A Material for Substructure and Road Works: Mechanical Characteristics of Pozzolana Fly Ash from Thermal Power Plant of Iasi, Romania

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Abstract: - One of the most interesting scientific and environmental subject develop in the last time is the study of fly ash produced in growing quantities by burning coal in thermal power plants. In the paper the mechanical characteristics of pozzola fly ash, a massive waste of thermal power station of Iasi, Romania, is investigated. Supplementing the data referring to the correlation between mechanical strength at various ages of stabilized material simplify laboratory studies by limiting the categories of testing. The suitability of using fly ash as a cement-like material is discussed in this study. This material is typically used for a soft, clayey layer beneath a road that will experience many repeated loadings. Using the fly ash from Iasi thermal power plant that requires dry capture insurance is part of the environmental protection, infrastructure construction and road field being great potential consumers for such products.

Key-Words: pozzolanic ash, fly ash from thermal power plant, cement-like material, mechanical methods, materials stabilized with fly ash

1 Introduction

Pozzolana, also known as pozzolanic ash, is a porous variety of volcanic tuff or fine, sandy volcanic ash with burnt granules resembling powdered brick.

Pozzolana is of rough, dusty, granular texture. It is a siliceous or siliceous and aluminous material which easily melts; but its most important property consists in its hydraulic cement-like compound capable of setting under water when it is mixed with hydraulic lime (calcium hydroxide - $Ca(OH)_2$) and water, which hardens very suddenly, and make it more durable under water than any other cement [43].

The term pozzolana also defines any of various artificially produced substances resembling pozzolana ash. Artificial pozzolana is made by calcined fire-clay and adding lime, sand and water, with fine brick dust [41].

Owing to its pozzolanic properties, fly ash is also used as a replacement for Portland cement [39].

An industrial source of materials with pozzolanic properties is the siliceous fly ash from coal-fired power plants.

Fly ash is a mineral waste, one of the residues generated from the combustion of solid fuels (coals) [21]. Fly ash is generally captured from the chimneys of coal-fired power plants.

Pozzolana cement is a cement to which pozzolana has been added, to reduce the liability of leaching. Mixed cements (CEM II) contain, in most of them, besides the main component - Portland clinker, only one component of the addition, which can be both natural pozzolana and ash from thermal power plant [37]. Modern pozzolanic cement, also termed as Portland composite cement, (CEM II/A-M and CEM II/B-M), is a blend of natural or industrial pozzolana and Portland cement or clinker and gypsum, which contribute to strength, impermeability, and workability [10].

In addition to underwater use, the high alkalinity of pozzolana makes it especially resistant to common forms of corrosion from sulfates.

Once fully hardened, the Portland Pozzolana Cement (PPC) blend may be stronger than Portland cement, due to its lower porosity, which also makes it more resistant to water absorption [16].

In Romania, fly ash is generally stored at coal power plants or placed in landfills. However, an important percentage is recycled, often used to supplement Portland cement in concrete production.

Worldwide, ash from thermal power plants is used extensively in roads of all classes of importance (from local roads to highways) [44], mainly on embankments [14], foundation layers, base layers or for dam performing and strengthening [1].

2 Pozzolanic activity determination for Iasi fly ash using mechanical methods

The gain in strength with time for high calcium fly ash is very high compared to that of low calcium fly ash due to presence of reactive minerals and glassy phase [34].
When replacing a part of the cement by a high amount of fly ash, changes in strength development and resistance to carbonation may cause problems in the applications of the concrete to actual building construction in respect to the structural and durability requirement [22]. Though the replacement of a part of fine aggregate by fly ash reduces low strength development, higher rates of carbonation of the concrete may remain as a problem, as calcium hydroxide will be consumed by pozzolanic reaction with the fly ash [35].
Shear strength tests conducted on fly ash samples show that fly ash derives most of its shear strength from internal friction, although some apparent cohesion has been observed in certain bituminous (pozzolanic) fly ashes [4]. The shear strength of fly ash is affected by the density and moisture content of the test sample, with maximum shear strength exhibited at the optimum moisture content. Bituminous fly ash has been determined to have a friction angle that is usually in the range of 26° to 42° [28].
The knowledge of pozzolanic activity of fly ash from Iasi thermal power plant is based on compression test of some mortars made from binders containing this type of ash [42].
Pozzolanic activity is determined on the basis of *I*, the physical activity index, given by the relation:

$$I = \frac{R_{cemtest}}{R_{refcem}} \text{ x } 100 \qquad [\%]$$

where: $R_{cemtest}$ means compressive strength, determined on mortar prisms (N/mm^2);
R_{refcem} means compressive strength, determined on referential mortar prisms (N/mm^2).

The index of activity for fly ashes of Iasi is "*I*" and must be the value of the minimum index of activity. It follows that using Iasi fly ashes as mortar addition it is not recommended [47].

Determination of pozzolanic activity of various materials such as fly ash is quite essential for their efficient application in cement [12]. It also plays an important role in the selection of the material as a stabilizer in various environmental projects [25]. This necessitates development of a methodology that can be employed for determining the pozzolanic activity of different materials, quite rapidly and easily. With this in view, a method that estimates pozzolanic activity of fly ash has been developed [19].
Modified ASTM method consists in determining the compressive strengths on samples made of a mixture composed of one part calcium hydroxide, two parts fly ash and three parts monogranular sand (particle size mainly between 1 to 2 mm) [9]. The quantity of water introduced corresponds to the compaction optimum moisture content. The mixture compaction is realized into cylinders with 5 cm diameter and 10 cm height kept at 23°C for 24 hours and at 55°C for 6 days [45]. To be considered active fly ash, the 7 days compression strength must be greater that 5.5 N/mm^2 [5]
The proposed method for pozzolanic activity establishing consists in compressive strength determination as follows:

- after 2 days for samples kept in moist atmosphere;
- after 7 days for samples kept in moist atmosphere and then subjected to strengthening under accelerated thermal conditions during 6 days;
- after 7 days in moist atmosphere;
- by strengthening under accelerated thermal conditions.

Mixtures are composed of 90% fly ash and 10% hydrated lime powder. The amount of added water corresponds to optimum moisture content from modified Proctor compaction test.
No matter chemically active they would be, alumino-siliceous fly ashes such as those from Iasi thermal power plant do not show hydraulic properties in the presence of water. In the presence of water and by activation with CaO the hydration, cementation and strengthening processes take place, displaying two stages. In the first stage forms etringite (calcium sulphoaluminate), and in the second stage the pozzolanic reactions for calcium-silicate-hydrate (C-S-H) and calcium-aluminum-hydrate (C-A-H) formation take place. This process of cementation compounds strengthening has a long-period development so that early-age mechanical resistances of cementation products are low, unlike those developed in a long period of time, which reach remarkable values [32].

3 Determination of materials characteristics stabilized with Iasi fly ash

Extensive use of pozzolanic binders in substructure and road techniques, especially in stabilization [15], aims to reduce the consumption of lime and cement, which are expensive and energointensive construction materials [3].

Worldwide there are many methodologies for determining the calculating parameters for layers consisting of materials stabilized with pozzolanic binders [33].

As Table 1 shows, samples with size depending on the maximum size of natural particles are made after the determination of compaction characteristics of natural aggregates mixtures containing fly ash from Iasi thermal power plant (maximum dry density ρ_{dmax} and compaction optimum moisture content w_{opt}).

Table 1 Sample dimensions based on D_{max}

Maximum particle size D_{max} mm	Sample dimensions: Diameter cm	Height cm	Sample volume cm^3
31	7.14	10.50	420
7	5.05	7.50	150

There are three series of natural ballast samples. The ballast is stabilized with fly ashes in dosage of 20%, 25%, and 30%, which were kept in moist atmosphere [8]. On these samples both physical and mechanical characteristics (compressive strength R_c, tensile strength by compression on generators R_{tg}) at ages of 14, 28, 60, 90, and 180 days were determined [6].

The bending-tensile strength of stabilized mixtures is determined by the relationship [46]:

$$\frac{R_{ti}}{R_{tg}} = 1 + 3tg^2\left(\frac{\pi}{4} - \frac{\varphi}{2}\right)$$

where: R_{ti} – the bending-tensile strength;
R_{tg} – tensile strength by compression on generator;
φ - internal friction angle.

4 Results, discussions and interpretations

The comparison of chemical composition with the admissibility conditions of fly ash from Iasi thermal power plant leads to the following results:

- It satisfy the conditions related to oxidic major components (SiO_2, Al_2O_3, Fe_2O_3);
- CaO content is in permissible limits;
- Although SO_3 content is greater than the permitted limit for use as additive in concrete and mortars, this compound is within 4%, a maximum value for use of fly ash in stabilized road structures [36].

In terms of pozzolanic activity the results obtained by the modified method presented in Figure 1 shows that with 96 daN/cm^2 strength the Iasi fly ash is a pozzolanic ash. As well, the proposed method shows that the compressive strength is over 55 daN/cm^2 (Table 2), certifying the pozzolanic activity of Iasi fly ash [20].

Table 2 R_c compressive strength for fly ash mixture and lime

Mixture type	Compressive strength R_c daN/cm^2 – Strengthening development: normal, at 7 days	normal, at 28 days	thermoaccelerated, at 7 days
90% Iasi fly ash; 10% lime	37.07	58.09	55.42

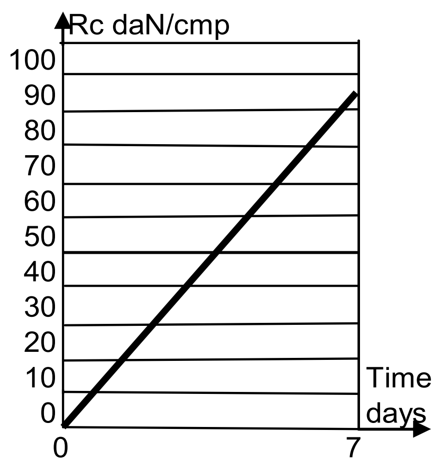

Fig.1 Hydraulic evaluation using the modified method

Table 3 Physical characteristics of Iasi fly ash stabilized natural ballast

Cement dosage %	γ_w daN/cm^3	γ_d daN/cm^3	γ_{dmax} daN/cm^3	Absorbtion %				Swelling %				Mass lost %			
				after 7 days	after 14 days	Admitted layer f*	Admitted layer b*	after 7 days	after 14 days	Admitted layer f*	Admitted layer b*	after 7 days	after 14 days	Admitted layer f*	Admitted layer b*
20	2.070	1.890		5.33	6.84			2.43	3.04			6.69	3.97		
25	2.034	1.858	1.890	7.39	9.03	10	5	2.94	4.09	5	2	2.98	4.02	10	7
30	1.983	1.811		8.26	10.04			3.07	4.43			2.12	6.72		

f* - fundation
b* - bedding

Table 4 Mechanical characteristics derived from stabilized ballast with Iasi fly ash

Age	Dosage %	R_c N/mm^2	R_{tg} N/mm^2	Admissibility conditions		
				R_c N/mm^2 foundation layer	R_c N/mm^2 bedding layer	R_{tg} N/mm^2
14 days	20	1.28	0.17			-
	25	1.42	0.19	0.7	1.3	
	30	1.76	0.23			
28 days	20	2.01	0.27			-
	25	2.17	0.29	1.2	2.2	
	30	2.82	0.34			
60 days	20	3.00	0.40			-
	25	3.16	0.42	-	-	
	30	4.56	0.43			
90 days	20	3.24	0.49			-
	25	3.33	0.52	-	-	
	30	4.83	0.63			
180 days	20	3.43	0.58			-
	25	3.81	0.59	-	-	
	30	5.05	0.70			
360 days	20	-	-			-
	25	6.22	0.75	-	-	
	30	-	-			

Table 5 Elasticity modulus for stabilized mixtures

Type of mixture	Modulus of elasticity, E daN/cm^2
Aggregate stabilized with granulated slag	12,000
Aggregate stabilized with fly ash	18,000
Aggregate stabilized with tuff	12,000

For 25% fly ash dosage the 180 days strength must represent about 2/3 of 360 days strength.

Physical characteristics obtained on three series of samples made from stabilized natural ballast with a dosage of 20%, 25%, and 30% Iasi fly ash [11] are presented in Table 3.

In Table 5 calculation values of elasticity modulus stipulated by Romanian regulations are presented.

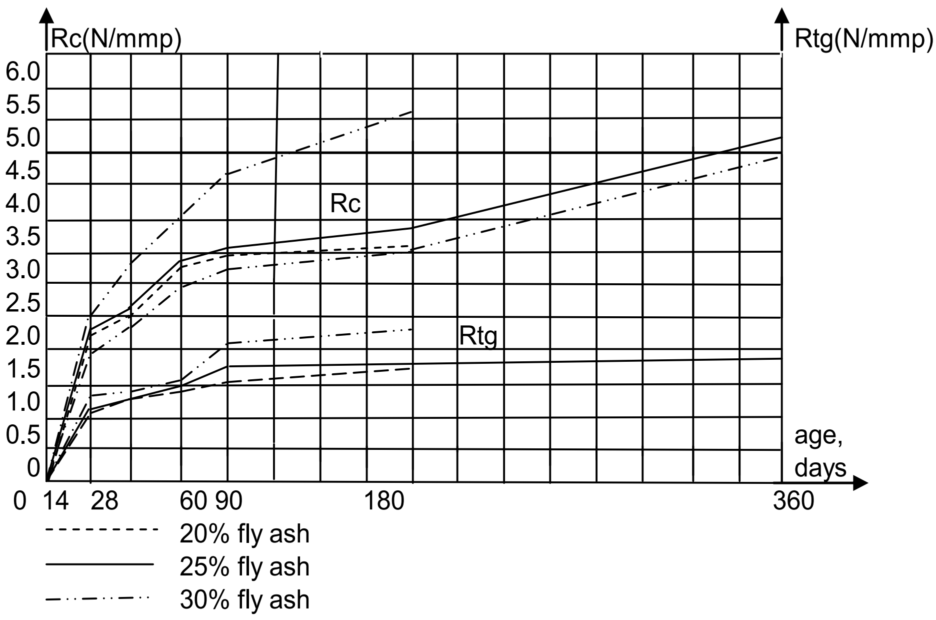

Fig.2 Dynamics of R_c and R_{tg} values

Since the results on absorption and swelling recommend reduced dosage of fly ash in bedding layer, the proposed admissible values becomes temporary values, and collecting data for finalization is necessary. The reduction of Iasi fly ash dosage seems possible taking into account the R_c and R_{tg} values presented as follows.

Experimental results obtained by samples tested in humid atmosphere at 14, 28, 60, 90, 180 and 360 days are presented in Table 4. Resistances' dynamics is shown in Figure 2 [7].

The angle of internal friction and cohesion of stabilized mixtures with fly ash can be determined using the following relations:

$$tg\varphi = \frac{R_c - 4R_{tg}}{2\sqrt{R_c R_{tg} - 3R_{tg}^3}}$$

$$c = \frac{R_c R_{tg}}{2\sqrt{R_c R_{tg} - 3R_{tg}^3}}$$

where: R_c – compressive strength;
R_{tg} – tensile strength by compression on generators;
φ – internal friction angle;
c – cohesion.

Using the determined angle of internal friction the bending-tensile strength of stabilized mixtures can be calculated with the above relation.

The results obtained for the internal friction angle and cohesion are presented in Table 6 and the results determined for tensile strength of stabilized mixtures at 90, 180, 360 days are presented in Table 7. Table 9 presents R_c , R_{tg} for stabilized mixtures.

Table 6 The internal friction angle and cohesion

Age days	Dosage %	Φ °	c N/mm^2	R_{ti} N/mm^2
90 days	20	33	0.85	0.92
	25	33	0.90	0.97
	30	40	1.12	1.04
180 days	20	29	1.00	1.18
	25	33	1.02	1.10
	30	42	1.25	1.11
360 days	25	37	1.31	1.32

Table 7 Tensile strength values

Age	Dosage %	$R_{ti\ adm}$ N/mm^2	
90 days	20	-	0.41 - 0.65
	25		0.42 - 0.67
	30		0.60 - 0.97
180 days	20	0.5	0.43 - 0.69
	25		0.48 - 0.76
	30		0.71 - 1.11
360 days	20	-	-
	25		0.78 - 1.24
	30		-

Mechanical characteristics obtained by thermo-accelerated strengthening at temperature regimes of 35°C and 60°C are presented in the first part of the Table 9. Experimental results obtained from specimens preserved in wet atmosphere at the age of 14, 28, 60, 90, 180 and 360 days are presented in the last part of Table 9.

The objectives proposed in this study are to reduce the time needed to establish optimum mixture and to establish correlations between mechanical properties and characteristics obtained by thermo-accelerated strengthening and the mechanical features obtained on pressed samples in wet atmosphere (storage condition according to Romanian norms in force).

The difference between values associated with different mixture dosages at 35°C is significant for R_c at 7 days; for R_{tg} the differences are significant for both sample ages. In the case of 60°C temperature the difference between dosages appears in case of R_c at both ages of samples.

In the last columns of the Table 9, the admissibility conditions of Romanian regulations are presented, in order to adopt the value of 1,000 daN/cm^2 for the deformation modulus.

The data analysis from Table 9 shows that de R_c admissibility conditions are not accomplished for realizing base layers, even for 20% fly ash dosage (Table 8). This condition is not of major importance since the elasticity modulus is effectively determined and it is not used a unique value for the deformation modulus as in the case of admissibility condition regulations.

Table 8 Non-admitted dosages for Iasi fly ash

Age days	Dosage %	Iasi fly ash mixture %
14	20	98,50
28	20	91,30
	25	98,60

Table 9 Mechanical characteristics R_c and R_{tg} for stabilized mixtures

Age days	Dosage %	Normal strengthening		Accelerated strengthening				Admissibility conditions		
				+35°C		+60°C		R_c		R_{tg}
		R_c N/mm^2	R_{tg} N/mm^2	R_c N/mm^2	R_{tg} N/mm^2	R_c N/mm^2	R_{tg} N/mm^2	foundation layer	base layer	
3	20			1.40	0.18	3.05	0.41			
	25			1.49	0.21	3.18	0.42			
	30			1.57	0.24	3.82	0.49			
7	20			2.08	0.21	3.54	0.57			
	25			2.12	0.23	3.87	0.58			
	30			2.88	0.35	5.39	0.61			
14	20	1.28	0.17					0.70	1.30	-
	25	1.42	0.19							
	30	1.76	0.23							
28	20	2.01	0.27					1.20	2.20	-
	25	2.17	0.29							
	30	2.82	0.34							
60	20	3.00	0.40					-	-	-
	25	3.16	0.42							
	30	4.56	0.43							
90	20	3.24	0.49					-	-	-
	25	3.33	0.52							
	30	4.83	0.53							
180	20	3.43	0.58					-	-	-
	25	3.91	0.59							
	30	5.65	0.70							
	20	-	-					-	-	-
360	25	6.22	0.75							
	30	-	-							

Table 10 The ratio between R_c, R_{tg} for normal strengthening versus R_c, R_{tg} for accelerated strengthening

Dosage %	Age days	R_c R_{tg} wet atm.	R_c and R_{tg} for accelerated strengthening							
			+35°C				+60°C			
			3 days		7 days		3 days		7 days	
			R_c N/mm^2	R_{tg} N/mm^2	R_c N/mm^2	R_{tg} N/mm^2	R_c N/mm^2	R_{tg} N/mm^2	R_c N/mm^2	R_{tg} N/mm^2
20	14	R_c	0.91	-	1.63	-	> 2.00	-	> 2.00	-
		R_{tg}	-	1.06	-	1.24	-	> 2.00	-	> 2.00
	28	R_c	0.70	-	1.03	-	1.52	-	1.76	-
		R_{tg}	-	0.67	-	0.78	-	1.52	-	> 2.00
	60	R_c	< 0.50	-	0.69	-	1.02	-	1.16	-
		R_{tg}	-	< 0.50	-	0.53	-	1.03	-	1.43
	90	R_c	< 0.50	-	0.64	-	0.94	-	1.09	-
		R_{tg}	-	< 0.50	-	< 0.50	-	0.84	-	1.16
	180	R_c	< 0.50	-	0.61	-	0.89	-	1.03	-
		R_{tg}	-	< 0.50	-	< 0.50	-	0.71	-	0.98
25	14	R_c	0.95	-	1.49	-	> 2.00	-	> 2.00	-
		R_{tg}	-	1.10	-	1.21	-	> 2.00	-	> 2.00
	28	R_c	0.69	-	0.98	-	1.47	-	1.78	-
		R_{tg}	-	0.72	-	0.78	-	1.45	-	2.00
	60	R_c	< 0.50	-	0.67	-	1.01	-	1.22	-
		R_{tg}	-	0.50	-	0.55	-	1.00	-	1.38
	90	R_c	< 0.50	-	0.64	-	0.95	-	1.16	-
		R_{tg}	-	< 0.50	-	< 0.50	-	0.95	-	1.12
	180	R_c	< 0.50	-	0.56	-	0.83	-	1.02	-
		R_{tg}	-	< 0.50	-	< 0.50	-	0.81	-	1.02
	360	R_c	< 0.50	-	< 0.50	-	0.61	-	0.74	-
		R_{tg}	-	0.50	-	< 0.50	-	0.71	-	0.77
30	14	R_c	0.89	-	1.64	-	> 2.00	-	> 2.00	-
		R_{tg}	-	1.04	-	1.52	-	> 2.00	-	> 2.00
	28	R_c	0.56	-	1.02	-	1.35	-	1.91	-
		R_{tg}	-	0.71	-	1.03	-	1.44	-	1.79
	60	R_c	< 0.50	-	0.63	-	0.84	-	1.18	-
		R_{tg}	-	0.56	-	0.81	-	1.14	-	1.42
	90	R_c	< 0.50	-	0.60	-	0.79	-	1.12	-
		R_{tg}	-	< 0.50	-	0.56	-	0.78	-	0.97
	180	R_c	< 0.50	-	0.51	-	0.68	-	0.95	-
		R_{tg}	-	< 0.50	-	0.50	-	0.70	-	0.87

Natural ballast stabilized with 30% fly ash from thermal power plant presents the largest compressive strength increases [38].

In Table 10 the ratio between R_c and R_{tg} for normal strengthening versus R_c and R_{tg} for accelerated strengthening is presented.

If the values create an improper fraction (the value of R_c is greater than the value of R_{tg}) the reports are useful to evaluate the mechanical characteristics of high ages of samples.

To enhance the confidence level of resistance assessment, which justify the use of proper fractions (the value of R_c is less than the value of R_{tg}), the difference of 25% is proposed.

The insurance of thermo-accelerated strengthening scheme at 35°C and 60°C allows obtaining a 90% confidence level for the significant mechanical characteristics as follows:

- Establishing, in the design stage, of the calculating value for the deformation module of the material stabilized with fly ash from thermal plants;
- Obtaining the R_c and R_{tg} values at standard ages to confirm the fulfillment of quality conditions of road layers stabilized with fly ash from thermal plants [13].

The correlations established between R_c and R_{tg} are

very useful in laboratories for achieving the compression test only and using the established conditions to determine the tensile strength by compression on generator.
The fatigue effect on bending tensile strength has been determined by comparing R_{tg1} and R_{tg2} values corresponding to samples of the same age. R_{tg1} is the bending tensile strength for control specimens, and R_{ti2} has the same signification for specimens prior subjected to fatigue. The obtained fatigue curves show a behaviour corresponding to materials stabilized with Iasi fly ash.

5 Conclusions

Fly ash properties are somewhat unique as an engineering material [2].
Unlike typical soils used for embankment construction [26], fly ash has a large uniformity coefficient consisting of silt-sized particles [40]. Engineering properties that will affect fly ash's use in embankments [23] include grain size distribution, compaction characteristics, shear strength, compressibility, permeability, and frost susceptibility [1].
Mechanical performances, which the materials stabilized with pozzolana can reach, the economic efficiency and the environmental benefits [29], are redoubtable trumps for challenge an official decision in order to resuscitate the interest of stakeholders (directors, producers and users) to maximize the use of pozzolana flash in road construction [1].
Correlations between mechanical strength achieved by thermo-accelerated strengthening at 35°C and 60°C at 3 and 7 days respectively and mechanical strength under standard conditions of storage (wet atmosphere) determined at significant ages, indicate the usefulness of thermo-accelerated method for laboratory studies. Correlations reduce the time needed to select the best recipes for pozzolana cement-type stabilization with fly ash from thermal power plants.
Correlations between compressive strength and tensile strength by compression on generator ensure the limitation of laboratory tests only to compression test, which provides sufficient practical equipments that fit in every geotechnical laboratory.
By the physico-mechanical performances that fly ashes can achieve when a proper design is realized in the laboratory stage and when the execution comply strictly the technology of the stabilized layers [27], the fly ashes from thermal power plants can successfully replace the cement, with both economic and environmental benefits [24].
Using concrete with thermal ash in addition for reducing costs is known from effectual norms and standards [18].
Implementation of concrete with addition of thermal ash in building construction elements such as boards or blocks is also an advantage [17].
It can replace up to 30% by mass of Portland cement [30], and can add to the concrete's final strength and increase its chemical resistance and durability [31]. Due to the spherical shape of fly ash particles, it can also increase workability of cement while reducing water demand [31].

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