Standard ISO 7500-1.), accuracy ± 1.0 %, speed of loading 2400 ± 200 N/s), which is loaded with a speed of 2400 ± 200 N / s and by means of automatic pressing the prism is broken. The result expressed in MPa is then read (1Mpa = Exercised force / surface in mm^2)

Figure 4. Laboratory mill with disks; bathtub where the prisms are kept; hydraulic press.

Results

1 The elemental composition of the samples (XRF results)

The results of the elemental composition of the bottom ash, fly ash and calcined clay samples are shown respectively in table 3 and presented graphically in fig.5.

Table 3. Elemental composition results for ash and slag.

	MgO %	Al_2O_3 %	SiO_2 %	CaO %	TiO_2 %	MnO %	FeO %
Bottom ash	9.44	4.34	10.54	41.11	1.025	0.624	1.9
Fly ash	7.1	0.21	1.25	56.03	0.26	0.0589	0.00013

From the elemental composition analysis of these two samples, it is observed that the richest sample with the three main oxides (calcium, aluminum and iron oxide), is the fly ash. The sum of the content of these oxides is close to 60%, which means that the material taken in study may have the potential to give positive compressive resistance results.

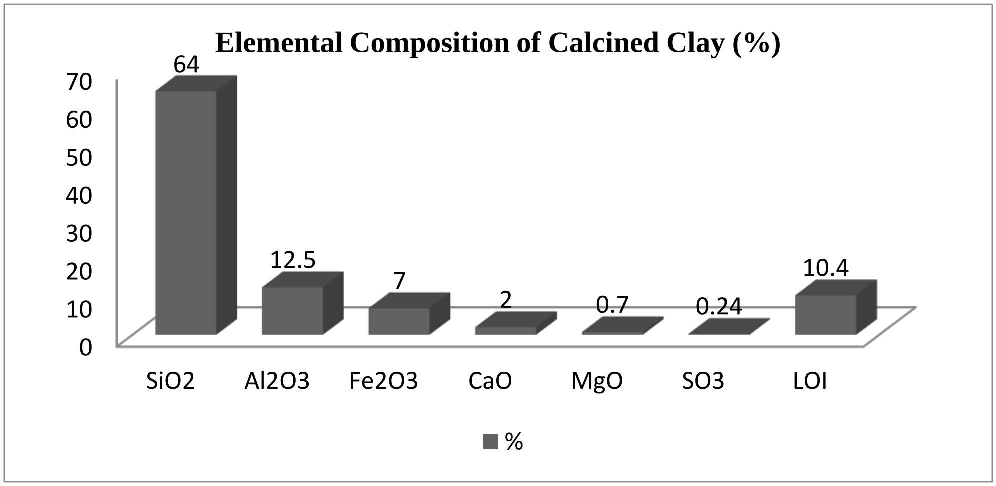

Figure 5. Elemental composition results for calcined clay.

Furthermore, from the results obtained for the elemental composition of the clay, we notice that the content of the main oxides such as CaO, SiO_2, Al_2O_3 and Fe_2O_3 is to some extent high. Therefore we expect positive results of the compressive resistance.

2 The compressive strength results

The results of the compressive strength for the bottom ash, fly ash and calcined clay samples after 2 and 28 days are given respectively in the following tables.

2.1 Compressive strength results for the ash samples

Table 4. Compressive strength results (MPa) of the bottom ash (BA) samples (Elbasan incinerator).

	Type	**2 days**	**28 days**
Compressive strength (MPa)	Cem I 42.5 R FK (control sample)	26.4	48.1
	70 % Cem I 42.5 R FK + 30 % brown BA	10.7	28.4
% of Resistance given compared to the control sample	70 % Cem I + 30 % brown BA vs Control Sample	40.5	59

In the case of brown bottom ash, what we observe is that the results are much weaker compared to the control sample (42.5 Mpa), which was up to a point expected based on in the elemental analysis of this sample. The percentage of resistance achieved by the sample with 30% brown bottom ash is 59% of the resistance of the control sample.

From the results obtained for the white fly ash, it is observed that the percentage of resistance compared to the control sample is approximately 74%. The resistance reached by the sample with 30% fly ash after 28 days is 35.4 Mpa, relatively far from the expected result to reach the cement mark.

Table 5. Compressive strength results (MPa) of white fly ash (FA) sample (Elbasan incinerator).

	Type	2 days	28 days
Compressive strength (MPa)	Cem I 42.5 R FK (control sample)	26.4	48.1
	70 % Cem I 42.5 R FK + 30 % white FA	14.4	35.4
% of Resistance given compared to the control sample	70 % Cem I + 30 % white FA vs Control Sample	54.5	73.6

2.2 Compressive strength results for the calcined clay samples

Table 6. Compressive strength results for cement samples with 30% calcined clay.

	Compressive strength [MPa]		
Sample	**2 days**	**7 days**	**28 days**
CEM I 42.5R	27.3	40.5	53.3
Calcined Clay 30%	-	22.4	42.5

The percentage of resistance achieved by the sample with 30% calcined clay, compared to the control sample, is approximately 79.8%. The results of the clay can be said to be satisfactory, since the resistance achieved by the sample with 30% replacement after 28 days is 42.5 Mpa, a value that indicates the achievement of the cement mark. What was noticed from the obtained results, is that based on the elemental composition of different samples we can, to some extent, predict the results that will be obtained during the compressive resistance analysis. Precisely this was verified by obtaining the results of compressive resistance, where it was clearly observed that the samples with calcined clay were more effective.

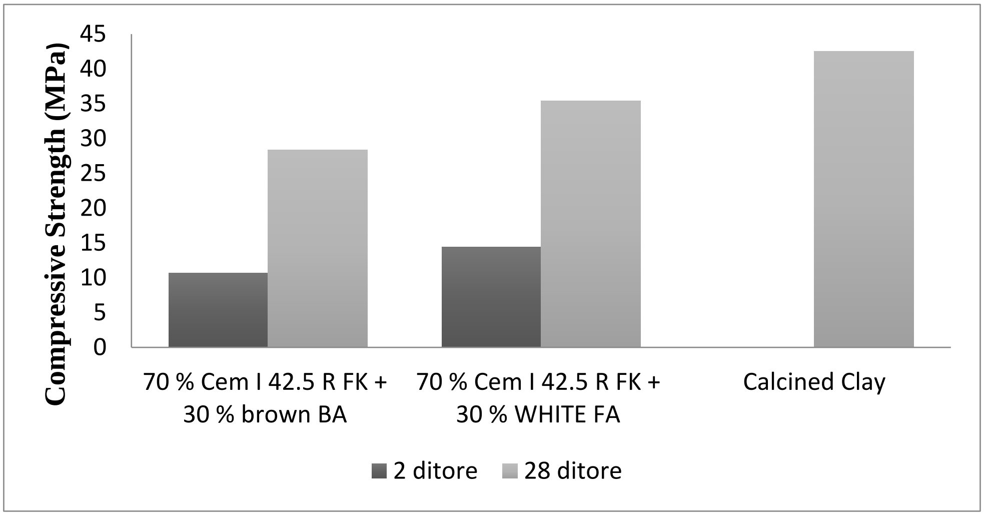

Figure 6. Comparison of compressive strength for all samples taken in analysis.

This is also verified by the above comparison chart where the 2 and 28 day compressive resistances of all the samples with 30% replacement are shown. The replacement percentage of the cement samples with the materials taken in the study was arbitrary chosen to be 30%. However, further studies can be carried out to try different replacement percentages in which more satisfactory results can be acquired.

Discussions

There are some arguments for the results obtained from the conducted experiments. Regarding the municipal solid waste ash, the overall results in our case do not support the use of this material with a 30% replacement percentage. In the case of ash, its chemical composition may be the main reason for these results. The high percentage of CaO compared to the other oxides and the non-uniform fineness of the clinker and this cementitious material has led to an inefficient hydration reaction. The mechanical properties are favored when the percentage of ash replacement is within certain limits. Beyond them, the resistances in compression and bending decrease gradually with the increase of the ash content.

Concerning the calcined clay, better results were obtained. During calcination, the hydroxyl bonds between the clay structures undergo a reorganization of the basic building units, thus, resulting in a highly amorphous material. This clay structure contributes to an increase in the specific surface area of the cementitious mixture and a finer porous structure than that of ordinary cement.

In our case, it is claimed that the amount of kaolin mineral is low, producing a small amount of metakaolin during calcination, and therefore its efficiency is low. Metakaolin reacts with $Ca(OH)_2$ to give calcium silicate hydrates, which are products that contribute to the development of mechanical properties of concrete. In addition, it is also thought that both the temperature and the calcination time may have influenced the results.

Conclusions

After performing the analyses for all the samples taken in study and after receiving the relevant results, the following conclusions are reached:

- The cementitious materials studied are a real potential for replacing cement in concrete if they present pozzolanic properties and have a content of 3 oxides ($CaO+Al_2O_3+Fe_2O_3$) in values close to 70%.
- For the samples of fly and bottom ash from Elbasan incinerator, as well as the clay taken in Fushë-Kruja for analysis, we had a decrease in resistances for replacement rate of 30%.
- In the case of ash, its chemical composition may be the main reason for these results. The high percentage of CaO compared to other oxides and the non-uniform fineness of the clinker, have led to an inefficient hydration reaction.
- Although the values of the compressive strength results were low, the best results were obtained from calcined clay. In this case, it is claimed that the amount of kaolin mineral is low.

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