ASSESSMENT OF NON-HAZARDOUS INDUSTRIAL BY-PRODUCTS AS SUSTAINABLE MATERIALS IN ENGINEERING APPLICATIONS

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ABSTRACT

The topic of the present study fits into the current internationally-spread approach, focused on efficient solutions for sustainable development, aimed to ensuring the application of a long-term and integrated waste management, in line with the principles of environmental protection and with the concept of circular economy.

Keywords: industrial by-products, stabilization process, geotechnical characteristics

REZUMAT

Tematica prezentului studiu se încadrează în abordarea actuală, extinsă la nivel internațional, care pune accent pe soluții eficiente de dezvoltare durabilă, care să asigure aplicarea unui management durabil și integrat al deșeurilor, în concordanță cu principiile protecției mediului și cu conceptul economiei circulare.

Cuvinte cheie: subproduse industriale, proces de stabilizare, caracteristici geotehnice

1. INTRODUCTION

During the last decades, industrial and technological progress has led to a significant increase of quantity and types of generated wastes. Recent studies on topics related to environmental and sustainable development strategies indicate a variety of wastes generated by the society activities, recovered in different applications of the construction field (Vaníček et al., 2013), and frequently used in geotechnical works (Dobrescu and Călăraşu, 2019).

Wastes can be classified into different types, depending on their source, such as industrial wastes (fly ash and blast-furnace slag, cement wastes, brick dust, mud, glass, tires, plastic etc.), construction and demolition wastes (used bricks, concrete and asphalt), mining wastes (mine tailings) etc.

Specialized studies have highlighted the usefulness of lime and cement materials as efficient additives in the stabilization process of clayey soils with expansive potential (Nalbantoğlu, 2004, Higgins, 2005, Yong and Ouhadi, 2007, Al-Mukhtar et al., 2010). However, the production of these building materials is well-known as a major global source of greenhouse gas emissions, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

At the same time, recent research in line with sustainable development objectives have noted the high potential of industrial by-products as: fly ash (Cokca, 2001; Anupam et al., 2013), blast-furnace slag (Cokca et al., 2009), cement dust (Miller and Azad, 2000), limestone dust (Brooks et al., 2010), used as replacement materials to conventional additives in the soil stabilization approaches.

The valorization of the abovementioned by-products was achieved given the economic benefits, more specifically cost savings for works. In addition, another benefit in terms of environmental protection is that greenhouse gas emissions can be significantly reduced by using such additional materials with pozzolanic properties, which are currently not being exploited to their maximum potential and placed in uncontrolled deposits.

The reuse of these types of waste in engineering projects within innovative technical solutions is considered worldwide as advanced practical tools to solve the problem of foundations on expansive soils, affecting buildings resistance and stability.

For example, the most important property for stabilizing the clayey soils with swelling potential involves the capacity of the stabilizer to provide sufficient calcium (Yang et al., 2012). Therefore, from the composition point of view, industrial wastes like fly ash or blast furnace slag can be used as optimum stabilizing aggregates, due to their predominant siliceous and calcareous compositions.

Waste generation by specific industries is considered a major environmental problem through air pollution (dust and very fine particles that spread into the atmosphere) and toxic chemical spills into rivers, seas or oceans, when improperly stored. As an example, Portland cement is conventionally used as a binder in the soil stabilization of unstable soils. Although, the use of this common type of cement for improving the soil parameters has financial and environmental implications, due to the relatively high costs of manufacturing, unsustainable use of natural resources and high carbon footprint related to the production process, which contributes to about 10% of world carbon dioxide emission.

On that basis, the reuse of waste as raw materials is considered a complex task in the process of waste management due to their varieties and some unknown properties that are under research.

Numerous scientific studies are focused on finding alternative ecological binders, with low carbon footprint, using industrial by-products such as fly ash and slag to produce new green cement materials. This solution can provide an environmentally friendly and efficient soil improvement option. Due to the urban expansion and large areas with unstable soils, there is an increasing demand for soil improvement projects. Traditionally, the pile foundation is a preferred solution for engineers, which however involve considerable costs. For this reason, new method and techniques for deep soil improvement are widespread implemented, one example being deep mixing method (DSM).

The deep mixing method is an in situ soil treatment, more rapid, less expensive and environmental friendly compared to the traditional methods (Porbaha, 1998; Bouazza et al., 2004). The method, initiated in Japan and Sweden simultaneously in the 70's (Bruce et al., 2013), refers to the blending of native soils or fills with a binder material, using mixing equipment, up to a desired depth, followed by binder injection. The results consist in circular soil columns, with a higher resistance and lower compressibility. DSM method is most suitable for cohesive soils with high moisture content (wet soils).

Among the industrial by-products, fly ash and slag have demonstrated the potential for transformation into geo-polymers. Fly ash is highly appreciated, due to the fineness of particles, as compared to the blast furnace slag, so it has high level of reactivity (Hardjito and Rangan, 2005). In addition, fly ash is produced in huge quantities worldwide and it is widely used, being the most popular geo-polymerization material (Al Bakri et al., 2013, Duan et al., 2016).

2. MATERIALS AND METHODS

The experimental applications were focused on assessing the geotechnical characteristics and the behavior of native soil mixtures with different types of non-hazardous industrial by-products. The laboratory tests have allowed both the quantification of the feasibility of industrial waste reuse as geo-materials in fulfilling adequate technical requirements, as well as the identification of benefits in geotechnical applications.

For the experimental tests, soft clay with high plasticity was used. Tests results have determined the grain size distribution and plasticity limits are presented in Table 1.

Native soil (AP) was mixed with spherical particles of fly ash and irregular and sharp shape particles of blast furnace slag. Ash and slag chemical composition is predominantly SiO_2, Al_2O_3 and Fe_2O_3 in over 70% proportion, with a lower content of CaO. As liquid alkaline activators, sodium hydroxide (NaOH) and potassium hydroxide (KOH) with

98% purity of grains were used and a combination of NaOH + Na_2SiO_3.

Table 1. *Properties of native soil*

Soil parameters	Determined values
Clay (A)	33%
Silt (P)	57%
Sand (N)	10%
Moisture content (w)	40%
Liquid limit (wL)	50%
Plastic limit (wp)	23%
Plasticity index (Ip)	27%
Consistency index (I_C)	0,435
pH	7,7
Organic content	4,4%

The moisture content of soil was set to the level of liquid limit in order to reproduce the natural soil conditions before mixing with other materials. For sampling preparation, the clay soil was first mixed with the industrial by-products for several minutes, and then the liquid binder was added by continuous mixing for about 5 minutes. Resulting mixtures were placed in a PVC molds and cylindrical samples were prepared (38 mm diameter, 76 mm height).

During the mixing procedure the viscosity of mixture varied, in some cases a very low value was recorded. These mixtures were placed in molds in two layers, the air being eliminated by shaking. In other cases, for the mixtures with higher viscosity, the removal of the air was not reach. In these cases, the samples were prepared in two layers, in order to eliminate gaps by using static compaction. In addition, to ensure that the samples do not contain air voids, the volumetric weights of the samples were compared with those of low viscosity mixtures.

The cylindrical samples were covered by plastic foil and maintained at standard room temperature for curing. Five sets of soil mixtures were prepared using industrial by-products (fly ash, FA, and blast furnace slag, S). Details regarding the composition of mixtures and curing periods are presented in Table 2.

Table 2. *Data of designed mixtures*

Mixture of soil with industrial by-products	Curing period (days)
AP+20%FA	3, 7, 14, 28
AP+15%FA+5%S	
AP+10%FA+10%S	
AP+5%FA+15%S	
AP+20%S	

The compressive strength was determined on samples at different curing time of 3, 7, 14 and 28 days. The uniaxial compression test consisted of applying on the specimen a monotonically increasing axial load, to determine the compression resistance and the specific axial deformation. The required deformation velocity was 0.02 mm/min. It is mentioned that during the test, the ratio between height and length (h/d) has been preserved equal to approximately 2.

3. RESULTS AND DISCUSSIONS

The values of compressive strength obtained from the uniaxial compression test (UCS) are presented in Table 3.

Table 3. *UCS values of samples from mixtures*

Mixture	Curing time (days)	UCS value (kPa)		
		Activators		
		NaOH	NaOH+Na_2SiO_3	KOH
AP+20%FA	3	0	28	0
	7	4	44	2
	14	5	58	2
	28	**8**	**90**	**4**
AP+15%FA +5%S	3	2	144	0
	7	4	253	3
	14	6	404	5
	28	**111**	**551**	**70**
AP+10%FA +10%S	3	5	377	0
	7	32	1705	2
	14	950	1849	9
	28	**1500**	**2429**	**520**
AP+5%FA +15%S	3	600	1103	60
	7	2500	3794	900
	14	3200	5104	1900
	28	**5000**	**5809**	**3700**
AP+20%S	3	1300	2333	8
	7	4200	6348	850
	14	5700	7831	2300
	28	**6500**	**8215**	**4800**

Compressive strength values obtained after 28 days curing time for the mixture sets prepared with three types of activating binders are represented into Figure 1.

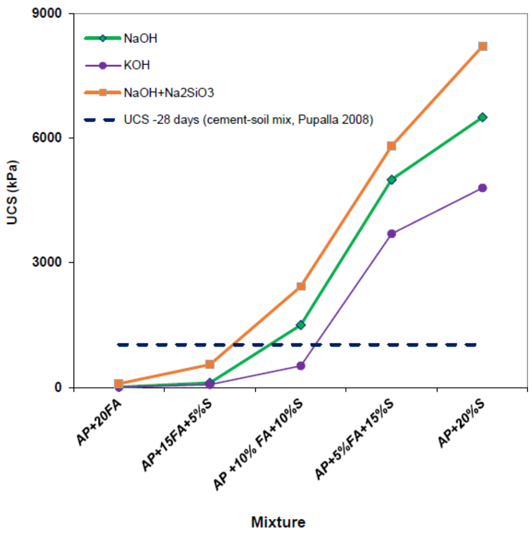

Fig. 1. Variability of UCS values for mixtures at 28 days

The minimum value of UCS at 28 days recommended by Puppala et al. (2008), i.e. 1034 kPa, for cement-soil mixtures using deep mixing method is presented by comparison. A significant increase of UCS value was observed with the increasing of about 15% addition blast furnace slag, a consistent increase starting from 10% to 15% slag waste addition, with a lower increase rate thereafter.

It is noted that even when the mixtures of AP+10%FA+10%S activated with NaOH and NaOH+Na2SiO3 meet the minimum criteria (1034 kPa), these mixtures cannot be considered reliable. The laboratory uniform mixing leads to three time's higher values than those obtained in the field conditions (Horpibulsuk et al., 2004, 2011a, 2011b).

Furthermore, use of $NaOH+Na_2SiO_3$ results in higher UCS values than those of NaOH and KOH mixtures. It has been reported that NaOH mainly dissolves alumina and silica, while Na_2SiO_3 accelerates the geo-polymerization process (Suksiripattanapong et al., 2015; Phoo-ngernkham et al., 2015). The combination of these alkaline binders' leads to higher values as compared to the highest values obtained for the mixtures activated with the combination NaOH+Na2SiO3.

In general, $NaOH+Na_2SiO_3$ (of which 30% is NaOH) appear to be a better and more cost-effective binder than NaOH and KOH (Nematollahi and Sanjayan, 2014). UCS minimum requirements were also met in the case of mixtures AP+5%FA+15%S and AP+20%S.

4. CONCLUSIONS

The aim of the performed studies was to assess the variability of the compressive strength on soft clay samples mixed with industrial by-products as fly ash (FA) and slag (S) and activated with three different liquid alkaline binders, in laboratory conditions.

The methodological approach was focused on the identification of a sustainable binder as alternative to the conventional ones, such as non-environmentally friendly Portland cement, in order to be used for soil improvement, respectively in deep mixing method (DSM). Furthermore, another purpose of the research was to develop an efficient technical solution with practical applicability on reusing industrial by-products as fly ash and blast furnace slag in geotechnical engineering works.

The results of experimental tests have pointed out that the binder type used for activation has a high influence in increasing the compressive strength of the mixtures. It has been demonstrated that the sodium-based binder is more effective than the potassium-based one.

The application of efficient and facile techniques for reusing industrial waste in the sustainable construction works are considered key tools in achieving the targets proposed by the national strategy for sustainable development and implicitly the global objectives of 2030 Agenda.

The results of the research studies were obtained in the experimental program in progress set up for reaching the envisaged goals within framework within the national research program PN 19 33 04 02, PN19 33 04 02 *"Sustainable solutions to ensure the health and safety of population in concept of open innovation and environmental protection"*.

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