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EARLY-AGE MECHANICAL PROPERTIES OF MORTARS WITH DIFFERENT PERCENTAGES OF ECO-CEMENT

BY

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Abstract. Concrete is a mixture between two main components: cement paste and aggregates. While the aggregates and the water can be easily found in nature, cement needs special processing plants to be produced. The production of cement alone has increased dramatically over the past 80 years due to a continuous increase in demand for concrete. Taking into account that the cement content in normal strength concrete ranges from 10% to 15% and that the concrete industry is the largest consumer of natural resources in the world, one could only imagine the environmental burden it creates. The present paper brings its contribution to the investigation concerning the use of a new binder, in the form of anhydrous calcium sulphate, as partial or total replacement of the ordinary Portland cement in concrete. The anhydrous calcium sulphate based binder is obtained exclusively from industrial wastes and can be entirely recycled after its expiration date. The obtained results so far show a decrease in the flexural and compressive strengths of mortars with small replacing percentages of anhydrous calcium sulphate compared to the reference sample made with Portland cement. However, the flexural strength increases tremendously for higher percentages of anhydrous calcium sulphate. Additionally, slight gains in the values of the compressive strength were observed for the corresponding specimens compared with the samples for which only small percentages of eco-binder were used.

Key words: eco-material; anhydrous calcium sulphate; cement replacement; mechanical properties.

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1. Introduction

Concrete is a mixture between two main components: cement paste and aggregates. The aggregates, usually sand and gravel, are embedded in the paste made of water and cement. While the aggregates and the water can be easily found in nature, cement needs special processing plants to be produced. The production on cement alone has increased dramatically over the past 80 years due to a continuous increase in demand for concrete. According to a U.S. Geological Survey statistic report, the cement production increased, worldwide, from 62.4 million metric tons, in 1926, to 3.06 billion metric tons, in 2009. Taking into account that the cement content in normal strength concrete ranges from 10% to 15% (Environm. Council of Concr. Org.,2010) and that the concrete industry is the largest consumer of natural resources in the world, roughly 11.5 billion tons a year (Mahta & Monteiro, 2005), one could only imagine the environmental burden the construction industry creates (Arikan, 2004; Koroneos & Dompros, 2007; Blom *et al.*, 2010).

Due to increased public and scientific community awareness on the environmental impact of the construction industry (Bremmer, 2001; Rehan & Nehdi, 2005; Spaargaren & Mol, 2008) extensive efforts have been put to reduce the CO_2 emissions of the Portland cement plants, particulate air emissions, noise pollution, water pollution, etc. It has been shown that about 480 kg of CO_2 is emitted for each cubic meter of concrete (Bremmer, 2001).

In spite of the above, concrete is still the most widely used construction material. This is mainly due to its low maintenance, low energy consumption and, lately, due to the possibility of mixing in production wastes from other industries. In spite of minor and temporary setbacks, *e.g.* freezing and thawing resistance, alkali–silica reaction, concrete is still the material of choice when it comes to severe exposure conditions. However, perhaps the biggest advantage of modern concrete is the possibility of including other industrial byproducts into the concrete mix (Pavlenko, 1998; Meyer, 2009) and create new, hybrid materials with tailored mechanical properties to meet any possible requirements. Considerable research effort has been put to develop concretes with large volumes of fly ash from electrostatic precipitators in power plants (Malhotra, 1999; Aggarwal, 2010; Karahan & Atiş, 2011). Ground granulated blast furnace slag (GGBFS), a glassy granular byproduct of the steel industry, has also found its use as partial Portland cement replacement but also as aggregate (Mozaffari *et al.*, 2009). The huge success silica fume, a by-product of the semiconductor industry, has as pozzolan and filler material (ACI Committee 234, 2006; Gonzales-Fonteboa & Martinez-Abella, 2008; Ivorra *et al.*, 2010) is another example of this great advantage of concrete.

Taking into account that demolition waste generates around 300 million tons of debris per year in the United States alone (Meyer, 2009) it becomes clear that storing these solid wastes in landfills is no longer a viable option.

Extensive research has been conducted in the field of using the solid wastes generated by the construction industry as recycled aggregates for concrete (Topcu & Şengel, 2004; Etxeberria *et al.*, 2007; Berndt, 2009). As with any new concept, there were technical issues involved with the use of recycled aggregates (ACI Committee 555, 2001) but recent research studies suggest that even these problems were addressed (Sarhat, 2007). Consumer glass waste is another example of a suitable aggregate for concrete. The most important issue with using the recycled glass waste is the alkali-silica reaction (ASR) it generates in the concrete mix (Saccani & Bignozzi, 2010). However, there are good indications that even this problem can be solved (Jin, 1998).

Hundreds of millions of scrap tires are generated in developed countries all over the world and start posing a serious environmental problem. One of the best methods of recycling used tires is to reuse them after rethreading (Pera *et al.*, 2004). Rubber particles and steel wires have a restraining effect on the crack propagation, leading to an increased ductility and energy absorption capacity (Turatsinze *et al*., 2005; Nguyen *et al.*, 2010).

The present paper brings a few contribution to the investigation regarding the use of a new binder, in the form of anhydrous calcium sulphate, as partial or total replacement of the ordinary Portland cement in concrete. Nowadays there is still little research related to the total replacement of the ordinary Portland cement (OPC) by equivalent binders (Yang *et al.*, 2007). The anhydrous calcium sulphate (ACS) based binder is obtained exclusively from industrial wastes and can be entirely recycled after its expiration date.

The results presented in what follows are part of a larger research project related to the use of eco-materials for the structural rehabilitations of buildings located in seismic areas. The influence of the ACS on the mechanical properties of mortars with mineral matrix is investigated for different percentages of OPC replacement. The main focus was on the flexural strength and on the compressive strength. The mechanical characteristics were determined according to SR EN 196-1 (2006) provisions at different curing ages of the mortar specimens.

The results obtained thus far show a slight decrease in the flexural and compressive strengths of ACS mortar compared to the reference sample made with OPC.

2. Materials and Methodology

2.1. Cement

Two types of cement were used at this stage of the research. Type II cement, CEM II B-M 32.5R, is a composite high early strength cement, produced according to SR EN 197-1 code (2002). When fully cured, the standard compressive strength of mortar made with this type of cement should be at least 32.5 MPa (SR EN 196-1, 2006). The other type of cement used in the experimental investigations was ordinary high early strength Portland cement, CEM I 42.5R, also produced according to SR EN 197-1 (2002). The standard compressive strength of mortar prepared with this type of cement should be at least 42.5 MPa (SR EN 196-1, 2006).

2.2 Anhydrous Calcium Sulphate

The ACS was used as a replacement for the cement. The percentages used in this research were: 10%, 15%, 20%, 25% and 30%. Together with the cement, the ACS is used to obtain a more eco-friendly binder for mineral matrices. The ACS, in the form of β anhydrite III′ (WO 003827 A1, 2010), was obtained from industrial wastes, most of them unrecyclable such as: phosphogypsum (industrial waste from the production of phosphoric acid, a key ingredient for fertilizers and detergents), flue gas desulphurization gypsum (FGD – industrial waste from coal fire power plants), lactogypsum (industrial waste from the production of lactic acid, used mainly in food preservatives), a.s.o.

According to the invention patent (WO 003827 A1, 2010), the production of ACS involves low temperatures and no CO_2 emission at all. Moreover, it is entirely recyclable after its expiration date. The grain size ranges from 5 μm to 100 μm and the surface area is larger than 10 m^2/g.

2.3 Experimental Set-Up

The specimens were cast in standard size molds having the dimension 40 × 40 × 160 mm. After 24 h the specimens were demolded and stored until the day of testing. The testing samples made only of ordinary Portland cement and sand were stored in water whereas the specimens made of Portland cement, calcium sulphate and sand were stored at room temperature.

Table 1
Mix Proportions Considered in the Research (only for CEM I)

Specimen designation	Binder		Sand	Water	Water / Binder
	OPC (CEM I / II) kg/m^3	ACS kg/m^3	kg/m^3	kg/m^3	%
CI-0	1,570	0	1320	628	40
CI-10	1,256	234		596	
CI-15	1,099	351		580	
CI-20	942	468		564	
CI-25	785	585		548	
CI-30	628	702		532	

Specimens for each mix proportion were tested at the ages of 1 day, 2 days, 3 days and 7 days, in order to determine the tensile strength and the compressive strength. The main parameters of the research were the type of cement and the percentage of cement replacement by the calcium sulphate. The replacement percentage was considered from the entire volume. The mix proportions made with CEM I 42.5R type of cement and considered at this stage of the research are summarized in Table 1. The same mix proportions were used for the CEM II B-M 32.5R type of cement. The water to binder ratio of 0.4 was kept constant for all mix proportions.

Fig. 1 – Three-point bending test of mortar prism.

Fig. 2 – Uniaxial compression test on a half prism.

Moreover, the same type of sand, with a grain size between 0.1 mm and 1.0 mm, was used. The sand is considered to fill 50% of the total volume and the remaining percentage is made by the binder. The binder consists either of OPC or a mixture of OPC and ACS. Each mix proportion was named in terms of cement type and percentage ACS used. Hence, "C" stands for cement, followed by the type of cement, either "I" or "II", and the designation ends with a number showing the percentage of ACS considered.

The tensile strength of the mineral matrix was determined by means of three point bending test (Fig. 1). Three prismatic specimens were used for each determination of the tensile strength. The compressive strength was determined on the two resulting halves of the prism (Fig. 2). *Prior* to subjecting them to uniaxial compression test, the two halves were examined for the presence of cracks that might have been generated during the three point bending test. The loading rates were 0.05 kN/s, for the three point bending test, and 2.4 kN/s, for the uniaxial compression test.

3. Results and Discussions

The obtained results are discussed in terms of tensile strength and compressive strength experimentally determined at the ages of 1, 2, 3 and 7 days. The main parameters in this study are the type of Portland cement and the percentage of ACS used in the mix proportion. A total number of 12 mix proportions were considered leading to 144 specimens cast and tested.

3.1. Tensile Strength

Fig. 3 shows the variation of the tensile strength, [MPa], for each mix proportion prepared using CEM I type of cement. It can be observed that at 24 h (1 day) from the time of casting, the tensile strength of specimens made of only sand and cement showed the highest tensile strength. Moreover, at the same age, the tensile strength decreased with the increase in the percentage of ACS used in the mix proportion. However, towards the end of the considered time interval, the specimens with higher percentages of ACS exhibited a tremendous increase in the tensile strength. The increase in the values of the tensile strength was between 15% and 45% compared to the reference sample consisting only of cement and sand. Whereas specimen CI-0 exhibited almost constant evolution of the tensile strength, in the considered time interval, CI-10 and CI-15 showed an increase in the values but within expected percentages (Cusson & Hoogeveen, 2007). On the other hand, a tremendous increase in the tensile strength of specimens CI-20, CI-25 and CI-30 was observed between the third and the seventh day of curing, higher than 200%. This is an unexpected behavior taking into account the general tendency exhibited during the first three days of curing by all specimens with ACS. The authors consider that further researches are necessary in this direction to fully explain this phenomenon.

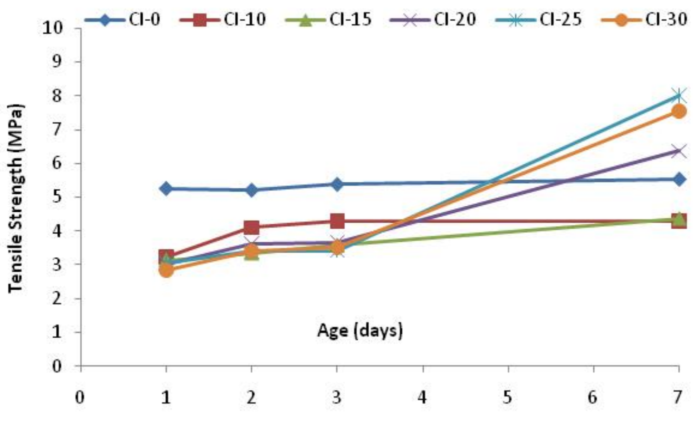

Fig. 3 – Variation of the tensile strength for the specimens made with CEM I cement.

Fig. 4 shows the variation of the tensile strength for all mix proportions prepared using CEM II B-M type of cement. Less scattering of the results are observed during the first three days of curing between the reference sample and the specimens having ACS in their mix proportions. However, at the end of the time interval, the scattering becomes higher, very similar to the specimens made of CEM I cement.

A closer look at the evolution of the tensile strengths for the reference specimens CI-0 and CII-0, shown in Figs. 3 and 4, reveal two different behaviors. While the CI-0 mix showed little variation in the values of the tensile strength, the CII-0 mix exhibited a continuous increase. The tensile strength at 7 days is higher for the CII-0 mix (7.24 MPa) than the corresponding value for the CI-0 mix (5.53 MPa).

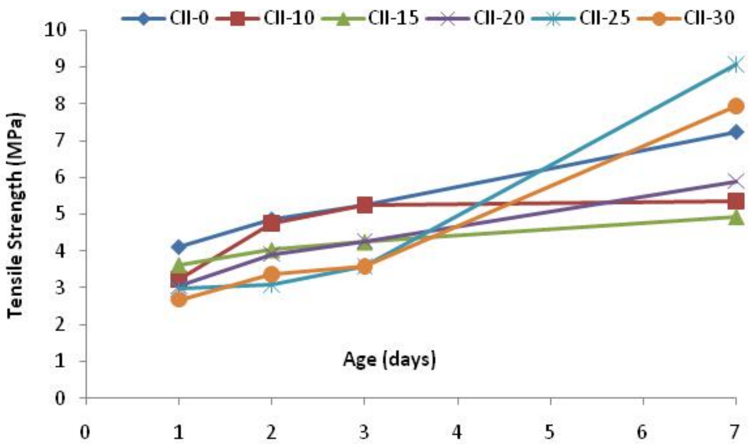

Fig. 4 – Variation of the tensile strength for the specimens made with CEM II cement.

Similarly to the trends exhibited by the specimens made with CEM I cement type, the tensile strength at seven days increased tremendously for CII-25 and CII-30 cases. Additionally, all specimens made with CEM II B-M cement showed a higher tensile strength at seven days, between 5% and 31% higher, compared to the specimens made with CEM I cement. This tendency is also valid for the values of the tensile strength determined at the ages of two and three days.

It can be concluded, therefore, that the type of cement used in the mix proportion plays an important role in the development of the tensile strength of mortar. Additionally, the percentage of OPC substitution by ACS represents also an important factor. Lower values of OPC replacement lead to a decrease in the tensile strength for the entire time interval considered in this research. However, large percentages of OPC replacement by ACS lead to very high values of the tensile strength at the age of seven days compared to every other mix proportion made from the same type of cement. Moreover, the ACS seems to favour the combination with CEM II B-M cement, since all the values of the tensile strength are larger than the ones obtained for the CEM I cement, with the single exception of the CII-20 case.

3.2. Compressive Strength

Fig. 5 shows the variation of the compressive strength, [MPa], for each mix proportion prepared using CEM I type of cement. It can be observed that even though there is a scatter in the values of the compressive strength at the age of one day, the values converge to a magnitude of the compressive strength of 30 MPa at the seventh day for all specimens having ACS in their mix proportion. Additionally, all these specimens exhibit a compressive strength lower than the reference sample for which a value of 47 MPa was measured.

The sharpest increase in the compressive strength was obtained during the last four days of the considered time interval for all mix proportions made with different percentages of ACS. On the other hand, the reference sample showed a large increase in the values of the compressive strength during the first three days of curing. For the remaining four days, the rate of strength gain was much lower, compared to the ACS specimens. This trend can also be observed from Fig. 5 when looking at the slope of the graph for the last four days.

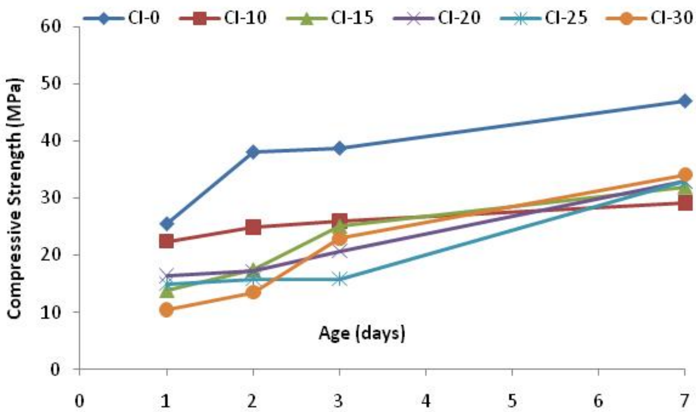

Fig. 5 – Variation of the compressive strength for the specimens made with CEM I cement.

Fig. 6 presents the variation of the compressive strength for each mix proportion prepared using CEM II B-M type of cement. A different behavior can be observed in this case compared to the CEM I samples. The compressive strength increases rapidly during the first three days from casting. Only slow variations of its values are recorded for the last four days of the considered time interval. Similarly to the results shown in Fig. 5, the compressive strength of the reference sample is greater than for the specimens made with different percentages of ACS. The scattering of the results at the end of the time interval is larger in this case, the interval being ranged between 26 MPa and 38 MPa.

A closer look at both Figs. 5 and 6 leads to the conclusion that, at the age of one day, the compressive strength is larger for the specimens made with CEM I by 1% to 35%. On the other hand, at the age of seven days, the situation is the other way around. The values of the compressive strength are larger for specimens made with CEM II B-M cement by 2% to 21%, with the single exception of CII-25 case. This leads to the conclusion that the type of cement to be used in combination with ACS is a very important factor in terms of the compressive strength of mortar.

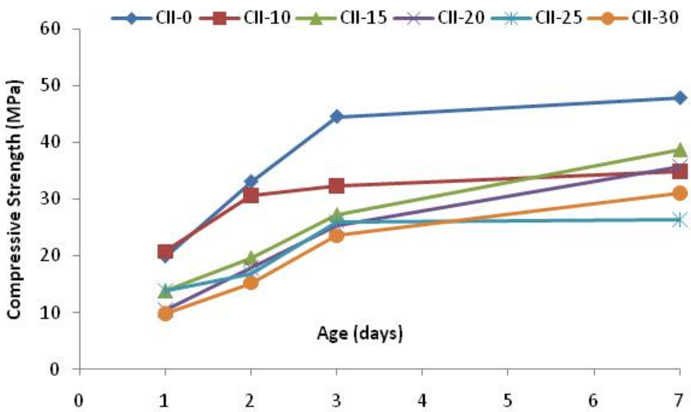

Fig. 6 – Variation of the compressive strength for the specimens made with CEM II cement.

Moreover, the increase in the percentage of ACS used in the mix proportion leads to a decrease of compressive strength values. This decrease can be up to 81%, for the CII-25 case, or as low as 23%, for the CII-15 case. When CEM I cement is used, the decrease may reach a maximum value of 61%, for the CI-10 case, or as low as 38%, for the CI-30 case.

However, even though the tendencies presented above may seem discouraging, it should be pointed out that a compressive strength of 26 MPa is considered to be a very good value for civil engineering structures. Taking into account that these values were obtained for mix proportions made with different percentages of ACS, an eco-material made entirely from industrial wastes, replacing the Portland cement as mineral binder, the outcome is very encouraging.

4. Conclusions

Based on the obtained results in the present research, the following conclusions can be drawn:

1. The type of cement has an important influence on the values of the tensile and compressive strengths of mortar pastes made with different

percentages of anhydrous calcium sulphate. It was observed that CEM II B-M type of cement yields better results than CEM I cement for the compressive strength. The values are with between 2% and 21% higher when CEM II B-M cement is used. A more significant increase is obtained for the tensile strength of mortar bars. The values are with between 5% and 31% higher compared to the specimens made with CEM I cement.

2. The use of anhydrous calcium sulphate leads to a decrease in the values of the compressive and tensile strengths of mortar bars. However, for higher percentages of anhydrous calcium sulphate, the tensile strength becomes equal to, if not higher than, the values obtained for the reference sample at the age of seven days. The increase in the value of tensile strength is between 25% and 45% and were obtained for the mix proportions made with 20%, 25% and 30% of anhydrous calcium sulphate.

Even though the obtained results so far are encouraging for the use of anhydrous calcium sulphate as a replacement mineral binder for the ordinary Portland cement, the authors deem necessary that further researches should be conducted in this field, especially in the direction of long term influence of anhydrous calcium sulphate and ordinary Portland cement on the mechanical properties of mortars.

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REZULTATE INIȚIALE PRIVIND PROPRIETĂȚILE MECANICE ALE MORTARELOR CU DIFERITE PROCENTE DE ECO-CIMENT

(Rezumat)

Betonul este un amestec dintre două mari componente: pasta de ciment şi agregatele. În timp ce agregatele şi apa se găsesc cu uşurință în natură, cimentul are nevoie de fabricație specială pentru a fi produs. Producția de ciment la nivel mondial a crescut foarte mult în ultimii 80 de ani. Având în vedere că cimentul reprezintă doar 10%...15% din rețeta unui beton normal, se poate deduce uşor impactul pe care industria construcțiilor o are asupra mediului. Lucrarea de față îşi aduce contribuția în ceea ce priveşte investigarea poisbilității de a folosi un liant mineral nou, sub forma de sulfat de calciu în forma β-anhidru III′. Acest liant poate substitui anumite procentaje din cimentul de tip Portland folosit la prepararea betoanelor. Sulfatul de calciu folosit în lucrarea de față este obținut în exclusivitate din deşeuri industriale, până acum nereciclabile. Rezultatele inițiale privind rezistențele la întindere, din încovoiere, şi cele la compresiune indică o scădere a valorilor acestora în comparație cu proba martor. Cu toate acestea, pentru procentaje mari de înlocuire a cimentului Portland, de 25%...30% din volum, rezistețele la întindere ale prismelor de mortar cresc semnificativ, depăşind valoarea obținută pentru proba martor. Se mai observă şi ameliorări ale rezistenței la compresiune comparative cu rețetele în care acest sulfat de calciu este folosit în procentaje mai reduse.