UTILIZARE ECO-DURABILĂ A DEȘEURILOR DE STICLĂ CA MATERIALE ALTERNATIVE PENTRU CONSTRUCȚII
ECO-SUSTAINABLE USE OF GLASS WASTE AS ALTERNATIVE CONSTRUCTION MATERIALS

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The paper aims to analyze the potential use of glass waste for the production of construction materials and the improvement of clayey soils. Experimental applications based on the integration of recycled products as binders have shown that glass waste contributes positively to the micro-structural properties of the mixture through an obvious improvement in mechanical performance. Within the paper, an experimental program is structured which represents a preliminary stage for small-scale modeling applied in the design of structures and eco-sustainable elements useful in construction works. The obtained results confirmed the efficiency of using recycled glass as a construction material in engineering applications. The advantages of using glass waste in the manufacture of construction elements consist in the durability of the material, the improved abrasion resistance of concrete, the improved rheological properties of fresh concrete, without using superplasticizers in the mixtures.

Lucrarea își propune analiza utilizării potențiale a deșeurilor din sticlă pentru producerea materialelor de constructii şi îmbunătăţirea pământurilor argiloase. Aplicaţiile experimentale bazate pe integrarea produselor reciclate cu rol de lianţi au evidenţiat că deşeurile de sticlă contribuie în mod pozitiv la proprietăţile micro-structurale ale amestecului printr-o îmbunătăţire evidentă a performanţelor mecanice. În cadrul lucrării este structurat un program experimental care reprezintă o etapă premergătoare pentru modelările la scară redusă aplicate în proiectarea de structuri şi elemente eco-sustenabile utile în lucrările de construcţii. Rezultatele obținute au confirmat eficienţa utilizării sticlei reciclate ca material de construcţie în aplicaţiile inginereşti. Avantajele utilizării deşeurilor de sticlă în fabricarea elementelor de construcţii constau în durabilitatea materialului, rezistenţa la abraziune îmbunătăţită a betonului, îmbunătăţirea proprietăţilor reologice ale betonului proaspăt fără a utiliza superplastifianţi în amestecuri.

Keywords: *stability, performance, improvement, alternative materials, clayey soils, waste glass*

1.Introduction

The effect of extended use of natural materials in road works and other types of infrastructure results in the gradual exhaustion of resources, while the acquisition and processing costs of these materials are constantly increasing. At the same time, large quantities of industrial and domestic waste produce serious environmental effects in terms of safe disposal or storage [1]. Research in the field of construction have focused on the implementation of sustainable techniques for using different types of waste as alternative materials with applications in the construction field and conservation of natural resources [2].

The studies conducted by the American Association of Highway Transportation Officials have analyzed the opportunity of using glass aggregates in road structures. By comparing the strength characteristics and engineering performances with those of natural aggregates [3], the potential use of crushed glass waste as filling material or drainage with real engineering valences was revealed. Recently, in order to encourage the widespread use of these types of alternative materials [4], numerous countries have integrated the use of glass waste into road infrastructure specifications.

Many research studies have been conducted on replacing natural aggregates with glass waste due to their positive contribution on the micro-structural properties of the mixture through an evident improvement of mechanical performance [5, 6]. The experiments carried out showed that the addition of 15% glass powder in concrete may lead to a 13% increase of compression strength [7].

The present study is focused on two composite series, with the purpose to assess the potential use of glass waste as alternative bonding agent for stabilizing expansive soils and the efficiency of producing sustainable construction materials.

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Table 1

Physical characteristics of the natural material / *Caracteristicile fizice ale materialului natural*

Grain size analysis (STAS 1913/5-85)			Atterberg limits (STAS 1913/4-86)				
Clay (%)	Silt (%)	Sand (%)	w (%)	w_L (%)	w_p (%)	I_p (%)	I_c (-)
62	34	4	38.22	68.00	23.0	45.00	0.662
Classification SR EN ISO 14688, CL			Very high plasticity/soft to firm				

In the first series, clayey soils were selected, by considering their classification in the class of unstable soils due to their swelling-shrinkage behavior and consolidation process, at long-term external loads [10]. Likewise, for assessing the geotechnical characteristics of clayey soil (80%) with 20% glass waste addition by weight and the effectiveness of this mixture in road layers [11], experimental applications have been carried out.

The resulting specimens were exposed to normal temperature and humidity conditions, drying-wetting cycles through accelerated induction of excessive heat conditions, and alternative freeze-thaw cycles. Optimum mixtures classified by considering the component type were selected in line with the average of the maximum values obtained for the mechanical characteristics linked to application types and performance criteria according to the principles of sustainable development [12].

The initial determination of the identification characteristics, corresponding to the selected native material, allowed to be classified in the soil category with expansive potential, with over 40% colloidal clay content (2 μm) and very high plasticity. Based on the results analysis (Table 1), the sensitivity of natural soil to volumetric changes due to humidity and temperature variations, high compressibility and activity in terms of swell potential have been outlined, being included in the class of unstable soil.

Subsequently, the necessary amount of soil for specimens' preparation was dried and crushed to obtain particle sizes smaller than 2 mm. In order to simulate excessive moisture conditions, the material was prepared to a high value of water content of about 31-38%, followed by the manually mixing of composition. As additional material in the soil mixtures, different dosages (5%, 10% and 20%) of glass wastes were considered, in the form of crushed and sorted with particle sizes between 0.5 and 2 mm. A number of 20 samples were prepared for each dosage.

In the second series, physical and mechanical testing were performed on masonry elements prepared with a mixture of 20% of glass recycled aggregates and pit aggregates for comparison of parametric performance.

In order to quantify the change progress of strength characteristics according to the pre-set exposure conditions and the treatment periods, laboratory testing were conducted to determine the specific strength at uniaxial compression by simulating specific working conditions as follows:

(a) immediately after preparation,
(b) after heat treatment by oven drying at 105° C for 24 hours,
(c) exposure under normal temperature conditions (19-22^{0}C) and humidity (40-60%) over a period of 7 days,
(d) exposure to 3 cycles of accelerated drying in the oven and excessive humidity by homogeneously distributing a quantity of 100 ml of water followed by drying periods by maintaining normal temperature and humidity conditions,
(e) exposure to 3 freeze-thaw cycles by freezing the samples at -10^{0}C for a period of 72 hours followed by normal temperature and humidity maintained for the same period.

Compression strength average values obtained for the clayey specimens in mixtures with glass waste showed an increasing trend of more than 3000% of the strength characteristics for all composite structures, associated with excessive drying conditions and normal temperature conditions over a curing time of 7 days (Figure 1), compared to the corresponding values after preparation.

In the case of the specimens subjected to 3 successive drying-wetting cycles, it was observed a significant increase of more than 700% of the resistance values, compared to the samples after preparation, respectively of 111-260% corresponding to the specimens exposed to 3 freeze-thaw cycles. Also, differences of 170-280% can be remarked between the strength values of the mixtures exposed to drying and wetting cycles and those to freeze-thaw cycles, which highlights the negative impact of low temperatures by lowering strength.

From the homogeneous glass waste mixtures, a series of cylindrical specimens were prepared to be tested in order to determine the compressibility characteristics and swelling pressure. The purpose of setting these tests is to perform a comparative analysis of the deformability parameters under normal and saturated conditions and the influence of the glass waste intake on them. The processing of data related to sample settlement at different loading stages allowed the calculation of compressibility indices: oedometric modulus ($E_{oed200-300}$); specific settlement consolidation at 200 kPa pressure (ε); the coefficient of volumetric compressibility (m_v); the compressibility coefficient (a_v).

The distribution of the stress-strain curves obtained on the structures composed by soil and glass waste is shown in Figure 2, and the variation

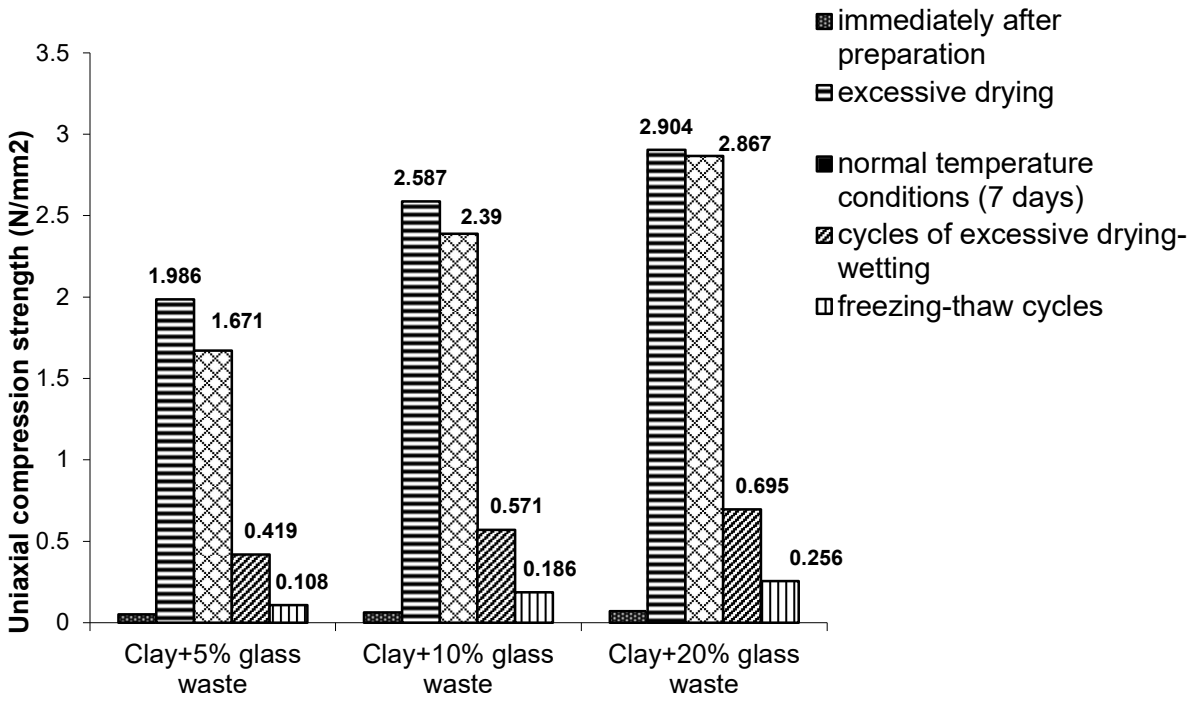

Fig.1 - Variation of strength uniaxial compression values for clay and glass waste structures
Variaţia valorilor rezistentei la compresiune uniaxială pentru structurile de argilă şi deşeuri de sticlă

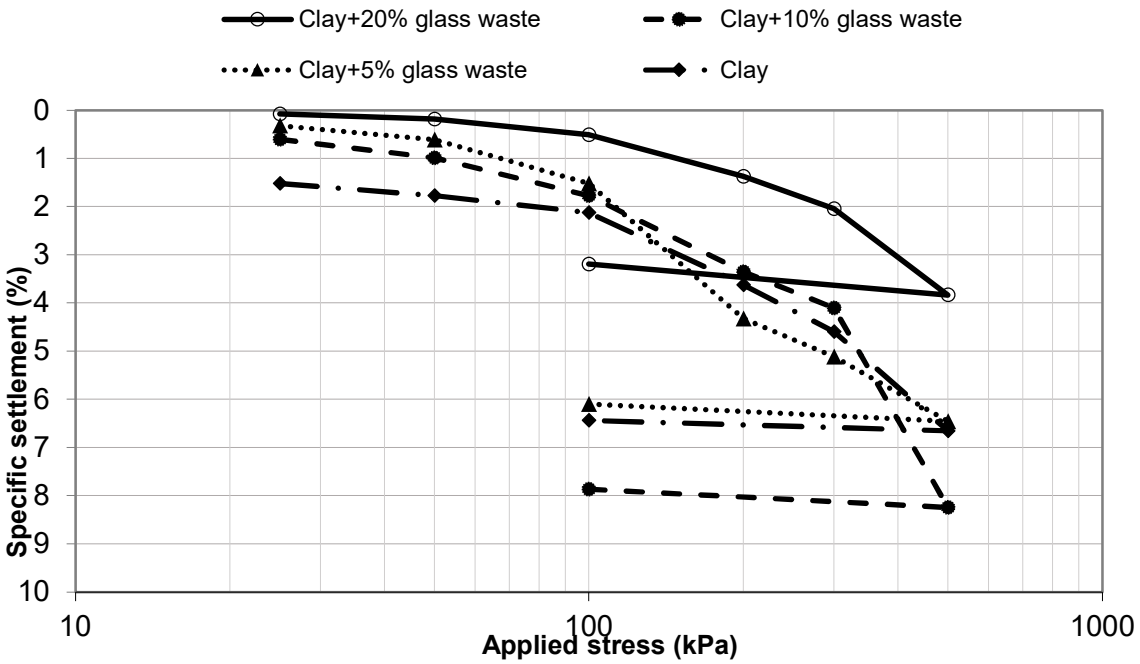

Fig. 2 - Distribution of stress-strain curves obtained for the clay and glass waste structures
Distribuţia curbelor de efort-deformaţie obţinute pentru structurile de argilă şi deşeuri din sticlă

Table 2

Variation of oedometric modulus obtained for the clay and glass waste structures
Variaţia modulului edometric obţinut pentru structurile de argilă şi sticlă de deşeuri

Mixture of clay and glass waste	Value of oedometric modulus ($E_{oed200-300}$, kPa)	% increase of $E_{oed200-300}$	Value of compressibility coefficient (a_v, 1/kPa)	% increase of a_v
Mix 1: clay (natural soil)	10277,49	-	1,66E-04	-
Mix 2: clay+5% glass waste	12618,30	22,78	1,41E-04	15,06
Mix 3: clay+10% glass waste	13271,40	29,13	1,43E-04	19,88
Mix 4: clay+20% glass waste	14869,89	44,68	1,20E-04	27,71

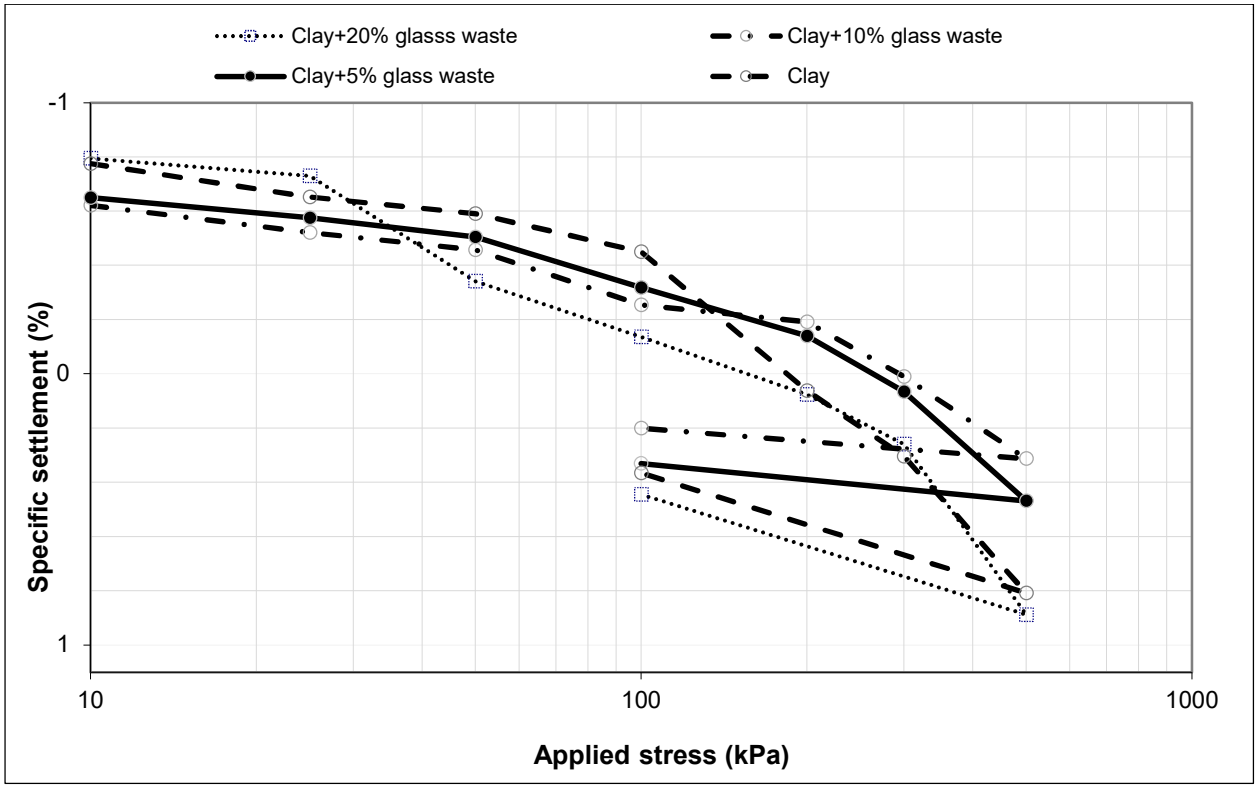

Fig. 3 - Plots of compression curves for swelling pressure on clay and waste glass structures
Distribuția curbelor de compresiune pentru presiunea de umflare pentru structurile de argilă și deșeuri de sticlă

of oedometric modulus values are summarized in Table 2.

The analysis of deformability indices obtained from the compression tests, indicates that a glass waste addition can conduct to a decrease in deformability up to 23-45% increased values of oedometric modulus and 15-28% reduced values of the compressibility coefficient, compared to the values corresponding to the natural soil. By adding glass waste, the improvement of deformability characteristics, outlined by changing the compressibility category, more specifically into medium compressibility class, was achieved.

The determination of swelling pressure consists of the volume changes estimation caused by water content variations under complete inundated conditions, and evolution records of the swelling at different time intervals. The plot measurements of swelling pressure are illustrated in Figure 3.

The analysis of the parameters obtained from swelling pressure measurements, similarly to the compression tests, shows an increase of 18-32% of oedometric modulus and a decrease of 12-23% of the compressibility coefficient, compared to the values corresponding to the native soil. Also, by adding glass waste, a 33-65% decrease in the swelling pressure was achieved, passing from the active soil category (p_u>100 kPa) to medium activity class (p_u=50-100 kPa), respectively low activity (p_u<50 kPa).

Regarding the assessment of potential use of glass waste in cement-based materials, as an aggregate replacement of natural aggregates, a set of mixtures as masonry elements were prepared, one with a replacement ratio of 20% recycled glass waste aggregates by weight and the other one only with pit aggregates as a reference mix for comparing the performance characteristics. This stage of preliminary research explore the benefit in terms of the behavior characteristics related to the substitution of traditional aggregates with waste glass.

For this purpose, mechanical tests after 28 days of curing were carried out on prepared masonry elements have the following dimensions: 300 mm length, 200 mm width and 200 mm height. Relevant laboratory testing were planned for masonry elements such as:

- drying shrinkage measurements on prismatic elements cured for 72h at 20 ± 2 °C and RH = 95% remoulded after 24h and then exposed at T = 20 ± 2°C and RH 45 ± 5% in a climatic chamber, indicates the percentage of weight loss corresponds to evaporation of free water. The values obtained for the specimens with recycled glass waste showed a slight reduction of about 20% in water loss with time due to the lower porosity of glass aggregates and high modulus of elasticity, compared to the ones resulted for pit aggregates;
- water vapour permeability measurements, where the specimen was sealed for 26 cuing time over a cylindrical recipient containing a saturated

potassium nitrate solution (KNO3). During the test, specimens were stored at RH = 50 ± 5% and T = 20 ± 1 °C. The mass loss due to water evaporation through the specimen was measured during that time and results were expressed in terms of coefficient of permeability in water vapor. It can be notice that the replace of pit aggregates with glass waste does not change the permeability of mixtures.

- capillary water absorption measurements on specimens cured at 70 ± 5°C, for determining the amount of water absorbed by a dried specimen placed on the saturated bedding layer through capillary suction, monitoring the specimen mass at 10, 30 and 90 minutes. A slightly decrease of about 6% in capillary water absorption was recorded only at 90 minutes for the specimens with recycled glass aggregates;
- thermal conductivity testing, confirmed that the doses with 20% recycled glass aggregate have thermal conductivity coefficients that are similar than those of the reference material;
- resistance to freeze–thaw cycles, for analyzing the effect of expansion and cracking by adding glass waste dosage rate. The results highlighted that the recycled glass aggregate is potentially able to improve resistance to freeze–thaw cycles, an increase of about 13% was recorded for those mixtures, compared to the ones corresponding to pit aggregates;
- compressive, tensile and flexural strengths at 28 days of curing, for examining the effects of replacement ratio of traditional aggregates with glass recycled aggregates on mechanical properties of specimens. A slight decrease in compressive mechanical performance, varying from 3% up to 13%, with the increase of the percentage of recycled glass ratio was observed. This can be the effect of the smoother surface of glass aggregate compared to pit aggregates, thus causing the decrease of the cohesion between the glass aggregates and mortar at the interface.

The results of measurements on masonry elements with recycled glass aggregates based materials are summarized in Tabel 3.

3. Analysis of the obtained results for the experimental options

The analysis and interpretation of the results obtained for the glass waste mixtures for the purpose of stabilization of expansive soils within road layers, revealed the following aspects:

- pronounced increase of over 3000% of the strength characteristics for all composite structures linked to excessive drying conditions and normal temperature conditions over a 7-day period, compared to the corresponding values at the time of preparation;
- significant increase of over 700% of the resistance values at 3 successive drying-wetting cycles compared to the samples after preparation, respectively of 111-260% corresponding to those exposed to 3 freeze-thaw cycles;
- maximum value of strength during uniaxial compression test was obtained for the soil structures with 20% glass waste (σ=2,8 N/mm^2 after 7 days maintaining under normal temperature conditions, σ=2,9 N/mm^2 after accelerated heat treatment);
- improvement of the deformability characteristics with the increase of the glass waste addition, consisting of increased values of 23-45% of the oedometric modulus, as well as reduced compressibility coefficient values of 14-28%, compared to the natural soil situations;
- 33-65% decrease of the swelling pressure, the expansive soil category passing from the high activity to medium and low activity class.

Table 3

Characteristics of masonry elements with recycled glass aggregates
Caracteristicile elementelor de zidărie cu agregate din sticlă reciclată

Characteristics	Masonry elements with 20% recycled glass aggregates	Masonry elements with pit aggregates
Compression strength on element, MPa (N/mm^2)	8,75	11,0
Loss of strength at 150 freezing-thaw cycles, %	2,8	1,9
Adherence of masonry mortar, MPa	1,06	1,25
Dry relative density, kg/m^3	2100	2200
Sizing variations at drying shrinkage, mm/m	0,034	0,041
Capillarity water absorption, g/m^{2}s$^{0.5}$ - water absorption at 10 min - water absorption at 30 min - water absorption la 90 min	 136 78 45	 140 81 48
Water vapor permeability, kg/m^{2}sPa	6,3x10^{-14}	6,3x10^{-14}
Coefficient of permeability in water vapor, kg/msPa	6,3x10^{-12}	6,3x10^{-12}
Tensile strength of element by bending, N/mm^2	2,38	2,59
Shear strength, N/mm^2	0,376	0,426
Compression strength on masonry, N/mm^2	5,9	6,1
Flexural strength on masonry, N/mm^2	0,337	0,359
Coefficient of thermal conductivity, W/mK	1,286	1,287
Coefficient of thermal conductivity (10°C), W/mK	1,270	1,271

The results obtained for masonry elements prepared with a mixture of 20% of glass-recycled aggregates and pit aggregates as reference mixture, indicate the following points:

- no change in water vapour permeability;
- similar thermal conductivity coefficients;
- slight decrease of about 6% in the durability properties in terms of capillary water absorption;
- slight decrease of drying shrinkage measurements of about 20% in water loss with time due to the lower porosity of glass aggregates and high modulus of elasticity, compared to the ones resulted for pit aggregates with gravel, can lead to an enhance durability of elements;
- slight increase of the resistance to freeze–thaw cycles of about 13% for masonry elements with glass-recycled aggregates, compared to the ones corresponding to pit aggregates;
- slight decrease in compressive mechanical performance, varying from 3% up to 13%, with the increase of the percentage of recycled glass ratio.

4. Conclusions

Based on the approach of using glass wastes into stabilization of expansive clayey soils, a number of relevant issues have been highlighted as follows synthesized as follows:

- improvement of the mechanical properties with higher values so that maximum strength may be reached for the 20% glass waste composition. Thus, the compression strength was significantly improved, obtaining values for σ=2,9 N/mm^2, relatively close to those of the paving elements existing on the construction materials market;
- positive influence of the glass waste dosages on the improvement of the strength characteristics may assure the effective substitute function for fine aggregates;
- puzzolanic properties may be highlighted, with high potential of obtaining good quality paving elements;
- significant reduction of the swelling potential and improvement of the deformability characteristics, assures the opportunity of applying similar compositions in stabilization works of road layers.

Considering the results of testing on producing lightweight construction elements with cement-based materials by using recycled glass aggregate as a substitute of natural aggregates, highlights the following:

- no decrease in the durability properties in terms of capillary water absorption and a slight decrease in water vapour permeability;
- increase durability due to decreasing in drying shrinkage, related to an increase of the modulus of elasticity;
- slight decrease in compressive mechanical performance, which can indicate that those type of mixtures can be use optimally as light-weight traffic pavements.

The results achieved in the laboratory testing indicate the potential use of glass waste in the field of soil stabilization as an alternative material of natural aggregates in the sub-grade and embankment of road pavement [13] in terms of mechanical parameters and implicitly load-bearing capacity. The tested specimens highlighted similar results of the relevant characteristics for the two sets of mixture.

The advantages of using glass waste as aggregate replacement for producing lightweight construction elements (pavements or concrete blocks) consist in the following: material durability increasing due to water absorption, abrasion resistance increasing of the concrete due to increased hardness, rheological properties improvement of fresh concrete without using superplasticizers in the mixtures. Moreover, the experimental applications show the efficiency of using recycled glass aggregates as replacement of traditional aggregate in the production of construction material, in terms of workability related to the optimization of the puzzolanic activity produced from the glass, resistance to freezing-thaw, thermal conductivity.

Therefore, the solutions proposed in the study is fully aligned to the sustainable approaches on environmental protection and circular economy resulted in eco-sustainable composites based on glass wastes, saving costings and conservation of natural resources. Further investigations on these topics are required to identify an optimized mix design for recycled glass composite material with clay soils by increasing gradually the dosages of glass waste, with monitoring the essential condition of maintaining or obtaining new performance indicators, meaning higher mechanical values. The investigations will also take into account the addition of supplementary ecological stabilizers in the mixtures for assessing behavior parameters. Another envisaged challenge is to extend the potential applicability of recycling glass waste to other type of soils, by investigating the behavior glass recycled composite material and setting optimum dosages in the production of various building products or other civil engineering applications.

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