ELASTIC PROPERTIES OF MINERAL MATRICES WITH HIGH CONTENT OF ENVIRONMENTALLY SUSTAINABLE BINDER

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Concrete made with hydraulic binders, the vast majority of which are based on Portland cement, is by far the most widely employed construction material worldwide in terms of volume. The biggest advantage of modern concrete is the possibility of including other industrial by-products into the mix. The use of waste materials becomes more and more attractive as an alternative in the construction industry mainly due to the increasing cost of raw materials and the continuous reduction of natural resources. The present paper brings its contribution to the investigation on the use of a new binder, the anhydrous calcium sulphate in its β anhydrite III' form, a new Cementitious material, as partial replacement of the ordinary Portland cement in concrete. The binder is obtained exclusively from industrial wastes and can be entirely recycled after its expiration date. Its influence on the elastic properties of mineral matrices, at various curing ages, is experimentally investigated. The results show a slight decrease in the values of the longitudinal modulus of elasticity and no change in Poisson's ratio. Given the fact that up to 40% of Portland cement was replaced by the environmentally sustainable binder, the obtained results recommend the new binder as a viable solution in replacing Portland cement in construction works.

Keywords: sustainable mineral binder, elastic properties, cement replacement.

INTRODUCTION

Mortars have been used for a variety of applications since ancient times using mainly three types of binders: mud, probably the oldest type of binder used for preparing the mortar, gypsum and lime. The binder contributes to the workability of the mortar, whereas the aggregate influences the mechanical properties and helps in controlling shrinkage related problems. With the first introduction of the Portland cement the strength of mortars and, subsequently, concrete became higher and higher, following the trend of constantly increasing expectations related to their performance (Bentur and Mitchell, 2008).

The innovation in the construction industry is continuously driven not only by the need of reducing the environmental footprint (Toma *et al.*, 2013) but also by the increasing demand of reducing the costs in compliance with the evolution of the global market. This can only be achieved by a constant and sustained innovation process which should also anticipate the future environmental constraints (Schneider *et al.*, 2011; Shi *et al.*, 2011).

A major step in the direction of sustainable development has been done with the development of alternative cementitious binders (Juenger *et al.*, 2011). An important source of such materials is the industry itself. Fly ash, a by-product of the coal-fired power plants and municipal incinerators, has been successfully used in construction industry to improve the properties of concrete, such as strength and durability (Lee, 2009). Ground granulated blast furnace slag has been used since 1950 either as partial replacement of ordinary Portland cement or as fine aggregate in concrete mix design with highly improved resistance to aggressive environments (O'Connell, 2012). Silica fume, a very reactive pozzolan due to its chemical and physical properties, has a relatively short period of time since its application in concrete industry. Significant improvements in the early age strength properties of mortars have been reported when silica fume was used (Sezer, 2012).

In view of the new stricter regulations in terms of CO2 emissions (Rehan and Nehdi, 2005) as well as continuous developments in both electric power and steel production one can only expect a significant decrease in the quantities of resulted fly ash and blast furnace slag. There are, however, other sources of production for the supplementary cementitious materials (SCM), some of them used for centuries (Yang *et al.*, 2007) but still requiring mining the natural deposits and some of them more recent, obtained from the treatment of industrial by-products such as phosphogypsum (PG) (Singh, 2002).

The present paper presents the results of a research work focused on the suitability of using a new mineral binder as partial replacement of ordinary Portland cement in concrete. Its effect on the elastic properties of mortars, when used in large percentages, is presented. The main parameters of the research were the type of cement and the replacement percentage with environmentally sustainable binder.

MATERIALS AND EXPERIMENTAL PROCEDURE

Cement

Two types of cement were used as this stage of the research, both of them being produced according to standard specifications. The first type was a CEM I 42.5R cement with high early strength. It is a general purpose cement being suitable for all uses in works requiring high strength values at early ages. The other type of cement was a CEM II B-M (S-LL) 32.5R cement also with high early strength. It is a composite cement with 65-75% Portland cement and 25-35% ground granulated blast furnace slag and lime. This second type of cement was considered in view of the fact that almost two thirds of the European cement market corresponds to CEM II cement. Both cement types are readily available on the market and widely used, this being the main reason of their selection for this research.

Environmentally Sustainable Mineral Binder

The binder is obtained from industrial by-products, most of them being disposed in landfills, such as phosphogypsum, lactogypsum, a.s.o. and can be entirely recycled after its expiration date (Kandco, 2010). Taking into account that gypsum results from the production process of many organic and inorganic fertilizers, pigments, metals etc. it has become a significant ecological problem (Singh and Garg, 2000). It is the belief of the authors that the use of a new mineral binder based on the anhydrous calcium sulphate in the β-anhydrite III' form as SCM has both environmental and economical advantages and justification (O'Rourke *et al.*, 2009). The opportunity for using such industrial unrecyclable wastes in construction industry, especially the phosphogypsum, has recently been recognized by researchers as having net benefits for the environment (Taher, 2007; Garg *et al.*, 2011).

Experimental Procedure

Table 1 presents the mix proportions considered for the mortars in this research. The mineral binder was assumed to occupy 50% of the total volume and consisted either only of Portland cement or as a mixture between the Portland cement and the environmentally sustainable binder (ESB). The water to mineral binder ratio of 0.4 was kept constant throughout the experimental works. Only tap water was used without any super-plasticizers or setting retarders. The mortar paste was cast in 50 × 100 mm cylinders.

The cylinders were used to determine the static modulus of elasticity in compression according to ASTM C469 specifications at the age of 28 days. The axial strain was measured with the help of a 50 mm gage length extensometer, Figure 1, whereas the transverse strain was measured by means of a circumferential extensometer, Figure 1. Six cylinders were cast for each age and mix proportion mentioned in Table 1, resulting in a total number of 48 cylinders.

RESULTS AND DISCUSSIONS

Nowadays the emphasis is more and more on the utilization of cementitious materials to produce sustainable cements (Gartner and Macphee, 2011; Zhang *et al.*, 2012).

Table 1. Mix proportions and specimen designation

Specimen designation	Binder			Sand	Water / Binder ratio
	Cement type		Environmentally Sustainable Binder (ESB)		
	CEM I	CEM II			
	[%]	[%]	[%]	[%]	-
C1ESB0	50		-		
C1ESB30	20	-	30		
C1ESB35	15		35		
C1ESB40	10		40	50	0.4
C2ESB0		50	-		
C2ESB30	-	20	30		
C2ESB35		15	35		
C2ESB40		10	40		

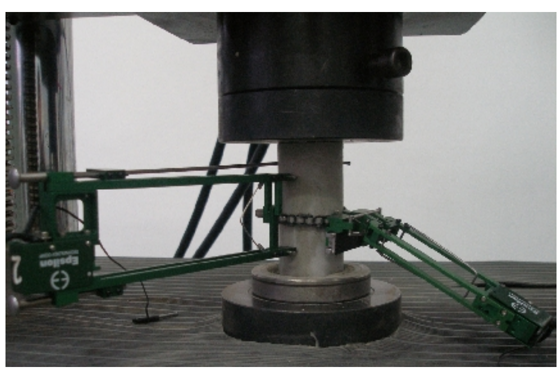

Figure 1. Loading set-up for the determination of elastic properties of mortar mixes

Their efficient utilization (Felekoglu *et al.*, 2009) has captured the interest of the scientific community due to their net benefits for the environment. However, there is still little information on their influence upon the elastic properties of the mineral matrix.

The modulus of elasticity, together with strength characteristics, is a key material property in design practice. Its assessment, especially for cement based materials, is quite difficult to be predicted because it is influenced by the properties and quantities of the constituent parts in the mix proportion.

The experimentally obtained values are presented in Table 2 for all mix proportions. The difference between the values of the modulus of elasticity of the control specimen and the other mortars, at the age of 28 days, is a mere 4% for high volumes of environmentally sustainable binder.

The mix proportions made with CEM II cement seemed to be less sensitive to the variation of cement percentage in terms of the values for the modulus of elasticity. When the volume of calcium sulphate mineral binder increased beyond 30% the obtained moduli of elasticity were 0.95% ~ 2% lower than the reference mix. The difference in behaviour compared to the mixes made with CEM I could be attributed also to the presence of other mineral admixtures in the CEM II cement. Even though further research should be conducted in this direction, the obtained results are encouraging and lead to the conclusion that the new ESB could be successfully used as replacement for the Portland cement.

Since there are no specially derived equations for the prediction of the modulus of elasticity of mortars, a few of the currently available equations for concrete have been used in order to check whether they are suitable to use in this particular case. The values are also presented in Table 2 for the equations proposed in ACI 363R-92 report and BS 8110-85 Part 2 and ACI 318M-05 codes. Previous research works have shown good agreement between the equation proposed in ACI 363R-92 and the experimentally obtained results for sprayed concrete on similar sized specimens with the present work (Goodier *et al.*, 2008). The other two equations, although derived for concrete, lead also to good approximations of the experimental results.

However, equations used in Table 2 should not be applied for any given case as they were not derived for mortars but for concrete.

Table 2. Elastic properties of mortars (average values determined on 6 cylinders)

Specimen	Experimental values (E) [GPa]	ACI363R-92 Eq. [1] (E) [GPa]	BS8110-Part2 Eq. [2] (E) [GPa]	ACI318M-05 Eq. [3] (E) [GPa]	Poisson's Coefficient
C1ESB0	32.55	36.16	35.53	41.42	0.199
C1ESB30	31.24	28.20	28.23	30.15	0.202
C1ESB35	31.12	28.56	28.52	30.67	0.201
C1ESB40	31.27	28.49	28.45	30.56	0.201
C2ESB0	28.28	33.91	33.24	38.24	0.198
C2ESB30	27.69	27.10	27.40	28.59	0.2
C2ESB35	28.01	27.17	27.45	28.69	0.2
C2ESB40	27.89	27.09	27.40	28.59	0.203

[1] $E_c = 3.32\sqrt{f_c^{'}} + 6.9$; $f_c^{'}$ is the compressive strength [MPa]; valid for $21\text{MPa} \le f_c^{'} \le 83\text{MPa}$

[2)] $E_{c,t} = E_{c,28}\left(0.4 + 0.6\frac{f_{cu,t}}{f_{cu,28}}\right)$; for t ≥ 3 days and $E_{c,28} = K_0 + 0.2f_{cu,28}$ where K_0 is a constant related to the modulus of elasticity of the aggregate, taken as 20 [GPa] for normal-weight concrete; $f_{cu,28}$ is the characteristic cube strength at 28 days [MPa]; $f_{cu,t}$ is the characteristic cube strength at any given age, provided the sample is at least 3 days old.

[3)] $E_c = 4.7\sqrt{f_c^{'}}$ where $f_c^{'}$ is the compressive strength in MPa

They can be used to obtain a quick estimation of the results but should not substitute the latter. Further research work should be conducted in this field in order to propose a similar equation that can be used to estimate the modulus of elasticity of mortars.

The obtained values for the Poisson's ratio are also presented in Table 2. It can be observed that there are no significant variations in the values of the ratio among the mix proportions. The obtained values of the Poisson's ratio are in line with the predicted values for high-strength concrete. Herve *et al.* (2010) obtained similar values for Portland cement based mortar made with different types of round siliceous sand having fine, medium and coarse grain sizes.

CONCLUSIONS

The paper presents the findings of a research work focused on the evaluation of the elastic properties of mortars made with high percentages of a new environmentally sustainable cementitious material. The construction industry has to look for alternatives to Portland cement if the concept of sustainability was to be fully implemented.

Substituting the Portland cement by the new calcium sulphate based mineral binder results in a drop in the values of the modulus of elasticity by an average value of 4% at the age of 28 days for specimens made with CEM I cement. On the other hand, the mixtures made with CEM II cement showed less scattering of the results for the modulus of elasticity. However, it can be observed that increasing the volume of ESB in the mix the values become closer to that of the reference mix. The specimens made with CEM II cement seemed to be less sensitive to the variation of cement percentage in terms of the values for the modulus of elasticity.

Some of the existing equations for predicting the values of the elasticity modulus for concrete succeed in quite accurately estimating the modulus of elasticity of mortar. However, a clear trend is difficult to establish given the small number of specimens available at this stage.

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