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Mechanical Study of the Utilization of Niger Coal Bottom Ash as an Additive in Cement Production

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Abstract: CBA (coal bottom ash) is an industrial waste generated by coal fired thermal power plant. In this work, we investigate the utilization as an additive material in composite cement of CBA resulting from the firing of the coal extracted in Tefereyre mine (TCBA) in a thermal power plant in Niger. Our investigations are carried out by using compressive mechanical tests on 40 × 40 × 160 mm^3 mortar specimens. These mortar specimens are made with a partial substitution of the cement by TCBA at levels of 0%, 5%, 10%, 15%, 20% and 25% by mass. The tests were performed on the specimens at 7, 14, 28, 45 and 56 days of age. The results were used to evaluate the pozzolanic activity index as the ratio of the compressive strength of mortar containing 25% of coal bottom ash on that of the control mortar containing 100% of cement, according to ASTM C618. From these data, the maximum rate of TCBA addition in Portland cement was derived. It was found that TCBA has a pozzolanic activity index of about 71% at 28 days and displays a maximum substitution rate of 15% in Portland cement. These results strongly support the development of composite cement using TCBA.

Key words: industrial waste, coal bottom ash, composite cement, pozzolanic activity, mechanic resistance, durability.

1. Introduction

The hydraulic concrete is one of the most used building materials in the world for its mechanical performance, fire resistance and competitive cost. Its production is mainly based on the use of Portland cement. However, conventional cement manufacturing releases large amounts of CO_2 (carbon dioxide) well known for its negative impact on the environment as a greenhouse gas. The CO_2 emissions from the cement industry were estimated at almost 5%–7% of global CO_2 emissions with 0.9 ton of CO_2 emitted into the atmosphere for producing one ton of cement [1]. This CO_2 comes from two major complementary sources: i) the fossil energy consumption necessary to produce very high temperatures in order to obtain the clinker, and ii) the transformation process of limestone ($CaCO_3$) under the effect of heat into lime (CaO) and carbon dioxide (CO_2). More than 60% of CO_2 during the conventional manufacturing of cement comes from this later phenomenon.

One solution that the cement industry has developed in order to reduce CO_2 emissions is the partial substitution of clinker in Portland cement by pozzolanic materials additions such as natural pozzolan[2], metakaolin[3], and industrial waste including blast-furnace slag [4], silica fume, fly ash [5, 6]and coal bottom ash[7, 8]. In addition to the reduction of CO_2 emissions, the utilization of pozzolanic materials in cement also provides other benefits. The first one is the economic advantage due to the substitution of a part of the expensive Portland cement by cheaper, environmental friendly, natural pozzolans or industrial waste [9]. The second one is the increased durability of the end product [2] thanks to the improvement of the compactness of the composite cement paste due to the formation of second generation calcium silicate hydrates CSH II [7, 8].

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The third advantage is the limited impact of the pozzolanic materials addition on the conventional manufacturing process of Portland cement. This characteristic opens the possibility to convert large amounts of industrial and societal waste into sustainable building materials[5, 10] at a competitive cost.

In the case of CBA, the first work was conducted in 1999 on CBA produced in Brazil [7]. These authors studied the possibility of using fine fraction (passing 75 μm sieve) of coal bottom ash as mineral addition in Portland cement. They obtained a pozzolanic activity index i = 88%, which increases when making further grinding to increase the fineness of the bottom ash. In 2007, a study showed that CBA produced in Turkey used to partially replace cement with a substitution rate of 10% increases the compressive strength of about 6% compared to ordinary cement [8]. In 2013, It is also showed in the literature that the grinding bottom ash can effectively replace up to 20% of cement without reducing the strength class of the concrete [9].

The present work goes after those predecessors. Its main objective is to study the usability as cement additive of coal bottom ash resulting from the combustion of coal extracted from Tefereyre mine (75 km north-west to Agadez City in Niger). Taking into account the large amount of the stock of these industrial waste (circa 3 million tons) as well as the average flux of 150,000 tons discharged per year, the ultimate goal of this study is to help finding a sustainable solution for both the environmental problems generated by fired coal electricity production and the crucial need of comfortable and affordable houses in Niger.

2. Materials and Methods

2.1 Materials

2.1.1 TCBA (Tefereyre's Coal Bottom Ash)

Tefereyre's coal bottom ash was grinded to obtain 80 micron sieve passing. TCBA fineness is an important factor in this study because the more the addition is fine the higher is the reaction [8]. Table 1 gives the physical characteristics of TCBA. It has a specific density of 2.31 t/m^3 and a bulk density of 0.77 t/m^3. These values correspond to those obtained in the literature[11, 12]. The BET (Brunauer-Emmett-Teller) specific surface area obtained is 13.89 m²/g and the Los Angeles index of the bottom ash is 62.78%.

Chemical analyses of TCBA (Table 2) made by Vinai R. et al [13] show that the content of hazardous elements is within the acceptable range recommended by WHO (World Health Organization). Leaching tests show that the amount of detected elements are below the examples in the literature [10], and the concentration of heavy metals detected in leachate is below the thresholds proposed by German standards [14]. Thus, the danger due to heavy metals is mainly the possibility of accumulation in the human body.

XRD (X rays diffraction) tests show that 61.3% of bottom ash is in amorphous form due to combustion temperatures[13]. Also the SEM (Scanning electron microscopy) analysis and XRD analysis showed that the silica, aluminum and iron oxides is about 99% of the total mass of the bottom ash [13].

As it can be followed from Table 3, the sum of SiO_2, Al_2O_3 and Fe_2O_3 concentrations in TCBA is 93.10%, showing that the chemical composition criteria is

Table 1 Physical properties of TCBA.

Tests	Norm use	Obtained results	Bibliographic reference
Specific density	EN 1097-7	2.31 (t/m^3)	[11]
Bulk density	P 94-050	0.77 (t/m^3)	[12]
BET surface area	-	13.89 (m²/g)	-
Los Angeles index	NF P 18-573	62.78 (%)	-

Table 2 Chemical analysis of TCBA [13].

Elements	Mg	Al	Si	K	Ti	Fe
Wt%	1.04	27.90	59.59	5.33	2.68	3.90
At %	1.23	30.01	61.53	3.97	1.63	2.05

Table 3 Mineralogical composition of TCBA [13].

Oxide	MgO	Al_2O_3	SiO_2	K_2O	TiO_2	FeO	CaO
Wt%	0.95	27.21	62.32	2.58	2.15	3.57	0.5

Table 4 Chemical composition of cement.

C_3S	C_2S	C_3A	C_4AF
60.2%	14.9%	7.9%	10.1%

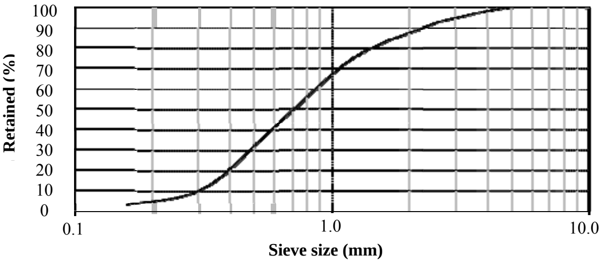

Fig. 1 Sand particle size distribution.

fulfilled. TCBA specimens verified the chemical composition rule: $SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$, according to ASTM (American Society for Testing and Materials) C618 [15].

2.1.2 Cement

The cement used in this study is a CPA45 produced in accordance with standard NF P 15-301 and produced by CIMTOGO Company and available locally. The chemical characteristic of cement is shown in Table 4. It has a specific density of 3.56 t/m^3, a bulk density of 1.06 t/m^3 and a BET surface area of 2.96 m^2/g. these values are measured in the lab. According to the manufacturer, its initial setting time is 180 min.

2.1.3 Sand

The sand used is a natural sand available locally with a maximum size of 5 mm. A particle size analysis carried out on the sand gives the particle size curve in Fig 1. It has a coefficient of uniformity Cu = 3 and a coefficient of curvature Cc = 0.9. According to USCS classification, it is a poorly graded sand, that is to say a uniform sand. The SE (sand equivalent) test [16] shows that the sand used is clean with low percentage of fine clay and good for high quality concrete. Indeed we obtained a sand equivalent SE = 77.81. Its bulk density is 1.53 t/m^3, its specific density is 2.67 t/m^3 and its fineness modulus is 2.90.

2.2 Methods

2.2.1 Specimen Formulation

For mechanical testing, mortar specimens containing TCBA at different dosages of substitution of cement by mass (0%, 5%, 10%, 15%, 20%, 25%) were made in accordance with the European standard EN 196-1 [17] (S/C = 3 and W/C = 0.5). In order to solve a workability problem of mortar with the addition of coal bottom ash, we added super plasticizer to a concentration of 2% of cement by mass in the mixture.

A laboratory electric mixer was used for the preparation of mortars according to the following procedure:

- Cement, sand and bottom ash (if any) are introduced into the mixer
- 2 minutes of dry mixing is achieved
- Water is introduced
- A 2-minute mixing is performed again
- Finally, after stopping mixing, manual scraping of sides of the bowl is made.

Prepared cement mortars were placed into 40 × 40 × 160 mm^3 steel moulds, surface of which were covered to prevent water evaporation. After 24 h, samples were removed from moulds and stored in lime water until the test day. Samples cured for 7, 28, 45 and 56 days were tested for compressive strength in accordance with EN 196-1 [17] standard.

2.2.2 Mechanical Test

The mechanical test consisted in evaluating the compressive strength. For this, 40 × 40 × 160 mm^3 sample was split in two by a flexural test and the compressive test is performed on the two half prisms obtained (Fig. 2). The compressive strength was used to determine the pozzolanic activity index of TCBA.

If F_c is the breaking load of the compressive test, the stress on the specimen is:

$$R_c = F_c/b^2 \qquad (1)$$

where R_c is the compressive strength

- If F_c is expressed in N (Newton), this strength expressed in MPa (mega Pascal) is [17]:

$$R_c\ (\mathrm{MPa}) = F_c\ (\mathrm{N})/1600 \qquad (2)$$

The compressive test used to determine the index of pozzolanic activity, which is the ratio between the compressive strength of the mortar with "p%" of coal bottom ash and the compressive strength of a control mortar with 100% of cement. This index is used to evaluate the pozzolanicity of a material. ASTM C618 standard [15] defines a material as pozzolanic if:

- Its chemical composition verified: $SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$
- Its activity index i at 28 days of cure is: $0.67 < i < 1$

$$i = R_p/R_0 \tag{3}$$

with

p = 25%

i = pozzolanic activity index

R_p = compressive strength of the mortar with p% of bottom ash by weight of cement

R_0 = compressive strength of the control mortar with 100% of cement.

3. Results and Discussion

3.1 Evaluation of Compressive Strength

The compressive test results are shown in Fig. 3. It is observed that strength decreases with the increasing of substitution rates. This can be explained by the decrease of cement rate in the mortar. In addition, the pozzolanic activity is a slow reaction explaining the low compressive strength at early age like 7, 14 and 28 days. Pozzolanic activity starts at 28 days and the calcium hydroxide consumption is very important at 90 days [8].

However, we note an increase of compressive strength over time for different substitution rates. This increase with time is more significant on the mortar with the addition than on the reference mortar. Indeed, in the reference mortar, we observe a shift from 63 MPa at 28 days to 65 MPa at 56 days representing an increase of 3.6%, while for the mortar containing 25% of TCBA, we observe a shift from 44 MPa at 28 days to 56 MPa at 56 days or an increase of 20%. This high increase in mixtures with coal bottom ash can be explained by the development of pozzolanic reaction in these mixtures. Indeed, Cheriaf et al [8] show that the low strength observed before 28 days of hydration is due to the fact that many of coal bottom ash particles remained unattacked by calcium hydroxide. It is at 28 days of hydration that bottom ash particles start to react with calcium hydroxide, resulting in the formation of C-S-H gel and needles.

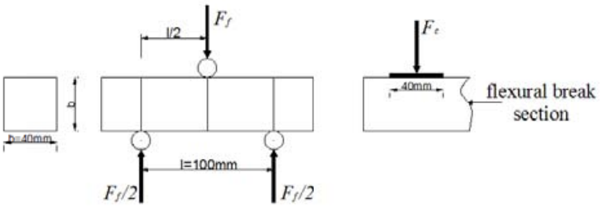

Fig. 2 Device of flexural and compressive breaking of specimens.

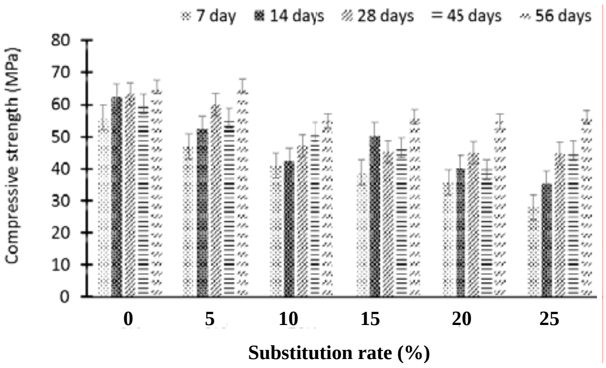

Fig. 3 Compressive strength with the substitution rate in the time.

3.2 Pozzolanic Index Activity Evaluation

A pozzolanic material is characterized by its pozzolanic activity index. This parameter describes quantitatively the degree of reaction over time or the reaction rate between a pozzolanic material and $Ca(OH)_2$ in the presence of water [15]. The rate of the pozzolanic reaction depends on the intrinsic properties of the pozzolanic materials, including the reactive silica and alumina content, the specific surface area and/or the reactive mineral and amorphous phases. The overall chemical composition of a pozzolanic material is considered as one of the factors governing long term performance such as compressive strength of the composite cement binder.

Results on the activity index evaluated at different ages with 25% of substitution rate are shown in Fig. 4.

We obtained at 28 days of cure an activity index of about 71%. This value is higher than the normative limit (67%) [15], we can conclude that TCBA presents pozzolanic reactivity.

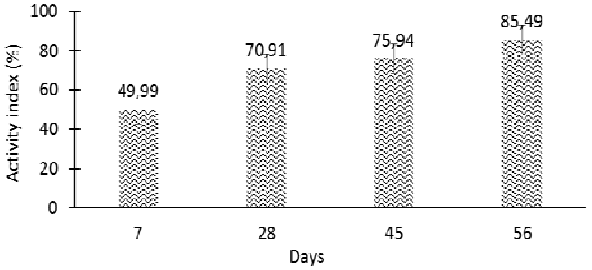

Fig. 4 Pozzolanic activity index of bottom ash at different ages.

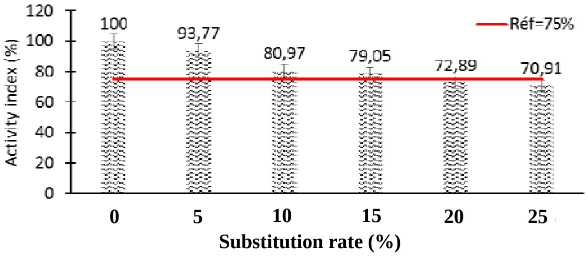

Fig. 5 Activity index evolution with substitution rate.

The evolution of this activity index with time illustrated in Fig. 4 shows that it increases with time. There is a shift from about 71% at 28 days to about 76% at 45 days and approximately 85% in 56 days. This time dependency is as expected. It is attributed to the increase of pozzolanic activity of TCBA with time.

3.3 Optimal Rate of TCBA Addition in Portland Cement

The variation of coal bottom ash substitution rate in the mortar allows the evaluation by the activity index of the optimal rate of TCBA that can be used in cement. ASTM C618 [15] standard requires a minimum of 75% in activity index for composite cements with pozzolanic addition. This evolution of activity index with the variation of substitution rate is shown in Fig. 5 and the maximum substitution rate of TCBA in the cement is 15%.

Thus, the maximum rate of TCBA at which we have an activity index of 75% at 28 days was 15%. This substitution rate of 15% will be used to test the confection of CEM II A composite cement in accordance with the European standard EN 197-1 [18].

4. Conclusions

Using compressive and flexural mechanical tests on different substitution rate specimens, the addition of Tefereyre's Coal Bottom Ash in ordinary Portland cement were studied.

The results indicate that TCBA is a pozzolanic material. Indeed, the estimated activity index is about 71% and the sum of SiO_2 + Al_2O_3 + Fe_2O_3 of TCBA reaches 93.10%.

The evolution of activity index with the variation of substitution rate shows that TCBA can be used in cement at a rate of up to 15%. This rate allows to have at least 75% of the strength that we would with standard cement.

The activity index of TCBA increase with time and we obtain at 56 days of cure with the rate of 15% an activity index of about 86%. This value could increase further with time up to 100%. Test at 90 days of cure will be carried out in order to confirm this prediction.

Future efforts will be focused on the confirmation of these preliminary results using different methods of evaluation of pozzolanic activity including chemical methods. We will also investigate the effect of TCBA addition to the physical and workability characteristics of the cement.

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