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Valorisation of the sewage sludge ash as cement replacement material

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ABSTRACT

Abstract: *The amount of sewage sludge from wastewater treatment plants is continuously increasing and becoming a serious issue for environment. Therefore, the valorisation of sewage sludge in sectors such as the construction field where there is high demand for naturel resources would be great for the environment. The present work reports the possibility of using sewage sludge ash as substitute for part of cement in mortars. The cement was mixed at various percentages of sewage sludge ash: 0% (as control mortar), 10%, 20% and 30% of the cement's weight. Several properties have been tested at various curing ages (2, 7 and 28 days) and compared with control samples: mechanical properties including flexural and compressive strengths, and physical properties namely the dry bulk density, the water absorption and the apparent porosity. The obtained results have revealed that both physical and mechanical properties of mortar was influenced by the ratio of sewage sludge ash which can be used as a substitute of part of the cement in mortar. Flexural and compressive strengths increased over time for all the samples of mortar. The substitution can be as high as 30% while maintaining a compressive strength within the standard requirements at 28 days. Also the use of up to 30% of the weight of cement in sewage sludge ash provides lower dry bulk densities, higher both water absorption and higher apparent porosity than control mortars.*

I. Introduction

A strong urban and industrialised growth worldwide lead to an increase in water consumption and thus in wastewater's volume. Hence, many wastewater treatment plants have been constructed and operate in order to solve the water pollution issue. Never the less, great quantities of sewage sludge, which is an inevitable by-product of the wastewater treatment process, is still been produced. Sewage sludge is causing an environmental pollution hazard and a potential threat to human health. Thus, sewage sludge has to be managed through environmentally friendly and sustainable applications. There are three (03) main manners to manage sewage sludge: Landfilling, land spreading and calcination. Landfilling of sewage sludge has become problematic because it is difficult to find suitable landfill sites and the risk of the contamination of water bodies and soil are great [1]. Soil application, whose heavy metals can be released from the sludge, may cause a problem of human toxicity as well as aquatic and terrestrial toxicity [2], and nowadays land spreading is limited by stringent legislation. Calcination is the most interesting way to manage sewage sludge in the long-term. It considerably reduces the high volume of the produced sludge and the obtained sewage sludge ash can be recycled in the building materials. In order to preserve non-renewable natural resources, an important number of researches have focused on the reuse of sewage sludge ash in construction materials since it is an economical and environment friendly alternative to the disposal this type of waste. Sewage sludge ash is used in mortars [3-14], lightweight aggregates [15-16], foamed material [17], concrete [18-19], tiles [20-22], ceramics [23-24], manufacturing of eco-cement [13,25-26], bricks [27-29] and asphalt paving mixes [30]. The literature's analysis shows that the effects of sewage sludge ash on the technical properties of building material can vary depending on the physical and the chemical properties of the obtained ash. These properties are determined by the origin of the wastewater, the volume of water treated in the plant, the process used to treat wastewater, and the nature and dosage of the additives introduced into the sludge conditioning process [31]. Obviously, the variability of the compositions of the obtained sewage sludge ash depends on the composition of the sewage sludge, and then on the fineness of the ash, the combusting temperature and even the duration of combustion [32]. Hence, the results of past work on the field cannot be generalized. Cement is the most used construction material worldwide. Hence, the present study focuses in the replacement of a part of the cement in the composition of mortar by sewage sludge ash. Several past studies demonstrated such application for mortar as well as concrete [7-14,33-34]. Also, previous researches has revealed that sewage sludge ash exhibits pozzolanic activity [12-13,35].

The aim of the present study is to provide an initial estimation about the possibility of using local sewage sludge ash as a replacement part of cement in mortars as an alternative in order to recycle such waste in construction materials for the preservation of the environment and human health. This study was conducted by following the influence of the incorporation of various amounts of sewage sludge ash on the mechanical and physical properties of the obtained mortar.

II. Material and methods

II.1. Material

The type of Portland cement used for the experiments is CEM II/A-L 42.5 R with 13% of limestone. This cement meets the requirements of NF EN 197-1 [36]. The chemical and physical characteristics of this cement are summarized in Table 1 and Table 2, respectively. The granulometric distribution of cement and sewage sludge ash are shown in Figure 1. The sludge used throughout this study is a dehydrated sewage sludge which was collected from the output of the band press of the municipal wastewater treatment plant of Boumerdès, Algeria. This sludge was sampled according to the international standards ISO 5667-13 [37], dried in an oven at 105°C, combusted at 750°C, and then grinded in the ball mill. Finally, the obtained ash (i.e. sewage sludge ash) was passed through a metallic sieve with 80µm pore diameter. The chemical analysis, physical properties as well as the particle size distribution of sewage sludge ash have been determined and the results are provided in Table 1, Table 2 and Figure 1, respectively.

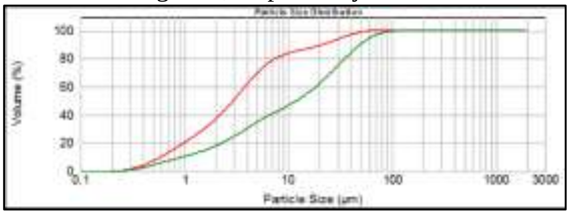

Figure 1. *Grain size distribution curves of cement (green) and sewage sludge ash (red).*

Chemically, the four major oxides present in the sewage sludge ash were SiO_2, Al_2O_3, Fe_2O_3 and CaO which are the main oxides in the cement used here. Bags of 1350 g of certified sand to the NF EN 196-1 standard [38] were used as fine aggregate.

II.2. Dosage and preparation of cement mortar samples

Mortar specimens were prepared by replacing a mass of the cement in the mortar composition. Different percentages of sewage sludge ash (dry basis) were used to replace the same mass of cement. A total of four mixtures were prepared. The reference mix was used as a control mortar with 0% of sewage sludge ash and was labelled CM. The mixtures with 10%, 20% and 30% of sewage sludge ash were denoted M10, M20 and M30 respectively.

The mortar specimens were prepared according to the standard NF EN 196-1. The control mortar preparation had cement to sand ratio of 1:3 (by mass) and water to cement ratio of 0.5. These mixtures were casted into 40x40x160 mm prismatic moulds.

Table 1. *Chemical composition of cement and sewage sludge ash (in % by weight).*

Cementitious materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3	Cl^-	CaO free	LOI*
Cement	17.09	5.12	3.10	63.65	0.93	0.72	0.26	-	1.72	<0.01	2.08	7.02
Sewage sludge ash	32.46	14.41	9.95	18.97	3.31	2.60	1.26	6.60	2.18	0.84	-	6.80

*LOI: Loss on ignition.

Table 2. *Physical characteristics and granulometric parameters of cement and sewage sludge ash.*

Cementitious materials	**Blain fineness (m^2/Kg)**	**Apparent specific gravity (Kg/m^3)**	**Bulk density (Kg/m^3)**	**Granulometric parameters**			
				D10 (µm)	**D10 (µm)**	**D10 (µm)**	**D10 (µm)**
Cement	412.1	-	3060	1.000	1.000	1.000	1.000
Sewage sludge ash	-	863	2722	0.584	0.584	0.584	0.584

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After 24 h of curing, the specimens were demoulded and cured by immersion in a bath of tap water bath for 2, 7, and 28 days then tested according to the standard NF EN 196-1. Table 3 shows the dosage of materials used to prepare mortars.

Table 3. *Dosage of mortar samples.*

Samples	Substitution ratio (%)	Sewage sludge ash (g)	Cement (g)	Sand (g)	Water (ml)
CM	0	0	450	1350	225
M10	10	45	405	1350	225
M20	20	90	360	1350	225
M30	30	135	315	1350	225

II.3. Mechanical and physical tests

With the aim to evaluate the performance of the obtained products (M10, M20 and M30) their mechanical and physical properties were tested at different ages against those of control mortar (CM).
The mechanical tests of the obtained prisms at every age (i.e. 2, 7 and 28 days) were performed according to NF EN 196-1 standard. The mortar samples compressive and flexural tensile strengths tests were performed using the TONICOMP SINTCO DKD-K-23301 Automatic Cement Compression Machine. The flexural strength of M10, M20 and M30 was tested after the curing times discusses previously. For each specimen the two broken pieces resulting from flexural test were used to assess their compression strength. Thus, the reported results are the average of 3 tests for the flexural strength, and the average of 6 tests for the compressive strength. The strength activity index is defined as the ratio of strengths between mortar with sewage sludge ash and the one without (i.e. reference mortar). For each percentage of sewage sludge ash, the average flexural and the average compressive strengths were used to compute strength activity index.
At each curing age, the undamaged fragments resulting from the compression tests were reserved to complete the physical tests; dry bulk density, water absorption and apparent porosity according to ASTM C 642 standard [39].

III. Results and discussion

III.1. Mechanical properties of mortars

The mechanical properties of the specimens of cement mortars with sewage sludge ash (i.e. M10, M20 and M30) and without sewage sludge ash (i.e. control mortar CM) at every curing age (i.e. 2, 7 and 28 days) were evaluated, respectively, by means of flexural strength and compressive strength values. The main objective of these measurements is to measure the influence of sewage sludge ash when used as a part replacement for cement on strengths of mortar. The flexural and compressive strengths of the mortars cured at 2, 7 and 28 days are represented in Figures 2 and 3, respectively, and Table 4 regroups the strength activity index of each average value for both flexural and compressive strengths.

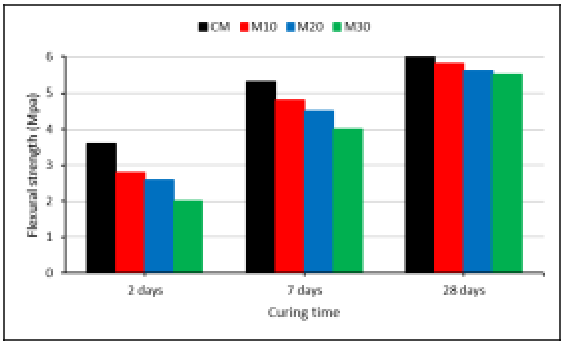

Figure 2. *Flexural strength of mortars at different ages.*

Table 4. *Strength activity index of flexural and compressive strengths of mortars at different ages.*

Specimen	**Strength activity index (%)**					
	Flexural strength			Compressive strength		
	100	100	100	100	100	100
CM	90.4	90.6	92.6	88.6	88.5	101.9
M10	75.0	82.8	88.2	80.9	82.2	96.0
M20	73.1	76.6	77.9	76.8	80.5	95.7
M30	100	100	100	100	100	100

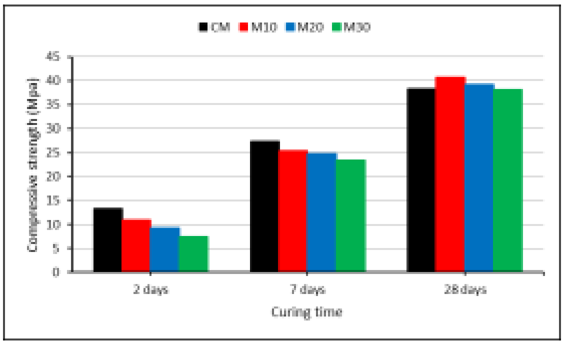

Figure 3. *Compressive strength of mortars at different ages.*

From the data in Figure 2 and Table 4, it is evident that the curing time affects the development of the flexural strength of mortar. The data shows that the flexural strength of all samples increases over time, which confirms that curing age has a significant positive on the development of the flexural strength. Also, the data shows that within the tested range SAA did not stop the development of the flexural strength while the mortar is curing. The flexural strengths of control mortars (CM) at 2, 7 and 28 days were, respectively, 5.2, 6.4 and 6.8 MPa. It can be observed from the data that the addition of sewage sludge ash from 10% to 30% in mortars reduced the flexural strength from 4.7 to 3.8 MPa at 2 days, from

5.8 to 4.9 MPa at 7 days, and from 6.3 to 5.3 MPa at 28 days, respectively. These results in Figure 2 and Table 4 indicate the reduction in the flexural strengths from 9.6% to 26.9% at 2 days, from 9.4% to 23.4% at 7 days, and from 7.4% to 22.1% at 28 days, respectively. Thus, it can be concluded that the effect of sewage sludge ash inclusion in mortars is less significant at low sewage sludge ash ratios. The same behaviour observed here is mentioned in Chen et al., (2013) [11] and Garcés et al., (2008) [34] which used CEM II/A-LL 42.5 R and CEM I 42.5 R cements, respectively. Whereas, the loss of strengths in the present study are lower than those listed in Chen et al., (2013) [11] and Graces et al., (2008) [34].

Figure 3 illustrates the relationship between the compressive strength and the different percentages of sewage sludge ash added to mortar specimens at different curing ages. Table 4 groups the strength activity index of all obtained mortars. As shown in Figure 3, the compressive strength of the mortars specimens increased positively over time. Control mortars (CMs) reached the strength of 24.6, 41.6 and 47 MPa at 2, 7 and 28 days, respectively. When comparing M10, M20 and M30, M10 has a higher compressive strength than M30, and M20 has a higher compressive strength than M30 and this is true regardless of the curing time (i.e. 2, 7 and 28 days). For example, respectively between M10 and M30 the compressive strength drops from 21.8 to 18.9 MPa at 2 days, from 36.8 to 33.5 MPa at 7 days, and from 47.9 to 45 MPa at 28 days (Figure 3). Compared to CM, the compressive strength of M20 and M30 are lower at all curing ages. The compressive strength of M20 and M30 is respectively reduced by 19.1% and 23.2% at 2 days, by 17.8% to 19.5%, at 7 days, and by 4% and 4.3% at 28 days (Table 4). The compression strength of M10 shows a comparable trend to those of M20 and M30 at 2 and 7 days since it is 11.4% and 11.5% respectively lower than those of CM at these same curing periods. However, at 28 days, the compressive strength of M10 is 1.9% better than that of CM (Table 4). These results obtained here are better than those found by Chen et al., (2013) [11] and Garcés et al., (2008) [34] for the curing period from 2 to 28 days and this is true for all samples with sewage sludge ash. The sewage sludge ash particles used for this study (Table 2) are smaller than those used in Chen et al., (2013) [11] which was maximum diameter of 500μm. The Blain fineness of the cement used here (Table 2) is higher than cement used in Garcés et al., (2008) [34]. The finer sewage sludge ash particles and the higher Blain fineness of the cement used here, could explain the better results when compared to Chen et al., (2013) [11] and Garcés et al., (2008) [34]. Compared to CM, although the lesser compressive strength of M20 and M30, their relative values (i.e. strength activity index) of over 95% at 28 days (Table 4) make the use of the combusted sewage sludge from the wastewater treatment plant of Boumerdès in mortar interesting. As shown in Figure 3, all the specimens exhibit compressive strength values close to the nominal strength of 42.5 MPa of the used cement, and comply with the strength requirement of the NF EN 197-1 standard [36]. It can be concluded that the activity of sewage sludge ash was perceptible from 28 days. This age being sufficient to reduce the gap between mortars compressive strengths with and without sewage sludge ash.

According to results in Figures 2 and 3, and Table 4, the development of both flexural and compressive strengths over time is not inhibited when sewage sludge ash is present in the composition of mortar. The decrease in cement content when incorporating sewage sludge ash incorporation is an influencing factor in lowering flexural strength. The results of including sewage sludge ash to mortars is less significant when the ratio sewage sludge ash/cement is low and the curing time is long. In contrast, sample with 10% of sewage sludge ash had slightly higher compressive strength than the control mortars at 28 days. These behaviours when 10% of cement is replaced with sewage sludge ash make it clear that the pozzolanic contribution of sewage sludge ash in the strength's development of mortar which occurred progressively over time. The progression of the hydration reactions is slow in the course of time for the mortar such is described in Li et al., (2021) [4]; Cyr et al., (2007) [8]; Lin et al., (2008) [10]; Baeza-Bortons et al., (2014) [19]; Lin et al., (2008) [33] and Pinarli et al., (1994) [40]. According to de Olivera Andrade et al., (2018) [14], sewage sludge ash may absorb the water and cement used in the mortar preparation. This cement paste hydrates inside the sewage sludge ash particles, leading to a physical interlocking between sewage sludge ash particles and other constituents of mortar. This phenomenon increases the strength of substituted mortars in the course of time. The reduction in strength of mortar when including sewage sludge ash is also due to the dilution of the cementitious materials that lead to lesser hydrated compounds [41-43]. When comparing early ages (i.e. 2 and 7 days) to 28 days, this phenomenon (i.e. binder dilution effect) reduces over time and leads to an improvement in the strength of mortars with sewage sludge ash. The compressive strength improvement of M10 at 28 days is the result of the synergic pozzolanic reactions and the filler effect, which increase compactness [13]. The fine particles of used sewage sludge ash are finer than cement's (Table 2) and they can fill the gaps and contribute to the mortars mechanical evolution. This filler action and pozzolanic activity have probably a synergetic action when only 10% of sewage sludge ash is added to mortar which leads to a compressive strength above CM's at 28 days. The filler effect may increase the porosity of the mortar

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matrix when sewage sludge ash ratio increases. This phenomenon could explain the loss of strength.

III.2. Physical properties of mortars: dry bulk density, water absorption and apparent porosity

The effect of sewage sludge ash as cement replacement material in mortars on the dry bulk density, water absorption and apparent porosity over time (i.e. 2, 7 and 28 days) are calculated and illustrated in Figures 4, 5 and 6, respectively.

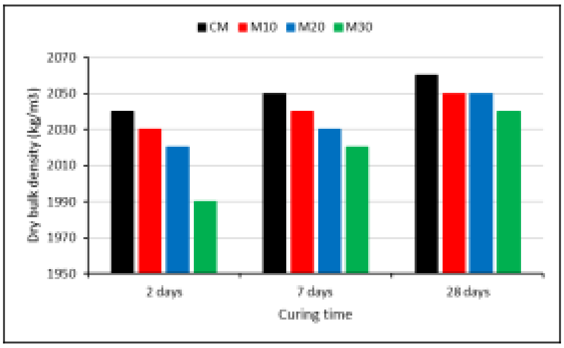

Figure 4. *Dry bulk density of mortars at different ages.*

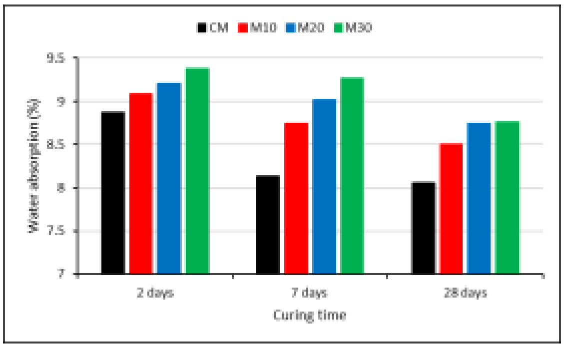

Figure 5. *Water absorption of mortars at different ages.*

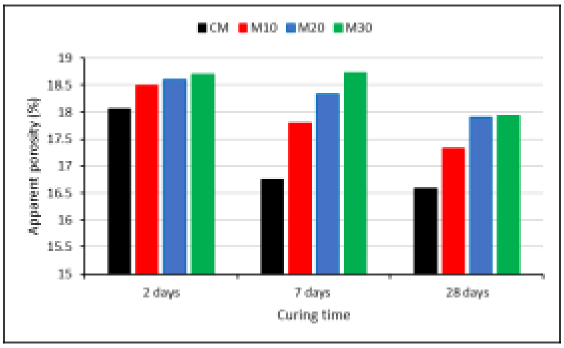

Figure 6. *Apparent porosity of mortars at different ages.*

As shown in Figures 4, 5 and 6, comparing CM to M10, M20 and M30 shows that increasing sewage sludge ash ratio for every curing age led to a decrease in the dry bulk density and consequently an increase in both of the water absorption and the apparent porosity. The above figures also show that the dry bulk density of all mortar samples increased when the curing times increased (i.e. from 2 to 28 days) and, the water absorption and the apparent porosity decreased. Figure 4 shows that dry bulk density values in CM at 2, 7 and 28 days are, respectively, 2040, 2050 and 2060 kg/m3. Increasing the ratio of sewage sludge ash in mortar from 10% to 30% led a fall of the dry bulk density from 2030 to 1990 kg/m3 at 2 days, from 2040 to 2020 kg/m3 at 7 days and from 2050 to 2040 kg/m3 at 28 days, respectively. The dry bulk density of the substituted mortars is over 96% of the dry bulk density of CM. With the regard to Figure 5, CM water absorption over time decreased from 8.87% to 8.06%. The increase of sewage sludge ash percentage in the mortar from 10% to 30% produced, respectively, a rise of water absorption from 9.09% to 9.38% at 2 days, from 8.74 to 9.27% at 7 days, and from 8.5% to 8.76% at 28 days. Figure 6 indicates that the apparent porosity of CM is 18.06%, 16.75% and 16.58% at, respectively, 2, 7 and 28 days of curing time. The apparent porosity of CM was compared to the apparent porosity of M10, M20 and M30. This comparison reveals an increase in apparent porosity of the substituted mortar from 18.49% to 18.7% at 2 days of curing, from 17.8% to 18.72% at 7 days of curing, and from 17.33 to 17.93% at 28 days of curing, for M10 to M30, respectively. This apparent porosity tendency is in accordance with the results in Garcés et al., (2008) [34].

Sewage sludge ash lower bulk density (2722 kg/m3) compared to the bulk density of cement (3060 kg/m3) may be considered the principal reason of the lower bulk density of the substituted mortars [14,41] when compared to CM. From 2 to 28 days, the apparent porosity and water absorption for all mortars (i.e. CM, M10, M20 and M30) decreases and their bulk density increases. These two phenomena are the results of the continuous hydration process filling up the void in the mortar matrix [44]. The above phenome explains the gain over time in both flexural and compressive strengths in all the studied mortar specimens (Figures 3 and 4). In contrast, aside from M10 after a curing time of 28 days, when compared with CM the loss of strength for all mortars with sewage sludge ash is due to the fact that sewage sludge ash increases the porosity of cementitious matrix. Also, sewage sludge ash might vender cement's hydration less effective. For mortar with 10% of sewage sludge ash as cement replacement with a slightly high compressive strength at 28 days, it could be supposed that in this porous cementitious matrix the pozzolanic activity are more important than pores development.

IV. Conclusion

The present work evaluated the feasibility of incorporating different amounts of sewage sludge ash in the composition of mortar as replacement part of cement. The recorded results show a moderate pozzolanic activity and a fine particles' filling action of sewage sludge ash which contribute in the development and improvement of both mechanical and physical properties of the obtained mortar over time. Thus, it can be concluded that it is acceptable to partially replace the cement in the composition of mortar with sewage sludge ash. This application in mortar might have an economical and environmental benefits. That said, additional investigations are still required to determine the long-term impact of sewage sludge ash on the properties of mortar before deploying this application at a large scale.

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