ISSN: 0975-833X

Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 17, Issue, 10, pp.34896-34904, October, 2025
DOI: https://doi.org/10.24941/ijcr.49621.10.2025

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

REVIEW ARTICLE

UTILIZATION OF FLY ASH FROM THE BARGNY COAL-FIRED POWER PLANT IN CEMENT MATRIX STRUCTURES UNDER MECHANICAL STRESS

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ARTICLE INFO

Article History:
Received 17th July, 2025
Received in revised form
11th August, 2025
Accepted 05th September, 2025
Published online 29th October, 2025

Keywords:
Characterization, Fly ash; Coal-fired power plant; Hydraulic concrete; Cement; Clinker, Durability

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ABSTRACT

The objective of this work is to valorize unconventional fly ash from the Bargny coal-fired power plant in order to address issues related to the durability of cementitious structures, but also to provide economic and environmental solutions related to industrial waste storage. To this end, an experimental study was conducted to characterize the materials used, in particular the physicochemical and mechanical properties of fly ash, Dangoté cement, and manufactured cement in which clinker is replaced by fly ash at different levels (0%, 5%, 10%, and 20%), as well as a complete identification of aggregates (sand, basalt, flint, and limestone) for hydraulic concrete. First, the results show that the ashes studied are siliceous, spherical in shape, and have a Blaine specific surface area equal to 4126 cm²/g. In addition, the activity indices found, with values of 77% and 96% at 28 days and 90 days respectively, show that the ash is pozzolanic according to the specifications of standard (1). Furthermore, the use of these fly ashes as a substitute product increases the Blaine specific surface area of the cement produced, and therefore its workability, and the mechanical strengths at 28 days are higher than the characteristic strengths given by the standard (3) for a substitution rate of up to 20%. The durability study proves that the use of ash results in fewer connected pores accessible to water in the material.

Citation:* Serigne DIOP, Oustasse Abdoulaye SALL, Diogoye DIOUF and Makhaly BA. *2025. "Utilization of fly ash from the bargny coal-fired power plant in cement matrix structures under mechanical stress.". *International Journal of Current Research, 17, (10), 34896-34904.*

INTRODUCTION

Today, the sustainability of hydraulic binder-based structures in a low-carbon environment is a real headache for the building materials production industry (concrete, mortar). Furthermore, cement production is a source of greenhouse gas emissions such as carbon dioxide (CO_2), which means that in 2022, global cement production emitted 1.6 billion tons of carbon dioxide, or 7 to 8% of global CO_2 emissions (3). These CO_2 emissions are largely generated during the clinker production phase, mainly through the combustion of limestone at 1450°C. The use of industrial waste, particularly fly ash, in the production of hydraulic binders and cement matrices as cement substitutes (0%, 5%, 10%, 20%, and 30%) or clinker (0%, 5%, 10%, 20%) is an alternative solution that meets the need for sustainable structures in a healthy and economically viable environment. To this end, the materials used (fly ash, Dangoté cement, manufactured cement, and hydraulic concrete) will be characterized in order to determine their physicochemical, mineralogical, and mechanical parameters, as well as to measure the durability and reactivity of these ashes.

MATERIALS AND METHODS

CHARACTERIZATION OF FLY ASH: Fly ash from the Bargny coal-fired power plant (in Senegal) was characterized at the civil and mechanical engineering laboratory of INSA Rennes in France.

PHYSICOCHEMICAL CHARACTERIZATION: The fly ash used comes from the Bargny coal-fired power plant in Senegal. According to SEM-EDS analyses (4), most of it is spherical in shape and siliceous in nature, with an estimated loss on ignition of 3%. Its pozzolanic activity indices are 77% and 96% for 28 days and 90 days, respectively. Its physical characteristics (5) are such that its Blaine specific surface area is 4126 cm²/g and its BET specific surface area is 7.3 m²/g. Its chemical composition is given in Table 1.

Table 1. Chemical composition of the fly ash used (5)

Chemical elements	Mass %		NF EN 450-1
Major elements	SiO_2	48.94	>70%
	Al_2O_3	29.65	
	Fe_2O_3	3.24	
	CaO	9.29	<10%
	MgO	1.55	<4%
	TiO_2	1.55	
	P_2O_5	2.19	<5%
	Na_2O	0.1	<5%
	K_2O	0.46	
	SO_3	2.67	<3%
Minor elements	In mg/kg		
	Mg	0	-
	Cd	0.08	-
	Pb	0.182	-
	S	2.24	-

EFFECTS OF FLY ASH IN THE FRESH AND HARDENED STATE: The effect of fly ash was characterized by a study of the behavior of mortar in its fresh and hardened states. To do this, we adopted a mortar formulation in which LAFARGEHOLCIM's CEM II/B-LL 32.5 cement was replaced by fly ash, as shown in Table 2. In the fresh state, slump and spread measurements were applied to mortars ready for molding using the Abrams mini cone then after preparing the test specimens $4\times 4\times 16$ followed by conditioning in water and at a temperature of 20°C for up to 28 days of curing, The behavior in the hardened state is assessed by mechanical bending and compression tests in accordance with standard (2).

Table 2: Mortar formulations in which cement has been replaced by fly ash at different rates (0%, 5%, 10%, and 20%)

Materials	% substitution			
	MCEMIICV0	**MCEMIICV5**	**MCEMIICV10**	**MCEMIICV20**
Cement (g)	900	855	810	720
Sand (g)	2700	2700	2700	2700
Water (g)	450	450	450	450
Ash (g)	0	45	90	180

EFFECTS OF FLY ASH ON DURABILITY: The durability study was assessed by measuring the capillary water absorption coefficient and water-accessible porosity (Figure 1) on test specimens $4\times 4\times 16$, which were pre-conditioned and then conditioned in accordance with standards (6) and (7).

a) b)

Figure 1. Measurement devices: a) capillary water absorption coefficient and b) water-accessible porosity

CHARACTERIZATION OF THE CEMENTS USED

CASE OF DANGOTÉ CEMENT: The cement used is type CEM II/B 32.5 R from the DANGOTE cement plant, whose physical, chemical, and mechanical characteristics are recorded in Tables 3, 4, and 5 below (8) and (9).

Table 3. Chemical composition of the cement used (%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	P_2O_5	Na_2O	K_2O	SO_3	Cl	PAF
15.17	3.88	3.23	63.31	0.19	0.65	0.04	0.3	0.87	0.007	13

Table 4. Physical parameters of cement

45 µm fines	90 µm fines	BLAINE	Loss on ignition	IST	FST	E/C
%	%	cm^2/g	%	min	min	%
15	1.2	3910	13.03	320	360	24.6

Table 5. Compressive strength of CEMII/B 32.5 cement

Age	2 days	7 days	28 days
Strength (MPa)	10.6	26.9	42.2

MANUFACTURED CEMENT: The cement manufactured in the laboratory is the result of raw materials (Figure 2) such as: clinker, limestone, fly ash, and phosphogypsum. The mass composition of this cement is 28% limestone, 3.2% phosphogypsum, and 68.8% clinker for a total cement mass of 5 kg (Table 4). As part of this work, four types of cement (Figure 3) were formulated based on the percentage of clinker replaced by ash (0%, 5%, 10%, and 20%). The grinding time was set at 35 minutes, followed by sieving through a 1 mm diameter sieve. The formulation of the four types of cement is given in Table 6.

Table 6. Formulation of the manufactured cement

Types	Clinker (kg)	Gypsum (kg)	Limestone (kg)	Ash (kg)
0	3.44	0.16	1.4	0
5	3.19	0.16	1.4	0.25
10	2.94	0.16	1.4	0.5
20	2.44	0.16	1.4	1

Figure 2. Raw materials used for cement production in the laboratory

Figure 3. Cement obtained after grinding and sieving through a 1 mm diameter sieve for different ash contents (0%, 5%, 10%, 20% respectively from lightest to darkest) [4] and [5]

The chemical composition of the manufactured cements and their constituents (Table 7) are determined using X-ray diffraction (XRD) analysis.

Table 7. Chemical composition of the types of cement produced (%)

Tests	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	P_2O_5	Na_2O	K_2O	SO_3	Cl
CIM. control	17.5	5.02	3.39	60.26	0.63	0.66	0.16	0.36	1.07	0.008
CIM.5% CV	16.25	4.39	3.5	61.62	0.61	0.65	0.1	0.3	1.31	0.009
CIM. 10% CV	18.24	5.78	3.39	57.76	0.68	0.7	0.15	0.33	1.28	0.009
CIM. 20% CV	20.96	7.65	3.89	51.78	0.77	0.72	0.2	0.39	1.3	0.011

The mineralogical composition of the clinker used is given in Table 8 below.

Table 8. Mineralogical composition of the clinker used

Phase	Clinker			
Minerals	C_3S	C_2S	C_3A	C_4AF
Content in %	54.9	15.8	7.0	14.6

The Blaine specific surface area is an important parameter for characterizing the fineness of cements. Other physical parameters were also determined, such as: the percentage of fines retained on 45-μ m and 90-μ m sieves, loss on ignition, and initial and final setting times (Table 9), in accordance with the protocols described in the standards (10).

Table 9. Physical parameters of cements

Tests	Blaine	45 µm fines	90 µm fines	Loss on ignition	IST	FST	E/C	Stability
	cm^2/g	%	%	%	mn	min	%	mm
Witness	4809	23.2	4.7	12.16	245	310	26.6	0.0
5% CV	5757	18.8	3.8	13.77	291	310	27	1
10% CV	6003	12.7	1.2	12.92	285	301	27.2	0.0
20% CV	6619	9.4	2.2	14.66	319	360	28.2	1

CHARACTERIZATION OF AGGREGATES USED

CASE OF SANDS

In this research, we used two types of sand:

- Standard sand,
- Dune sand.

CEN standardized sand, which complies with French standard (2), is natural silica sand, packaged in bags of 1350 ± 5g. Its particle size ranges from 0.08 to 2mm with a maximum moisture content of 0.2%. Dune sand comes from the Makha quarry in Taïba Ndiaye in the department of Tivaoune (Senegal). This dune sand is used as a raw material in the manufacture of concrete. Its characteristics are such that its fineness modulus is less than 2.2 with a sand equivalent of 39%. Its specific weight and bulk density are 2.398 and 1.485 g/cm³ respectively. However, the sand has been corrected with 0/3 aggregates (basalt, flint, and limestone) to obtain a fineness modulus between 2.2 and 2.8.

OTHER AGGREGATES: Natural and crushed aggregates (classes 0/3, 3/8, and 8/16) were used in the composition of hydraulic concretes (Figure 4), both for the control concretes and for the concretes in which the cement was replaced by fly ash.

These are:

- Basalt (Talix mine, Grand Lefèvre quarry in the Ngoudiane area of Senegal)
- Flint (SOCOBE quarry in the Taïba Ndiaye area of Senegal)
- Limestone (Le sable de Allou Kagne quarry, a few kilometers from Thiès, Senegal)

Figure 4. Aggregates used in hydraulic concrete formulations

These materials were fully identified at the LNR-BTP Laboratory, formerly CEREEQ, to obtain the physical and geotechnical parameters shown in Table 10.

Table 10. Physical and geotechnical parameters of aggregate

Aggregates		FLA (%)	MD (%)	LA (%)	SW	BD (g/cm3)	ES control	ES (mix 50x50%)
Basalt	**0/3**	-	-	-	2,809	1,623	74	46
	3/8	74.22	9.6-9.2	14.2	1.464	1.568	-	-
	8/16	15.12	7.4-7	8.8	1.479	1.647	-	-
Flint	**0/3**	-	-	-	2,304	1,204	74	31
	3/8	35.9	12.2-12.6	28.4	1.221	1.240	-	-
	8/16	14.52	8.4-7.8	34.52	1.252	1.376	-	-
Limestone	**0/3**	-	-	-	2,398	1,363	32	46
	3/8	8.53	62.2-57.8	47.34	1.192	1.279	-	-
	8/16	6.53	59.2-58.8	44.74	1.195	1.257	-	-

RESULTS

EFFECTS OF FLY ASH IN ITS FRESH AND HARDENED STATE AND ON DURABILITY

Table 11 and Figures 5 show the results obtained for slump and mini cone spread of mortars in which cement was replaced by fly ash at different contents (0%, 5%, 10%, and 20%) with a water-to-binder ratio of 0.5. Table 12 and Figure 6 show the results relating to the mechanical performance in bending and compression of the different types of mortars made with or without replacing Lafarge CEM II 32.5 cement with fly ash. Table 13 and Figure 7 show the values and evolution of the capillary water absorption coefficient over time on mortar test specimens in which the cement was replaced by fly ash at different contents (0%, 5%, 10%, and 20%) after 28 days of curing.

Table 11. Measurement of mortar consistency with and without fly ash

Measurements	Mortars			
	0	5	10	20
Settlement (cm)	8.5	9.2	9.5	9.8
Spreading (cm)	13.95	13.6	13.2	12.7

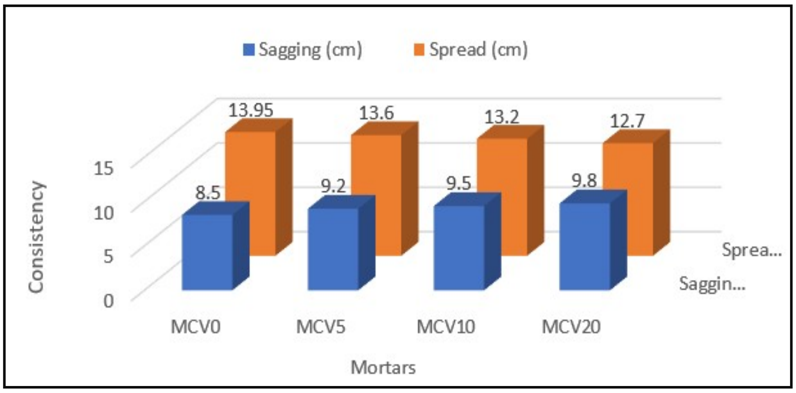

Figure 5. Measurement of mortar consistency as a function of fly ash substitution rate

Table 12. Flexural and compressive strengths of mortars after 28 days of curing

Mortars at 28 days	Flexural		Compression	
	Force (kN)	**Stress (MPa)**	**Force (kN)**	**Stress (MPa)**
MFA0	3.5	7.0	58.5	35.9
MFA5	2.8	5.6	54.5	33.1
MFA0	2.9	6.1	53.2	32.9
MFA20	2.7	5.5	48.3	29.9

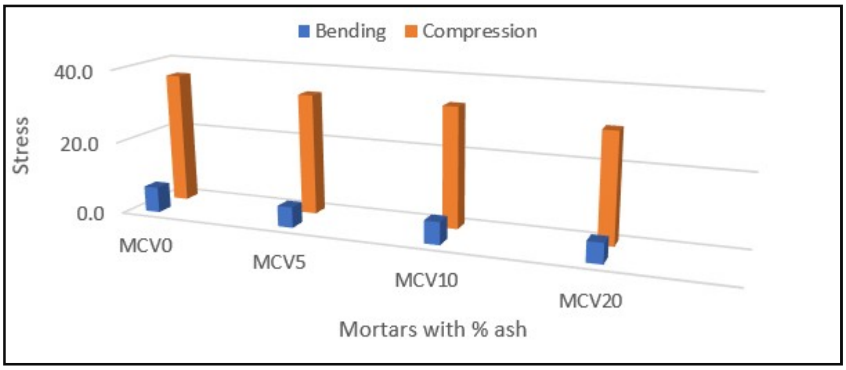

Figure 6. Evolution of bending and compressive stress as a function of the rate of cement substitution by fly ash

Table 13. Capillary absorption coefficient values as a function of time for mortars in kg/m²

Mortars	1/4h	1/2h	1h	2h	4h	19h	24h
MFA0	2.87	4.03	5.89	8.56	11.98	19.20	20.67
MFA5	2.80	3.98	5.81	8.35	11.83	20.03	21.66
MFA10	2.05	2.50	3.66	5.49	8.04	16.97	18.20
MFA20	2.29	2.83	3.96	5.81	8.70	16.38	17.29

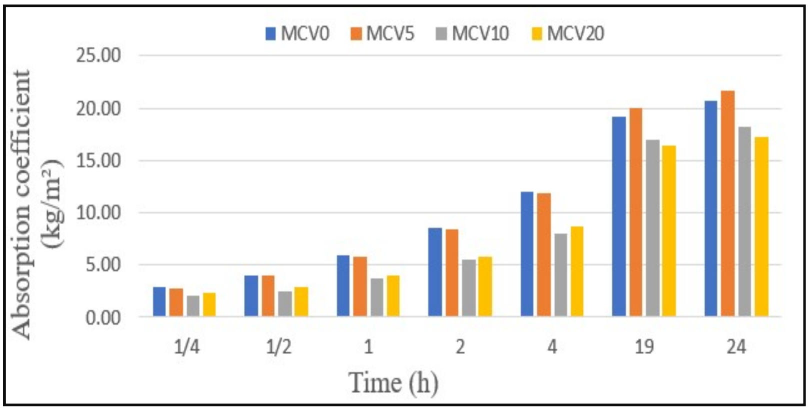

Figure 7. Histogram showing the evolution of the capillary absorption coefficient with the rate of cement substitution by fly ash as a function of time

Table 14. Water open porosity values of mortar test specimens

Test specimens Mortar	M_{water} (kg)	M_{air} (kg)	Msec (kg)	$\rho_{(d)}$ (kg/m3)	$\rho_{(water)}$ (kg/m3)	ε (%)
0%	0.164	0.291	0.265	2088	998.6	20
5%	0.166	0.297	0.272	2080	998.6	19
10%	0.160	0.284	0.260	2094	998.6	19
20%	0.139	0.279	0.254	1865	998.6	18

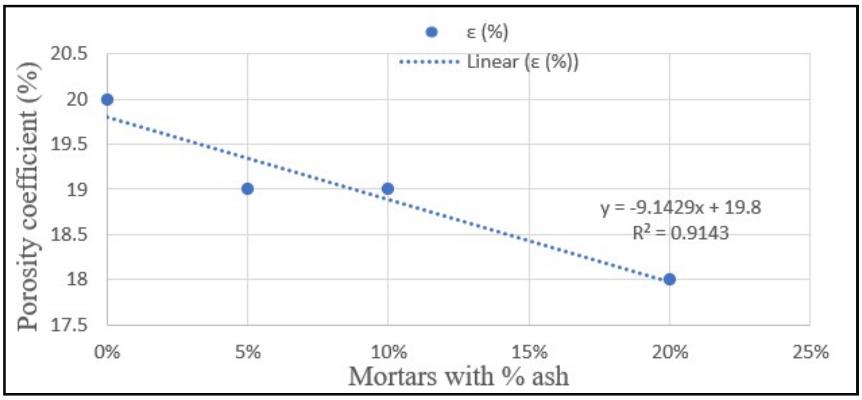

Figure 8. Change in water-accessible porosity with the rate of cement substitution by fly ash

Table 14 and Figure 8 show the values of water-accessible porosity. Table 10 and Figure 5 show an increase in slump and a decrease in spread compared to the control mortar (MCV0) as the substitution rate increases. The results show that replacing cement with fly ash improves the consistency of the mortar and therefore its workability.

The results in Table 11 and Figure 6 show that mechanical performance in compression decreases as the ash content increases, but nevertheless, up to a 10% substitution rate, the stresses found are higher than those characteristic of the cement used at 28 days. This therefore confirms the results obtained with DANGOTE CEM II 32.5 cement in Senegal.

Analysis of Figures 12 and 7 initially shows an increasing trend in the absorption coefficient of all mortars over a 24-hour period. However, there is a noticeable decrease in this coefficient when the ash content is high. Over the same period, a decrease in water-accessible porosity is observed in Table 13 and Figure 8. However, this decrease in the absorption coefficient when the ash content is high could be explained by the fact that the use of ash results in fewer connected pores accessible to water in the material.

EFFECT OF FLY ASH ON CEMENT MATRICES

EFFECT ON CEM II/B 32.5 R CEMENT MORTARS: As part of the recovery of cementitious material, a formulation was adopted whereby fly ash was substituted at different rates (0%, 5%, 10%, 20%, and 30%) at the DANGOTE CEMENT laboratory. Subsequently, 4x4x16 test specimens were prepared and conditioned, followed by crushing tests to determine the mechanical performance of the cement (Table 15).

Table 15. Compressive strength with or without substitution of the control cement with fly ash

Substitution rate	Compressive strength of mortars (MPa)		
	2 days	28 days	90 days
0%	10.6	42.2	55.3
5%	11.2	45.4	59.5
10%	9.6	40.2	56.7
20%	7.9	34.1	52.9
30%	4.9	26	41.2

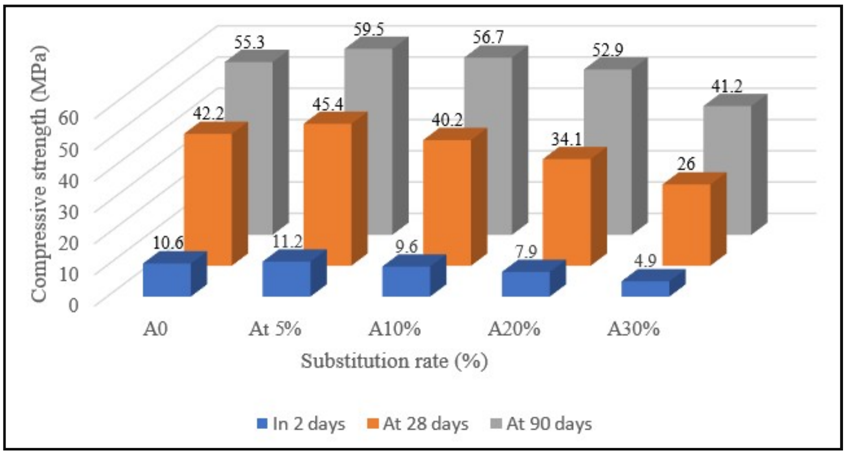

Figure 9. Compressive strength of DANGOTE cement at different substitution rates

EFFECT OF FLY ASH ON THE PERFORMANCE OF CEMENT SYNTHESIZED IN THE LABORATORY: This type of cement was designed using limestone, clinker, phosphogypsum, and ash as raw materials, with ash replacing clinker at different levels (0%, 5%, 10%, and 20%). The physical, chemical, and mechanical parameters were then determined in order to study the effect of ash on the cement obtained.

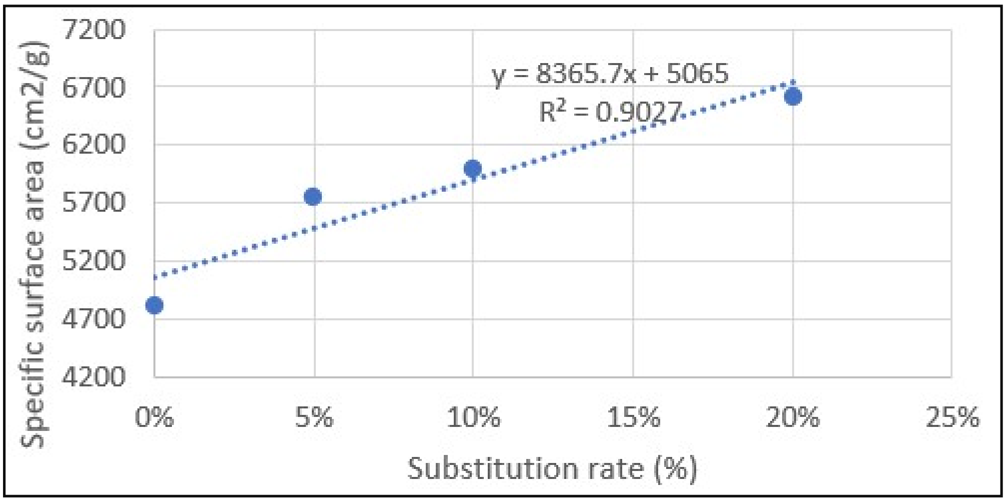

Figure 10. Change in the specific surface area of the cement obtained as a function of the rate of clinker substitution by fly ash

Figure 10 shows a variation in Blaine specific surface area as a function of the rate of substitution of clinker with ash between 4700 cm^2/g and 6400 cm^2/g. This increase can be explained by the fine particle content of fly ash from the Bargny coal-fired power plant, and therefore its reactivity. This will have a beneficial effect on the workability of concrete and mortar, reducing the time lost during their application and therefore lowering labor costs. Figure 11 shows that the compressive strength of cement manufactured for a given substitution rate increases with the age of the mortar test specimen, which is in line with regulations (2).

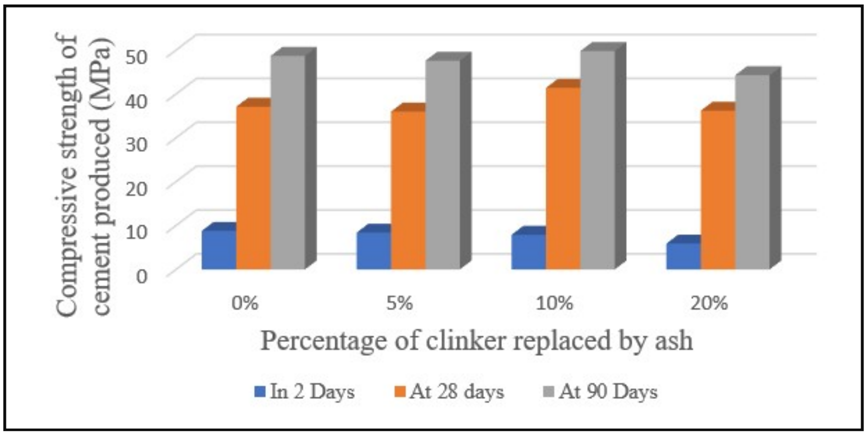

Figure 11: Compressive strength of cement obtained by substituting clinker with fly ash

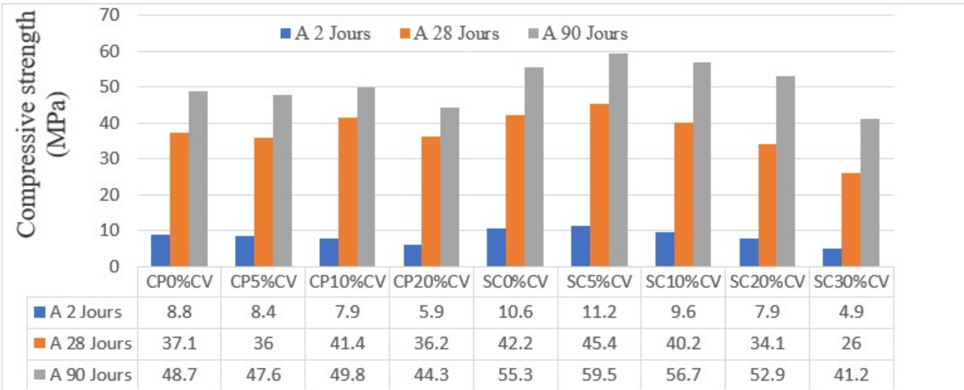

Figure 12. Performance of the cement produced and that of CEM II/B 32.5 R from Dangoté Cement substituted with fly ash

Furthermore, these strengths, with or without clinker substitution by ash, are higher than the target strength at 28 days, i.e., 32.5 MPa. Figure 12 shows that the mechanical performance obtained with direct cement substitution is better than that obtained with clinker substitution.

EFFECT OF FLY ASH ON CONCRETE DEPENDING ON THE TYPE OF AGGREGATE: After formulating hydraulic concretes in which cement was replaced by fly ash at different rates (0%, 5%, 10%, and 20%), cylindrical test specimens measuring 16x32cm were made and then crushed at 7 days, 14 days, and 28 days. The results obtained are shown in Table 16.

Table 16. Compressive strength of concrete in which cement has been replaced by fly ash at day j

		% substitution			
Concrete	Age	0	5	10	20
Basalt-based	7 days	22	14	12	10
	14 days	31	22	20	17
	28 days	39	33	26	25
Flint-based	7 days	11	8	8	7
	14 days	17	12	11	10
	28 days	20	18	16	13
Limestone-based	7 days	10	9	9	8
	14 days	16	15	15	12
	28 days	19	17	16	14

According to Table 16, the compressive strengths obtained for basalt-based concrete at 28 days are greater than or equal to the target compressive strength at 28 days (25MPa) for a substitution rate of up to 20%, and the compressive strength decreases as the percentage of ash increases compared to the control concretes (0% ash). The strengths obtained at 28 days with flint and limestone-based concrete are lower than those obtained at the same time (25MPa).

CONCLUSION

The aim of this work was to propose ways of utilizing unconventional fly ash from the Bargny-Sendou coal-fired power plant for use in the construction industry, particularly in cementitious matrix materials or structures (concrete, mortar, cement), as a substitute for cement and clinker, with a view to improving the properties of these materials in terms of their long-term behavior under mechanical stress. This work addresses problems such as those related to the storage of fly ash at the power plant, which can degrade the immediate environment, and those related to the emission of greenhouse gases such as CO_2 into the atmosphere. To achieve this objective, a physicochemical, mineralogical, and mechanical characterization of the influence of these fly ashes on the behavior of cement matrix structures was first carried out, in which CEM II/B 32.5 R cement was replaced by fly ash at different substitution rates (0%, 5%, 10%, 20%, and 30%). Next, the other materials used were characterized, namely cement (CEM II 32.5R from Dangoté Cement), manufactured cement using limestone, clinker, phosphogypsum, and ash as a clinker substitute at different levels (0%, 5%, 10%, and 20%), as well as aggregates for hydraulic concrete (sand, basalt, flint, and limestone). The results of the recovery of fly ash in cement matrices showed that:

- An increase in the Blaine specific surface area for the cements formulated and produced,
- Good mechanical performance corresponding to the limits acceptable by regulation (2) for cement and clinker substitution by ash up to 20%;
- The strengths obtained for basalt-based concrete at 28 days are greater than or equal to the target strength at 28 days (25MPa) for a substitution rate of up to 20%, and that the strength decreases as the percentage of ash increases compared to the control concrete con (0% ash). The strengths obtained at 28 days with flint and limestone-based concrete are lower than those obtained at the same time (25MPa).
- The durability study showed that the use of fly ash results in fewer connected pores accessible to water in the material, as low porosity of the material can lead to a decrease in the water absorption coefficient.

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