COMPORTAREA LA COMPRESIUNE A AGREGATELOR STABILIZATE CU CENUȘĂ ZBURĂTOARE DE TERMOCENTRALĂ

THE COMPRESSIVE BEHAVIOUR OF AGGREGATES CEMENTED WITH FLY ASH COLLECTED FROM COAL-FIRED POWER PLANTS

ANCUŢA ROTARU[1], VASILE BOBOC[1], NICOLAE ȚĂRANU[1,2] * , MONTHER ABDELHADI[3], ANDREI BOBOC[1], OANA-MIHAELA BANU[1]

[1]"Gheorghe Asachi" Technical University of Iasi, Romania, 67 Prof.dr.doc. D.Mangeron Bvd., Iasi, 700050, Romania
[2]The Academy of Romanian Scientists, 54 Splaiul Independentei, sector 5, Bucharest, 050094, Romania
[3]American University of Madaba, Amman 11821 P.O. Box 2882, Madaba, Jordan

The paper analyses the compressive behaviour of aggregates stabilized with fly ash in Romania, investigating the possibility to use the fly ash residue obtained from the combustion of lignite type coal as a cement substitute material for road construction works. The experimental testing of some proposed mixes embedding 20%, 25%, and 30% of fly ash by weight of total mixture, collected from Iaşi and Vaslui coal-fired power plants, reveals that only the mixtures of aggregates stabilized with 30% of fly ash fulfil the acceptability conditions to be used as a base layer in road construction works. Instead, the mixtures stabilized with 20% and 25% of fly ash could be used as sub-base layers.

Lucrarea analizează comportarea la compresiune a agregatelor stabilizate cu cenușă de termocentrală din România, investigând posibilitatea de a utiliza reziduurile de cenușă zburătoare rezultate din arderea lignitului ca pe un substituent al cimentului în lucrările de drumuri. Încercarea experimentală a unor amestecuri de agregate cu adaosuri de cenușă zburătoare colectată de la termocentralele din Iași și Vaslui de 20%, 25%, respectiv 30%, raportat la masa totală a amestecurilor, indică faptul că doar în cazul amestecului de agregat stabilizat cu 30% cenușă zburătoare sunt îndeplinite condițiile de acceptabilitate pentru utilizarea ca strat de bază în lucrările de drumuri. Amestecurile stabilizate cu procente de 20% și 25% cenușă zburătoare ar putea fi utilizate, în schimb, ca straturi de fundare.

Keywords: *compressive strength, fly ash, aggregates, cement-like material, road building work.*

1. Introduction

Natural pozzolana, also known as pozzolanic ash, is a porous variety of volcanic tuff or fine sandy volcanic ash with burnt granules resembling powdered bricks that were used since Antiquity as an activator in the mixture called "pozzolanic cement", considered as the first cement in history. Pozzolana is a siliceous or siliceous-aluminous material of rough, dusty, granular texture that easily melts [1]. Added in the pozzolanic cement, it reduces the liability of leaching. Its most important property, however, consists in its hydraulic cement-like constituent able to set under water when mixed with hydraulic lime (calcium hydroxide - $Ca(OH)_2$) and water. As it hardens quickly, it is more durable under water than any other cement.

Currently, most of the mixed types of cement (CEM II) contain, apart from the principal component, named the Portland clinker cement (65-79%), one additional component that can be either natural pozzolana or fly ash collected from a coal-fired power plant (21-35%) [2]. For instance, the modern cement that is also known as Portland-composite cement CEM II/B-M (V-LL), is a blend of natural / industrial fly ash (V), Portland cement and limestone (LL), which gives it good strength, impermeability, and workability [3]. For underwater use, the high alkalinity of pozzolana, due to sulfates, makes it especially resistant to the common forms of corrosion [4]. Once fully hardened, the Portland Pozzolana Cement (PPC) blend may be stronger than the Portland cement due to its lower porosity, which also makes it more resistant to water absorption [5, 6].

The current study aims to investigate the compressive behaviour of natural aggregates stabilized with fly ash examining the potential of employing the fly ash – a residual product acquired by direct combustion of the lignite type coal – as a cement substitute material for ground stabilization, especially in roads and embankments completion works [7 - 9].

In Romania, 95% of the lignite deposits are located in a relatively small area of 250 square kilometres in the Southeastern part of the country called the Oltenia mining basin, where more than 80% of lignite reserves are surface mined in twelve opencast pits. Lignite reserves total up to 280 million tonnes with a further 10 billion tonnes of resources [10]. Romanian thermal power plants

* Autor corespondent/*Corresponding author*,
E-mail: taranu@ce.tuiasi.ro

widely use lignite to obtain more than 50% of the total electric energy and one of the essential concerns about exploiting it is the environmental impact of its by-product, namely the fly ash produced from the lignite combustion through the retort residue process [11]. In Romania, the fly ash collected from thermal power plants is either stored inside the plant or laid out in landfills occupying significant land areas. This issue created environmental and health concerns which prompted laws aiming to attenuate the fly ash emissions [12]. Environmental protection measures aim to find areas of efficient use of these wastes. The road-engineering domain uses most of the fly ash collected from thermal power plants, replacing large quantities of standard materials [13]. For this reason, a significant percentage of the recycled fly ash is often used to supplement Portland cement in the concrete manufacture process [14]. Aside from its commercial advantages, there are significant environmental, technical and sustainability benefits associated with the use of fly ash as a binder in hydraulically bound mixtures consumed in road construction works [15, 16]. Fly ash applicability as a cement-like material maintains the natural aggregate capacity and diminishes the greenhouse gas emissions [17, 18], while its self-hardening features offer a marked benefit over granular materials in soil stabilization and hydraulically bound sub-bases [19, 20]. Worldwide, the fly ash collected from thermal power plants is extensively used in road works [21], from local roads to highways, mainly on embankments, sub-base layers, base layers or dam performing and strengthening.

Currently, three mechanized methods are available in the manufacturing processes for stabilizing aggregates with binders like cement, lime or fly ash:

1) The Mixed-in-Place Method, where mixing is done directly on site, all or most of the operations being worked out with a single multifunction equipment, called single pass soil stabilizer machine. It blends the aggregates with fly ash in one pass as scaling and compaction processes are performed separately.

2) The Plant-Mixing Method, where the preparation of the mixture is carried out centrally in plants usually located near the site of the aggregates production. The mixture is then transported to the roadbed, where it is laid and compacted.

3) The Moving-Mixing Method, where machines equipped with a high capacity mixer, moving on the road platform and mixing the aggregates with binder and water, realize the blending. The materials are lifted from the platform and passed through the mixer for processing, thus ensuring the homogenization of the mixture. Scarification and compaction are usually carried out with specialized equipment.

2. Materials and methods

The primary concept in this study is to mix natural aggregates collected from sites located in the Northeastern part of Romania, along the Siret River, with 20%, 25%, and 30% fly ash of total mixture weight. The fly ash results as a waste from the combustion of coal in Iaşi and Vaslui thermal power plants [22]. Then, compressive strength tests on the mixtures go through.

A comparison between the compressive strength of aggregates and fly ash mixtures from both Romanian thermal power plants was performed as well. [23, 24].

2.1. Materials

2.1.1. Aggregates

The Northeastern area of Romania, particularly Iaşi and Vaslui counties, has limited resources of natural aggregates from quarries, so the use of the local ballast collected mainly from the gravel pits along the Siret River at Paşcani and Moldova River at Timişeşti is strictly necessary for the construction and modernization of roads in this part of the country.

Figure1 shows the grain size distribution curves for both natural aggregates and partially crushed aggregates collected from either the Siret River or Moldova River as per SR EN 933-1:2012 [25].

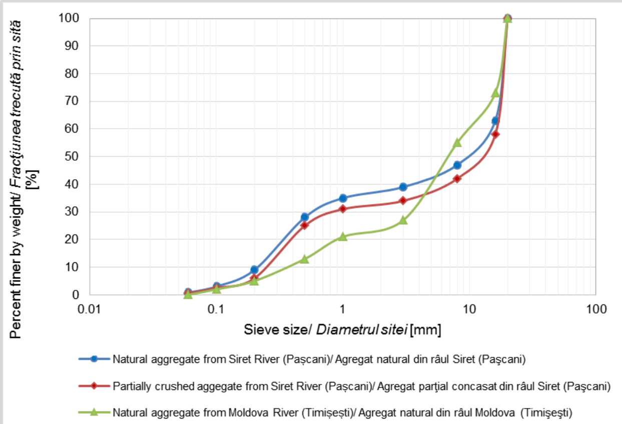

Fig.1 – Grain size distribution curves of aggregates/ *Curbele granulometrice ale agregatelor*

Table 1 presents the characteristics of the natural aggregates utilized for stabilization.

All three studied types of natural aggregates meet the technical requirements stipulated by the Romanian Technical Instructions for the Execution of Road Layers from Natural Aggregates Stabilized with Pozzolanic Binders CD 127-2002 [26]. They are usable equally as sub-base layers and base layers in reinforcing the existing flexible road systems. However, for laboratory testing purposes

Table 1

Physical characteristics of natural aggregates/ *Proprietățile fizice ale agregatelor naturale*

Type of aggregate/ *Tipul de agregat*	Coefficient of uniformity/ *Coeficientul de neuniformitate*, U (SR EN ISO 14688/2-2018) [27]	Sand equivalent/ *Echivalentul de nisip* (SR EN 933-8+A1:2015) [28] [%]	Crushing index/ *Indicele de concasaj, Ic* (SR EN 1097-2:2010) [29] [%]	Shape index/ *Coeficientul de formă* (SR EN 933-4:2008) [30] [%]
Natural aggregate from Siret River/ *Agregat natural din râul Siret*	62	51	-	-
Partially crushed aggregate from the Siret River/ *Agregat parțial concasat din râul Siret*	60	55	80	20
Natural aggregate from the Moldova River/ *Agregat natural din râul Moldova*	24	83	-	-

as well as for the examination of layers made from stabilized materials under accelerated traffic, aggregates collected from the Siret River only, either natural or partially crushed, were used in this study.

The ballast collected from both sites is a quartzy sandstone having the following mineralogical composition determined by Röentgen analysis: quartz 95%, plagioclase feldspar 3-5% and trace elements such as sericite (less than 1%), limonite, pyrite, magnetite, hornblende, and kaolinite.

2.1.2. The fly ash

Figure 2 shows the grain size distribution curves for fly ashes collected from Iași and Vaslui thermal power plants as per SR EN 933-1:2012 [25]. It is arguable that the grain size of the fly ash collected from Vaslui thermal power plant is smaller than the one of the fly ash gathered from Iași thermal power plant.

The physical characteristics of the studied fly ashes are shown in Table 2.

Compaction characteristics acquired from the modified Proctor test [34, 35] are as follows: ρ_{dmax} =1.084 g/cm^3 in the case of the fly ash from Iași coal-fired power plant, and ρ_{dmax} =1.067 g/cm^3 for the fly ash collected from Vaslui coal-fired power plant, while the optimum water content is the same for both types of fly ash, i.e. w_{opt} = 35%.

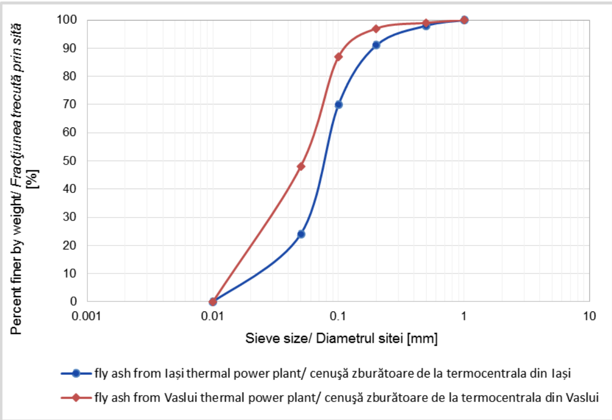

Fig.2 - Grain size distribution curves of fly ashes collected from thermal power plants/ *Curbele granulometrice ale cenușii zburătoare de termocentrală*

For oxic components, the fly ash from Iaşi and Vaslui coal-fired power plants meet the technical conditions of employment for material stabilization [36, 5] regarding the road building works. These are aluminosilicate fly ashes with SiO_2 / Al_2O_3 < 2 and CaO% < 15 showing hydraulic activity by activation with hydrated lime powder [1, 37].

Table 2

Physical characteristics of fly ash/ *Proprietățile fizice ale cenușii zburătoare de termocentrală*

Characteristics/ *Caracteristici*		Fly ash/ *Cenușă zburătoare*	
		Iași thermal power plant/ *Termocentrala din Iași*	Vaslui thermal power plant/ *Termocentrala din Vaslui*
Blaine specific surface area/ *Suprafața specifică prin metoda Blaine* (SR EN 196-6:2010) [31], [cm^2/g]		3490	3800
Apparent specific gravity/ *Densitatea aparentă* (SR EN 12697-6:2012) [32] [g/cm^3]		2.209	2.349
Bulk density/ *Masa volumică în vrac* (SR EN 1097-3:2002) [33] [g/cm^3]	**Loose state/ *Stare afânată***	0.735	0.819
	Dense state/ *Stare îndesată*	0.947	0.958

Table3

The timeline of tests / *Programul de încercări*

Type of aggregate/ *Tipul agregatului*	Percentage of fly ash/ *Dozajul de cenușă zburătoare* [%]	No. of samples kept in a wet atmosphere/ *Nr. de probe ținute în atmosferă umedă*	No. of samples to determine the physical properties/ *Nr. de probe pentru determinarea caracteristicilor fizice*	No. of samples tested to compressive strength, R_c, at different ages/ *Nr. de probe încercate la compresiune, Rc, la diferite vârste:*				
				14 day/ *zile*	28 day/ *zile*	60 day/ *zile*	90 day/ *zile*	180 day/ *zile*
Natural ballast stabilized with fly ash from Iaşi power plant/ *Balast natural stabilizat cu cenușă zburătoare de la centrala termică Iași*	20	52	12	8	8	8	8	8
	25	52	12	8	8	8	8	8
	30	52	12	8	8	8	8	8
Natural ballast stabilized with fly ash from Vaslui power plant/ *Balast natural stabilizat cu cenușă zburătoare de la centrala termică Vaslui*	20	52	12	8	8	8	8	8
	25	52	12	8	8	8	8	8
	30	52	12	8	8	8	8	8
TOTAL		312	72	48	48	48	48	48

2.2. Methods

The experimental programme starts with the determination of the compressive strength of the binder at 28 days for samples kept in a humid atmosphere as per SR EN 196-1:2016 [39]. The binder used in the tested mixtures consists of 90% fly ash and 10% lime powder.

Fly ash is considered active if the compressive strength of samples kept in wet atmosphere, determined at 28 days, reaches at least 5.5 MPa [40]. Samples for the determination of the compression strength of fly ash are manufactured from a mix embedding one part calcium hydroxide, two parts fly ash and three parts monogranular sand. The amount of added water corresponds to the optimum water content of Proctor compaction test [34, 35]. The compaction test is done in cylinders with 50 mm diameter and 100 mm height kept at +23ºC for 24 hours and at +55ºC for 6 days.

Both sets of specimens containing fly ash from Iaşi and Vaslui sources mixed with 10% of lime powder comply with the requirement: R_c = 5.81 MPa for the mixture including fly ash from Iaşi coal-fired power plant and R_c = 5.52 MPa in the case of the mixture with fly ash collected from Vaslui coal-fired power plant, respectively.

Next, the aggregates were mixed with a cement substitute material as follows: 1) fly ash from Iaşi thermal power plant (20%, 25%, and 30% of total mixture weight, respectively); 2) fly ash from Vaslui thermal power plant (20%, 25%, and 30% of total mixture weight, respectively).

The physical properties of mixtures were determined according to STAS 10473/2-1986 [41] provisions, adapted to fly ash instead of cement. In order to minimize the possible errors caused by taking the average value, three distinct sets of eight cylindrical specimens (Φ = 50 mm and h =100 mm) of natural ballast stabilized with 20%, 25%, and 30% of fly ash, for each of the two sources, the thermal power plants of Iaşi and Vaslui, were cast, then preserved in a humid atmosphere as shown in Table 3 [42].

The specimens were tested under compression as per STAS 10473/2-1986 [41] to determine the compressive strength, R_c, at the ages of 14, 28, 60, 90, and 180 days, taking into consideration that a 25% decrease in the compressive strength, compared to the standard characteristics of stabilized mixtures after 7 days of immersion in water, is the maximum allowed in the case of the mixtures made of aggregates and fly ash [43]. The maximum allowed values follow on the stipulations of the Romanian Standard STAS 10473/2-86 [41] for aggregates stabilized with cement.

As Fig.3 shows, after 7 days of immersion in water, the decreasing rate of the compressive strength for the samples made of natural aggregates stabilized with fly ash was found to be lower than 25% compared to the standard characteristics of stabilized mixtures with cement as per the Romanian standard STAS 10473/2-1986 [41]. Therefore, the admissibility condition is satisfied [42].

The experimental results obtained by testing the samples of natural aggregates stabilized with different percentages of fly ash at the ages of 14, 28, 60, 90, and 180 days [43] are shown in Figure 4 and Figure 5.

According to the Romanian Standard CD 127-2002 [26], the admissibility conditions for the compressive strength at 14 and 28 days limit the use of the fly ash as a binder for the sub-base and/or base layer in road works, as Table 6 shows. Moreover, both absorption and swelling characteristics of the stabilized mixture consisting

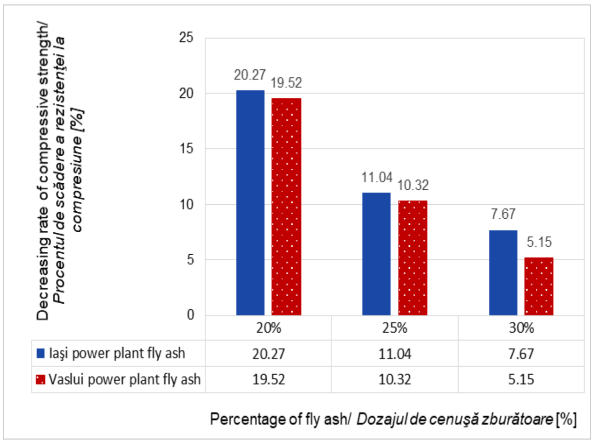

Fig. 3 – The decreasing rate of compressive strength of aggregate mixtures stabilized with fly ash compared to maximum values of aggregate mixtures stabilized with cement as per Romanian Standard, *STAS 10473 / 1-86 / Procentul de scădere a rezistenței la compresiune a amestecurilor de agregate stabilizate cu cenușă zburătoare comparativ cu procentul maxim admisibil adoptat conform standardului românesc pentru agregate stabilizate cu ciment, STAS 10473 /2-86 [41]*

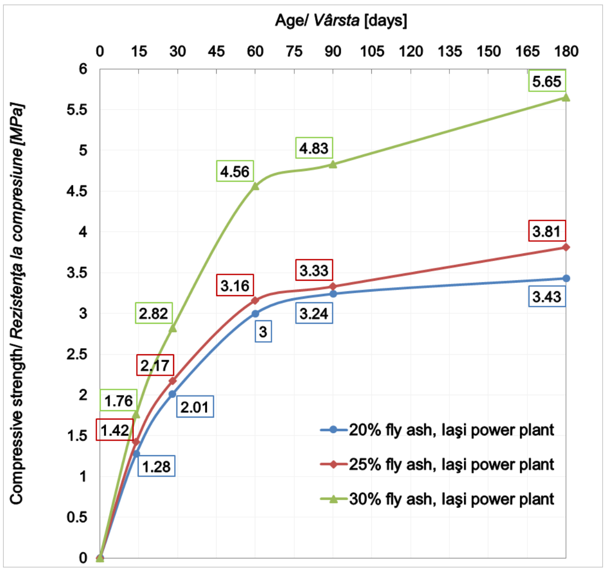

Fig. 4 - Compressive strength values for aggregates stabilized with fly ash collected from Iaşi thermal power plant/ *Valorile rezistenței la compresiune obținute pe agregate stabilizate cu cenușă zburătoare de la termocentrala din Iași.*

Table 4

Compressive strength values for mixtures of aggregate-fly ash collected from Iaşi thermal power plant, Romania/ *Valorile rezistenței la compresiune a amestecurilor agregat-cenușă zburătoare de la termocentrala din Iași, România*

Age/ *Vârsta* [days]	Compressive strength/ *Rezistența la compresiune* [MPa]		
	20% fly ash	25% fly ash	30% fly ash
14	1.28	1.42	1.76
28	2.01	2.17	2.17
60	3.00	3.16	2.82
90	3.24	3.33	4.56
180	3.43	3.81	4.83

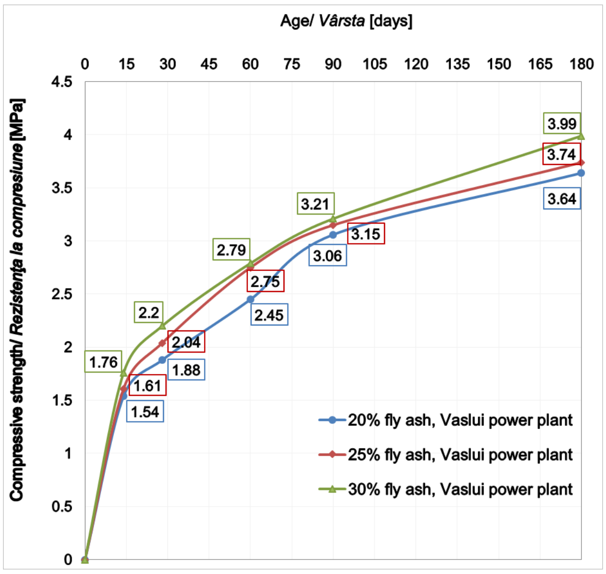

Fig. 5 - Compressive strength values for aggregates stabilized with fly ash collected from Vaslui thermal power plant/ *Valorile rezistenței la compresiune obținute pe agregate stabilizate cu cenușă zburătoare de la termocentrala din Vaslui*

Table 5

Compressive strength values for mixtures of aggregate-fly ash collected from Vaslui thermal power plant, Romania *Valorile rezistenței la compresiune a amestecurilor agregat-cenușă zburătoare de la termocentrala din Vaslui, România*

Age/ *Vârsta* [days]	Compressive strength/ *Rezistența la compresiune* [MPa]		
	20% fly ash	25% fly ash	30% fly ash
14	1.54	1.61	1.76
28	1.88	2.04	2.20
60	2.45	2.75	2.79
90	3.06	3.15	3.21
180	3.64	3.74	3.99

Table 6

Admissibility conditions/ *Condiții de admisibilitate*

Binder age/ *Vârsta liantului* [days]	RO Standard admissibility conditions/ *Condiții de admisibilitate conform standardului românesc*	
	R_c [MPa]	
	Sub-base layer/ *Stratul de fundare*	Base layer/ *Stratul de bază*
14	0.70	1.30
28	1.20	2.20

of aggregates and fly ash [36], lead to the recommendation of decreasing the fly ash percentage used in base layers as much as possible [37].

The Romanian Standard CD 127-2002 [26] provides some other recommendations and technical requirements as follows:

a) The use of unprocessed natural aggregates such as sand, gravel, ballast, processed quarry aggregates, as well as quarry wastes for the preparation of sub-base and base layers stabilized with pozzolana fly ash.

b) The minimum thickness of the layers stabilized with pozzolana fly ash has to be 12 cm for both sub-base and base layers.
c) To establish optimal percentages in the laboratory and for a proper design of semi-rigid road systems, samples need to stay a period of 180 days in standard storage conditions. That is a significant time of transition from mechanical to chemical stabilization [38].
d) Pozzolana fly ash dosages for both sub-base layers and base layers are between 10 and 30%.

3. Results and discussion

The recorded data corresponding to the mixtures of aggregates stabilized with fly ash collected from Iaşi thermal power plant show that the admissibility conditions for compressive strength at the age of 14 days are not met for the mix embedding 20% of fly ash, if it is supposed to be used as a base layer. However, either 20%, 25% or 30% addition of fly ash satisfies the admissibility conditions for the compressive strength at the age of 28 days if the mixture is used for a sub-base layer (Figure 4, Table 6).

Similarly, the percentage of 20% fly ash from Vaslui thermal power plant added to the mixture does not fulfil the admissibility conditions for the compressive strength at the age of 28 days. These requirements are not satisfied if the mixture is designed as a base layer even when using a percentage of 25% fly ash from the same thermal power plant. Nevertheless, if the tested binder is meant to be used for a sub-base layer, any percentage of added fly ash, ranging from 20% to 30%, meets the admissibility conditions for the compressive strength at the age of 28 days (Figure 5, Table 6).

The mixtures of natural aggregates stabilized with 30% of fly ash collected either from Iaşi or Vaslui thermal power plants, fulfil the admissibility conditions to be used as base layers in road building works. Generalizing and considering the recommendation of decreasing the fly ash percentage as much as possible, everything leads to the conclusion that, from all tested mixtures, only the mixture consisting of aggregates stabilized with 30% of pozzolanic fly ash collected from thermal power plants may be successfully used as a base layer for road construction works. Other mixtures of aggregates stabilized with less than 30% of fly ash may be used only as sub-base layers for road construction works.

4. Conclusions

The current construction industry needs a large number of materials belonging to the modern era to meet the resistance, safety, and environment-friendly requirements. Experimental results confirm the possibility of using fly ash waste in road building works as a cement-like compound of stabilized mixtures of natural aggregates used as sub-base layers without compromising the structural integrity of the work. Using of fly ash as a cement-like material is encouraging, mainly due to the followings:
1) Large quantities of fly ash are occupying extensive areas in the vicinity of thermal power plants. Therefore, the safe disposal of these large quantities becomes hazardous and particularly acute in countries like Romania, where the rate of used fly ash is low compared to the average global rate of 16% [44].
2) The neighbouring climate is polluted by suspended fly ash in the air, causing bronchial and lung diseases to human beings and the deterioration of landscape.
3) Using of fly ash contributes to minimization of the environmental impact caused by the output of solid waste from the coal combustion in thermal power plants. Replacing the Portland cement processed from virgin aggregates in some road applications, the fly ash contributes to the mitigation of resource depletion. Moreover, Portland cement is high CO_2 emitter during its manufacture as it involves the calcination of calcium carbonate releasing about 550 kg of CO_2 for each tonne of manufactured cement. Consequently, the use of fly ash generated in large quantities in thermal power stations significantly reduces the greenhouse gas emissions providing sustainability benefits while maintaining the strength and durability of the road structure. Moreover, unlike the raw materials used for cement clinker production, fly ash is already a fine powder, so there is no need to ground it through an energy-intensive process.

The results obtained on natural aggregates stabilized with 30% of fly ash from thermal power plants are optimum, allowing the applicability of the mixture in road building works as either sub-base layers or base layers to minimize the use of virgin aggregates and cement to leave sufficient resources for future generations and reduce the global warming effects.

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