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Review Article

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Turning Algerian Pulp-Mill Black Liquor into a Cementitious Admixture: Laboratory Evaluation and Practical Implications

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ABSTRACT
Black liquor, a lignin-rich waste effluent from Algerian pulp mills, was evaluated as a chemical admixture for cement paste, mortar, and concrete. Dosages ranging from 0.20 % to 0.60 % (by cement mass) were tested. At 0.35 % in paste, water demand fell by 10 % and initial set time shortened from 195 min to 62 min. Concrete containing 0.25 % black liquor and a 7 % water reduction achieved 22 % higher 28-day compressive strength than the control while maintaining workability. Mortar shrinkage likewise decreased by up to 35 %. These results suggest that treated black liquor can serve as a low-cost, eco-friendly plasticiser and strength enhancer for cementitious materials, simultaneously diverting waste from waterways.

Keywords: Black Liquor, Lignin Plasticiser, Sustainable Concrete, Workability Enhancement, Waste Valorisation

Introduction

In Algeria, the paper industry, which has gradually developed since independence, has an important place given, on the one hand, the growing need for paper and, on the other hand, the availability of raw materials, especially esparto grass called ALFA (Halfa as an Arabic name). The use of the ALFA in the Algerian industry and its importance were based on Alfa's unique fibre character, making it one of the finest pulps for high-grade printing paper [1].

For a long time, the Alfa plant was used as feedstock for the Algerian paper industry and produced a large amount of black liquor waste. The black liquor of the paper industry, Algeria's only potential source of lignin material, is still discharged into rivers and sewers, causing serious environmental impacts [2].

Given the nature of this highly polluting waste and its large volume, it is vital to research the possibility of valorising it in the form of a useful product with commercial value, since it can advantageously replace imported products.

Among the numerous possible applications of black liquor in industry, it was chosen for use as an admixture in cementitious materials in this research.

Admixtures are substances introduced into mortar or concrete mixes to alter or improve the properties of fresh or hardened concrete or both [3]. In general, these changes are affected by the influence of the admixtures on hydration, heat liberation, pore formation, and gel structure development. Concrete admixtures should only be considered for use when the required modifications cannot be made by varying the composition and proportion of the basic constituent materials, or when the admixture can produce the required effects more economically.

The present experimental work, revealed that black liquor, a waste product from the paper industry taken from the BABA ALI paper plant, has low viscosity and high solubility, and is composed mainly of lignin, which is usually used as a binder,

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surface-active agent dispersant, and emulsifier [4,5]. Lignin refers to lignosulfonate acids, which are commonly used as water-reducing and fluidity-improving agents in concrete.

This study is significant because it demonstrates a circular-economy path way for Algeria's pulp-mill waste while offering concrete producers a locally sourced plasticiser that may lower costs and reduce embodied carbon. Many researchers have reported that the amount of lignin is continuously increasing around the world [4,5,6]. The authors also reported that current trends in the solution of world energy crisis problems cannot be regarded as environmentally safe and completely admissible until the problem of the utilization of lignin wastes via their conversion into commercial products remains unsolved [7].

The main objective of this paper was to investigate the feasibility of using black liquor as an admixture. The experimental approach followed in this paper aims to study the effects of black liquor on the properties of fresh concrete and hardened concrete [8].

Materials

Black Liquor

The black liquor used in this study was obtained with sodium hydroxide, produced by the National Society of Cellulose and Paper Alfa plant in the BABA ALI region (Algeria). Black liquor is a by-product (waste) of the manufacturing industry's paper paste. This is a concentrated aqueous phase that contains dissolved organic and inorganic material, mostly polysaccharides derived from the degradation of hemicelluloses and cellulose; lignin, which is more or less transformed and degraded; extractable timber; organic and mineral residues; and chemical residues added for cooking (mainly sodium, potassium, sulfate, sulfide, thiosulfate, sulfite and carbonate). It is a brown liquid with a density of 1.004 (very diluted) and has an acrid odor. To increase the amount of dry matter in the solution, black liquor was subjected to heat treatment (100°C). The main properties of the black liquor are shown in Table 1.

Table 1: Analysis of black liquor produced by the National Society of Cellulose and Paper

Density (g/cm^3)	Solid Content (%)	Lignin content (g/l)	PH	Surface tension $dyn.cm^{-1}$
1.1	27	125	10	40

Lignin is the main substance in the composition of black liquor, and has a high surface effectiveness. This property makes concrete or mortar a highly workable material, so the process of finding a water-reducing substance from the heat treatment process of the black liquid from the Algerian paper mills seems very feasible, and the research conducted on this liquid confirms that this substance after heat treatment has the same properties as the substance known as lignosulfonic acid, which is currently used as a water-reducing additive in concrete and mortar, and if it contains a quantity of sugar, it is used as an anti-freeze additive. The purpose of heat treatment of black liquid is to increase its concentration and increase its surface tension, which leads to an increase in the effect of additive activity on the fluidity of fresh concrete and mortar.

Aggregates

The fine aggregates used were dune sand (local natural sand), which was clean and siliceous, and contained very little fine dust or clay. Its characteristics are shown in Table 2. The coarse aggregate is also a local aggregate obtained from crushing limestone rock from the quarry of COSIDER, which is situated in the El-EUCH region. This aggregate has two fractions, 3/8 and 8/15. Its principal characteristics are shown also in Table 2.

Table 2: Some characteristics of the sand and gravel used in the tests

Materials	Density	Porous/dense	compactness	Porosity	Sand equivalent
Sand	2.56	1.64/1.83	36.42/70.76	36.58/29.24	75.4/77.2
Gravel 3/8	2.68	1.28	47.46	52.24	……………….
Gravel 8/15	2.68	1.32	49.25	50.75	…………………

Cement

The cement used in this study was ordinary Portland cement (OPC). It comes from the cement factory of the AIN-TOUTA Company, and is composed of clinker (95%) and gypsum (5%), for the regularization of the setting. The chemical analysis of the cement showed that it conforms with standard NFP 15-301, with a % [MgO + CaO (free)] < 5%. The chemical and physic-mechanical properties of the cement used are presented in Tables 3 and 4, respectively [9].

Table 3: Chemical composition of O.P.C. (C.P. A325)

Content %								
SiO_2	Al_2O_3	CaO	MgO	MnO	K_2O	FeO	SO_3	IR
22.64	4.79	63.6	1.63	1.18	0.2	3.44	2.29	< 3

Table 4: Physical and mechanical properties of O.P.C. (C.P.A325)

Specific density (kg/dm^3)	Blaine fineness m^2/kg	Normal consistency (%)	Setting time(mn) Intial Final	Compressive strength (MPA)	Shrinkage µm/ml
3050	3200	25	210 360	40	800

Preliminary Tests

To determine the effect of black liquor on the physical, rheological, and mechanical properties of cement paste and concrete, several tests have been carried out. However, before starting these tests, trail tests on the black liquor were carried out to evaluate the dry matter in the liquid. The test results are presented in Table 5. The relationship between black liquor and its density is presented in Figure 1.

Table 5: Relationship between black liquor density and dry matter content

Test number	Black liquor density (kg/l)	Dry matter density (kg/l)	Dry matter content by	
			Tests (%)	Calculation (%)
1	1.04	1.5	12	13
2	1.08	1.5	22.5	22
3	1.10	1.5	25.5	27
4	1.17	1.5	41.92	43
5	1.18	1.5	18.10	46

The cement pastes and concrete specimens were demolded after 24 hours of preparation and cured under laboratory conditions (25 °C and 50–60 RH). The compressive strength and shrinkage strength were evaluated after 7 and 28 days of curing under the conditions cited above, and the arithmetic mean of three values was calculated. Cubic specimens (150×150×150 mm) were used for compressive strength measurements, and prismatic specimens (40×40×160 mm) were used for shrinkage measurements.

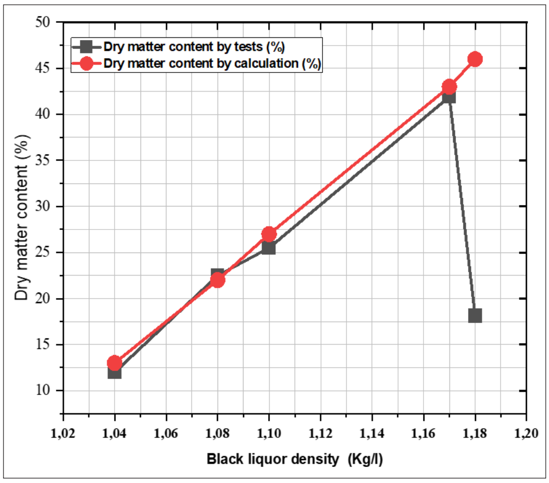

Figure 1: Relationship between black liquor density and dry matter content

Results and Discussion

Effect of Black Liquor on the Setting Time and Consistency of Cement Paste

Initial experiments to determine the effect of adding black liquid to the cement paste used Portland cement CPA 325, and the results can be summarized in the Table 6, which shows the effect of black liquor on the consistency of the cement, and the setting time. The use of black liquor decreases the consistency of the cement. For example, incorporating 0.35% black liquor reduces the water consistency by 10% in comparison with that of the control mixture (without black liquor). On the other hand, the initial setting time decreased from 195 minutes to 62 minutes, which means that the black liquor accelerated the mixture. Moreover, the final setting time was not a major change.

Table 6: Consistence of cement paste as function of black liquor content

Time	Penetration, E (mm)				
h, (mn)	CPA+W	CPA+W+0.20 BL	CPA+W+0.25 BL	CPA+W+0.30 BL	CPA+W+0.35 BL
$10^h.45$	40	40	40	38.5	39
$11^h.00$	40	40	40	37	37.5
$11^h.15$	40	40	40	36	36.5
$11^h.30$	40	40	40	35	36
$11^h.45$	40	40	40	34	36
$12^h.00$	40	40	40	32.5	36
$12^h.15$	39	39	40	32	35
$12^h.30$	38	32	40	31	34
$12^h.45$	33	30	39	30	33
$13^h.00$	26	27	36	28	32
$13^h.15$	22	26	30	27	30.5
$13^h.30$	20	25	27	26	30
$13^h.45$	18	24	25	24	29
$14^h.00$	15	23	24	22	27
$14^h.15$	14	22	23	21	25
$14^h.30$	12	18	21	20	24
$14^h.45$	6	17	18	17	23
$15^h.00$	1	12	16	13	21
$15^h.15$		9	13	10	20

15^{h}.30		5	11	1	19
15^{h}.45		1	7		16
16^{h}.00			1		9
16^{h}.15					5
16^{h}.30					1

The results obtained are presented in the Table 7 and illustrated in Figure 2 and Figure 3, which show that the black liquor admixture reduces the normal consistency of the cement paste, i.e., increases its plasticity. This can be explained as follows: the admixture is concentrated on the contact surface between two phases (water and cement grain), and the physicochemical forces exerted on this surface are loaded. The admixture is also absorbed onto the cement particles, giving them a negative charge, which leads to the particles replying to each other, resulting in stabilization of their dispersion, and air bubbles are also repelled and cannot attach themselves to the cement particles. In addition, the charge causes a layer of oriented water molecules to form around each particle, which prevents a firm approach between the particles, which is why the particles have a high degree of mobility. The setting time of the cement remains almost constant with different percentages of black liquor admixture, but from a dosage of 0.30% onwards, the setting time is significantly shortened (Figure 4). It should be noted that in any case, the setting time exceeds the standard time (45 minutes); this shows that concrete and mortar with black liquor admixtures can be used in a wide range of applications.

Table 7: consistency, water reduction and setting time in function of black liquor content

Black liquor, %	0	0.2	0.25	0.3	0.35
Consistency, %	25	24	23.6	23	22.5
Water reduction (%)	00	04	05	08	10
Initial setting time, min	195	225	183	77	62
Final setting time, min	360	375	378	362	407

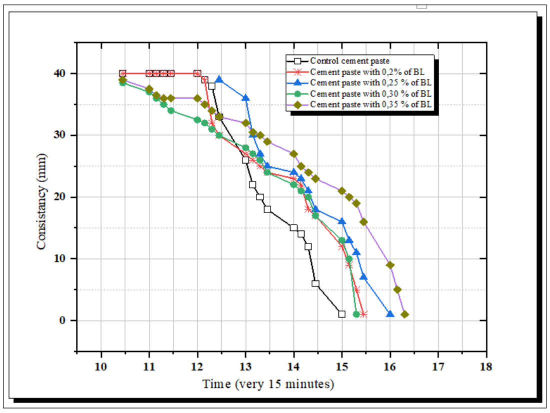

Figure 2: Paste cement consistency in function of time

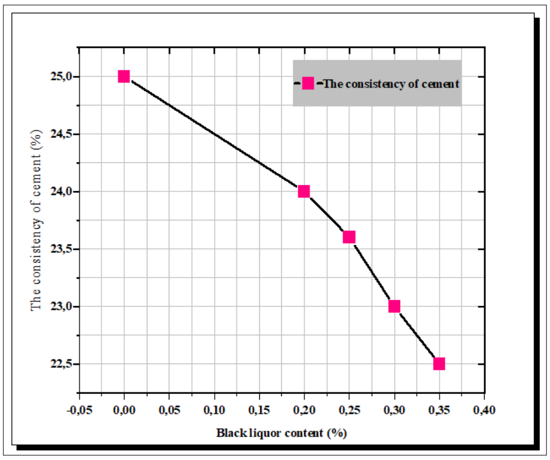

Figure 3: Paste cement consistency in function of black liquor content

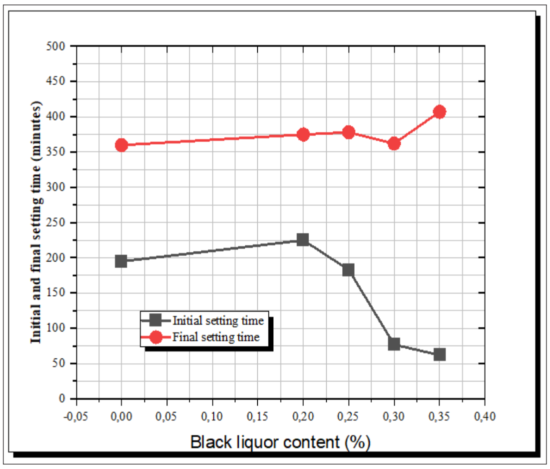

Figure 4: Paste cement setting time in function of black liquor content

Effect of Black Liquor on Cement Paste Evaporation.

Water evaporation is much slower for cement paste containing black liquor than for cement paste not containing black liquor. The results were obtained after exposing the cement paste samples to a dry medium, at a temperature of 35 °C, and the amount of evaporation lost by the paste, was calculated daily. The samples were weighed at the beginning and after each day; evaporation is expressed as the difference between the initial weight and the successive weight, which is presented as a percentage relative to the weight of the water released from the paste. The results obtained from this experiment are summarized in Table 8, which shows the evaporation of water from the cement paste over time. Figure 5 shows the percentage of water evaporation with time. From the Table 8 and Figure 5, we can conclude that the slowing down process of the cement paste is favourable for the complete completion of the dehydration process. Increasing the resistance of the concrete and mortar and providing enough time for heat leakage reduces the phenomenon of cracking of the concrete surface limited by evaporation.

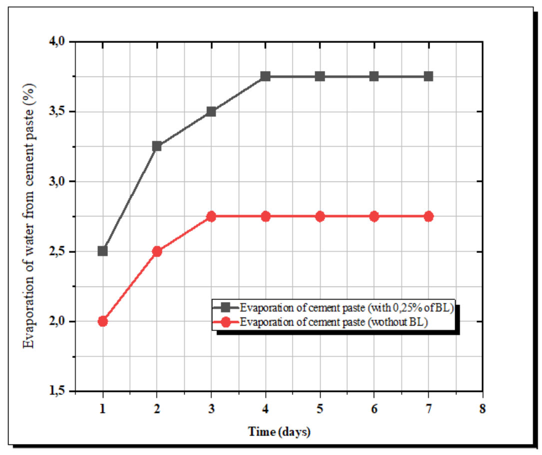

Figure 5: Water evaporation from cement paste (with and without BL) in function of time

Table 8: Rate evaporation of cement pastes in function of black liquor content

Time (days)	Black liquor content (%)	
	Rate of evaporation (%),Without BL	Rate of evaporation (%), With 0.25 BL
1st day	2.5	2
2nd day	3.25	2.5
3rd day	3.5	2.75
4th day	3.75	2.75
5th day	3.75	2.75
6th day	3.75	2.75
7th day	3.75	2.75

Effect of Black Liquor on Mortar

Impact of Black Liquid on Mortar Workability and Volume Weight

We prepared fifteen mortar mixtures containing M_0, M1...M_{14}. The compositions of all mixtures are presented in the Table 9.

- M_0 mortar is the mortar without additives (control),
- Mortars M_1, M_3, M_5, M_7, M_9, and M_{11} are mortars with different proportions of additives (0.05, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45) and no water reduction.
- The M_2, M_4, M_6, M_8, M_{10}, and M_{12} mortars with additives in the above proportions, but with reduced water content and almost the same workability as the control mortar.

The workability of a mortar is expressed by the depth of penetration in the mortar of a standardized cone weighing 300 g with an angle at the top of 30°. The results obtained are shown in the Table 9 and illustrated in Figures 6 and 7.

The densities of the mortars do not differ considerably, showing that they have almost the same compactness. However, compared with that of the control mortar, the workability of the mortars increased with increasing dosage of the black liquor admixture. To keep the workability almost constant, the water content or the W/C ratio of the mortar can be significantly reduced.

Table 9: Mixtures composition of mortars and the results of workability and volumic weight

Specimen appellation	Ratios by weight			Water reduction ΔE (%)	Mortar workability Slump test (cm)	Volume weight (kg/l)
	Cement: sand	Water: cement	Black liquor			
M_0	1/3	0.55	0	0	4.25	2.37
M_1	1/3	0.55	0.05	0	5.57	2.37
M_2	1/3	0.51	0.05	7	2.73	2.37
M_3	1/3	0.57	0.20	0	6.58	2.32
M_4	1/3	0.52	0.20	6	4.35	2.37
M_5	1/3	0.55	0.25	0	7.18	2.30
M_6	1/3	0.51	0.25	7	4.68	2.31
M_7	1/3	0.55	0.30	0	7.86	2.30
M_8	1/3	0.48	0.30	12	4.12	2.35
M_9	1/3	0.55	0.35	0	7.96	2.28
M_{10}	1/3	0.47	0.35	14	4.06	2.305
M_{11}	1/3	0.55	0.40	0	7.98	2.28
M_{12}	1/3	0.46	0.40	16	3.58	2.31
M_{13}	1/3	0.55	0.45	0	8.16	2.30
M_{14}	1/3	0.46	0.45	17	3.41	2.33

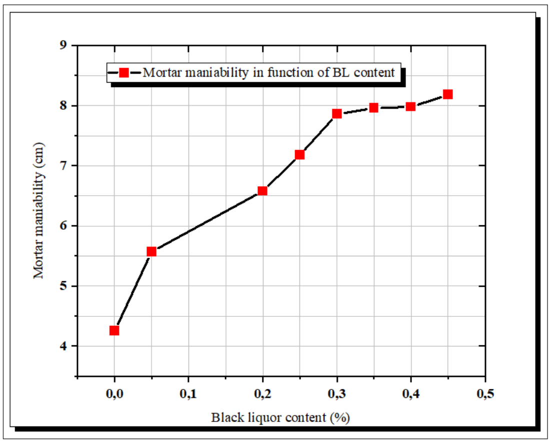

Figure 6: Mortar workability in function of black liquor content

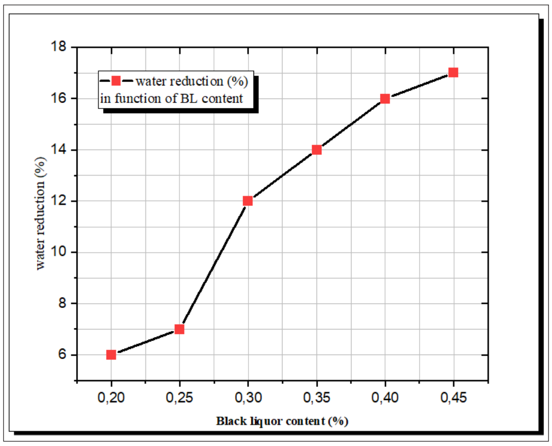

Figure 7: Water reduction in function of black liquor content

Effect of Black Liquor on the Workability Loss of Fresh Mortar

To evaluate the loss of workability of a fresh mortar exposed to a hot climate, three mortar mixes, M_0, M_7 and M_8, were prepared. The initial weights of the three mixtures were determined, and then the mixtures were exposed to open air under sunlight at a temperature of 35 °C. workability tests were carried out every 15 minutes. The results obtained are illustrated in Figure 8. From these results, it can be seen that there was no clear difference between the loss of workability of the mortars without adjuvant and with adjuvant without water reduction. It is obvious that the loss of workability of the mortar with admixture and water reduction is much lower than that of the mortar without admixture. This also reveals the remarkable advantageous effect of the admixture on concrete and mortar made under the hot and humid conditions of Algeria. Resurgence does not occur in mortar with admixture and water reduction, whereas it is serious in mortar without admixture and mortar with admixture without water reduction. This can be explained by the water reduction and high-water retention capacity of the admixed mortar.

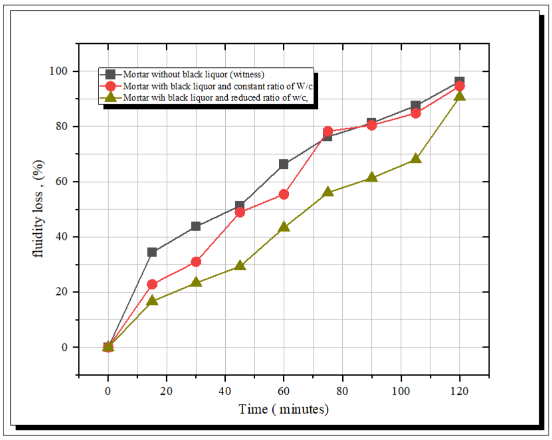

Figure 8: workability loss of Mortar in function of time

Effect of Black Liquid on Mortar Shrinkage Phenomena

Test specimens (4x4x16 cm), were used to determine the shrinkage of the mortar. Four types of mortar were prepared according to the compositions shown in the Table 9. Both mortars were used to mould two similar test pieces. A small screw with a spherical head was placed at the end of each test piece. After 24 hours, the specimens were stripped, and the distance between two screws in each specimen was measured almost every day on a device equipped with a 1 µm precision dial gauge to determine the shrinkage of the mortar and its increase over time. The results are shown in the Table 10 and illustrated in Figure 9.

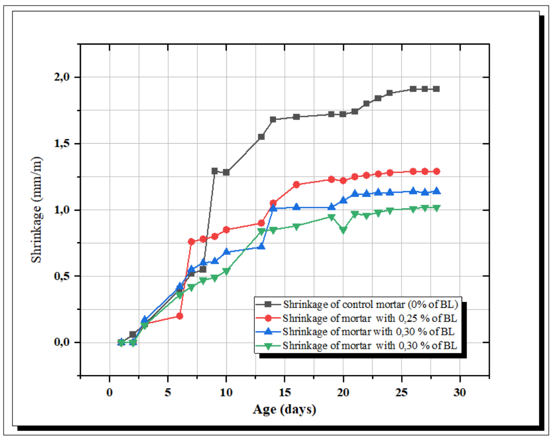

Figure 9: Free shrinkage of Mortar in function of time

Table 10: Results of free shrinkage of mortar in function of time

Age (days)	03	04	06	9	7	10	14	16	19	20	21	22	23	24	26	27	28
M_0	0.14	0.40	0.52	0.55	1.29	1.28	1.55	1.68	1.70	1.72	1.74	1.80	1.84	1.88	1.91	1.91	1.91
M_4	0.14	0.18	0.76	0.78	0.80	0.85	0.90	1.05	1.19	1.23	1.25	1.26	1.27	1.28	1.29	1.29	1.29
M_5	0.17	0.42	0.55	0.60	0.61	0.68	0.72	1.01	1.02	1.02	1.12	1.12	1.13	1.13	1.13	1.13	1.14
M_6	0.13	0.36	0.42	0.47	0.49	0.54	0.84	0.85	0.88	0.95	0.47	0.49	1.58	0.98	1.01	1.02	1.02

According to these results, the mortars with different black liquor dosages always had lower shrinkage than did the mortars without additives (control). The shrinkage decreases when the black liquor dosage is increased (compared to M_4 to M_6). When comparing

M_5 to M_6, it is apparent that mortar that has a black liquor admixture and water reduction shrinks less than mortar without it, even when the black liquor dosage is the same.

Effect of Black Liquid on the Mechanical Properties of Mortar.

To determine the mechanical properties (compressive, tensile, and flexural strengths) of the mortar, 14 mortar mixtures were prepared, and from each fresh mixture, 06 specimens with dimensions of 4x4x4x16 cm were obtained. After 24 hours, the specimens were demoulded and kept in a humid place in the laboratory until the testing process, which was carried out for seven days and 28 days. Table 9, shows the different mortar mixtures used to prepare the tested specimens. The bending test, (3-point method) is carried out with a bending apparatus, and the tensile strength is calculated. The two parts resulting from the bending process in the bend were subjected to compression using a hydraulic press with a force of 300 kN. The results obtained are listed in Table11, and illustrated in Figures 10 and 11.

Table 11: Results obtained of flexural, tensile and compressive strength of mortar

Mortar	Flexural strength (bars) at age of		Tensile strength (bars) at age of		Compressive strength (bars) at age of	
	7 days (Rf7)	28 days (Rf28)	7 days (Rt7)	28 days (Rt28)	7 days (Rc7)	28 days (Rc28)
M_0	33/100	37/100	28/100	34/100	156/100	194/100
M_1	31/94	48/130	27/96	41/121	200/128	281/145
M_2	41/122	54/146	35/125	46/135	239/153	330/170
M_3	40/121	43/116	34/121	37/109	200/128	306/158
M_4	38/115	48/130	33/118	41/121	200/128	313/161
M_5	35/106	37/100	30/107	31/91	187/120	272/140
M_6	40/121	41/111	34/121	35/103	200/128	278/143
M_7	38/115	33/89	32/114	29/85	183/117	244/126
M_8	38/115	38/103	32/114	33/97	208/133	283/146
M_9	37/112	42/114	32/114	35/105	181/116	257/132
M_{10}	38/115	44/119	32/114	38/112	241/154	296/153
M_{11}	32/97	40/108	27/97	34/100	170/109	248/128
M_{12}	38/115	43/116	32/114	37/109	211/135	252/130
M_{13}	37/112	43/116	31/111	36/106	172/110	239/123
M_{14}	40/121	44/119	34/121	38/112	206/132	274/141

Note: The denominator represents the percentage of increase in strength after adding black liquid, considering that the sample without black liquid represents 100%.

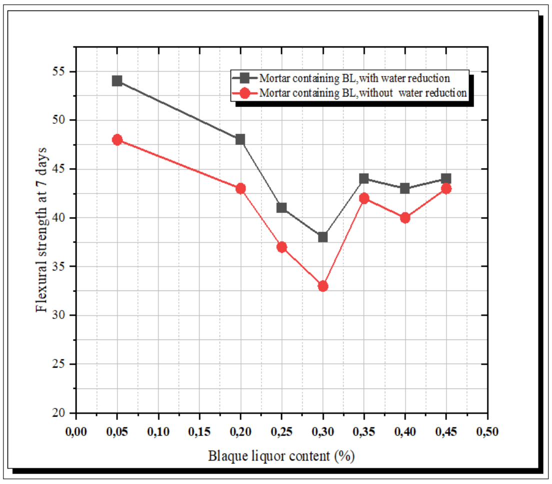

Figure10: Flexural strength at 28 days in function of black liquor content

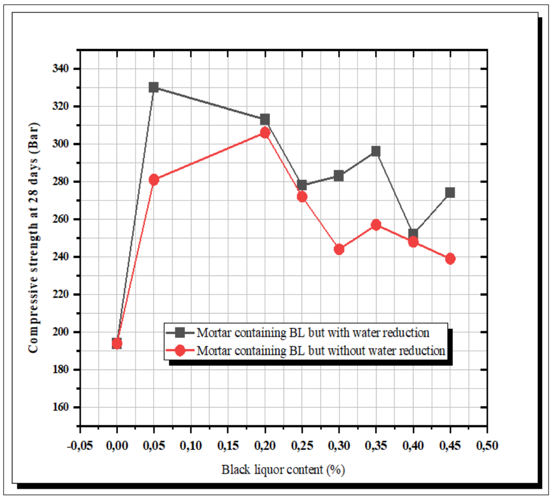

Figure 11: Compressive strength at 28 days in function of black liquor content

From the results obtained, we observe the following:

- The resistance of solid mortars of different proportions to black liquid without water reduction does not vary but rather increases compared to that of typical samples despite their high workability.
- The resistance of the solid mortar in different proportions to black liquid with water reduction increases significantly compared to that of the witness sample; the mortar with 0.05% black liquid (M_2) has the greatest strength compared to the witness sample at 28 days with 170%.

Effect of Black Liquor on Concrete.

The effect of the admixture on the main properties of the concrete was judged by comparing the properties of the concrete without the admixture and with the admixture at different dosages. The composition of the concrete was determined by the SCRAMTAIEV method [10]. The results are presented in the Table. On the basis of this concrete composition, 18 mixes were prepared. Samples B_1, B_2, B_4, B_6, B_8, B_{10}, B_{12}, B_{14} and B_{16} are concrete mixes with admixtures. Mixes B_3, B_5, B_7, B_9, B_{11}, B_{13}, B_{15} and B_{17} are concrete mixes with admixtures but with a reduction in water content and almost the same workability as the control concrete [11].

Fresh properties: workability and volume weight

The concrete workability was measured using a slump test for each black liquor content. The obtained results are shown in Table 12. It should be noted that at a low amount of black liquor (less than 2%), the slump remained unchanged because the added quantity was insufficient.

When the amount of black liquor in the mixture changes from 0.2 to 0.5%, a regular increase in slump is observed. For example, the addition of 0.5% black liquor improved the workability by 125%. In this interval (0.2-0.5% of black liquor), it was observed during tests that the density increased slightly. Furthermore, when the black liquor content exceeded 0.5%, the slump decreased slightly. In the same Figure, it can be seen that the decrease in the w/c ratio in the mix (by decreasing water and increasing black liquor content) remained constant, which confirms that black liquor improves the workability.

As shown in Table 12, using black liquor in the concrete mix as an admixture allowed the quantity of water to decrease by 12% while maintaining the same level of workability. In the presence of black liquor, the components of the mixture were arranged better and made a denser mixture.

Table 12: composition of elaborated concretes and its volume weight and fluidity in function of black liquor

Specimen appelation	Ingredients for 1 m³ of fresh concrete					Water reduction ΔE (%)	workability Slump test (cm)	Volume weight (kg/l)
	Cement (kg)	Sand (kg)	Gravel (kg)	Water (litre)	Black liquor			
B_0	463	532	161	200	0.00	0	4	2.35
B_1	463	532	1161	200	0.20	0	4	2.29
B_2	463	532	1161	200	0.25	0	4.1	2.23
B_3	463	532	1161	186	0.25	7	3.5	2.43
B_4	463	532	1161	200	0.30	0	4.5	2.26
B_5	463	532	1161	182	0.30	9	3	2.43
B_6	463	532	1161	200	0.35	0	5	2.41
B_7	463	532	1161	180	0.35	10	3	2.41
B_8	463	532	1161	200	0.40	0	6	2.36
B_9	463	532	1161	180	0.40	10	3	2.43
B_{10}	463	532	1161	200	0.45	0	8.5	2.37
B_{11}	463	532	1161	178	0.45	11	3	2.42
B_{12}	463	532	1161	200	0.50	0	9	2.49
B_{13}	463	532	1161	189	0.50	8	3	2.44
B_{14}	463	532	1161	200	0.55	0	9	2.41
B_{15}	463	532	1161	180	0.55	10	4	2.43
B_{16}	463	532	1161	200	0.60	0	9.2	2.38
B_{17}	463	532	1161	176	0.60	12	3	2.42

Compressive Strength of Concrete with and Without Admixture

To study the effect of using black liquor in the mix on the mechanical properties of the concrete, 15×15×15 cm³ test specimens were produced. Then, the compressive strengths were measured at 7, 28 and 60 days, with variations in the black liquor content and w/c ratio. The results are shown in Table 13 and illustrated in the Figure 12.

The numerators are the strengths of the concrete (bars), and the denominators are their percentages in relation to the strength of the control concrete (B_0), which is assumed to be 100%.

According to the results obtained, the strength of concrete with different dosages of black liquor does not decrease; but rather increases slightly compared to that of the control concrete (B_0), despite the considerable increase in workability. This is due to the more uniform distribution of cement grains throughout the concrete (11).

Table 13 : Compressive strength of concretes

Specimens appellation	Compressive strength at age of		
	7 days	28 days	60 days
B_0	220/100	289/100	319/100
B_1	245/112	314/105	332/104
B_2	271/123	308/103	342/107
B_3	236/107	364/122	375/118
B_4	232/105	306/103	338/106
B_5	257/114	357/120	340/160
B_6	224/102	301///101	346/109
B_7	264/120	350/117	387/121
B_8	258/117	297/100	332/104
B_9	260/118	339/114	380/119
B_{10}	225/102	299/100	325/102
B_{11}	258/117	340/114	364/114
B_{12}	-	312/104	335/105
B_{13}	-	326/109	371/116
B_{14}	--	309/103	336/105
B_{15}	--	317/106	360/113
B_{16}	224/102	308/103	332/104
B_{17}	278/126	317/106	351/110

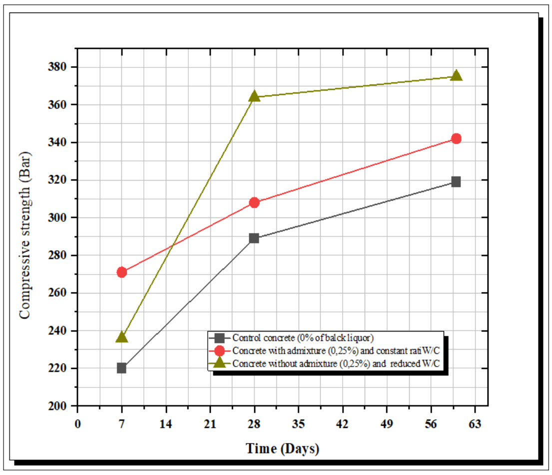

Figure 12: Compressive strength of concrete with and without black liquor addition in function of time

compared with those of the control concrete with the same workability, the strengths of the concrete with black liquor admixtures at different dosages and water reduction at 7 days, 28 days and 60 days increase considerably.

A peak increase in strength (22%) is observed for the concrete with the addition of 0.25% black liquor. Beyond this higher dosage, the increase in strength becomes weaker. This shows that the optimum black liquor admixture content can be equal to 0.25% to obtain a maximum increase in strength, while the increase in fluidity increases with increasing black liquor admixture up to 0.5% of the weight of the cement.

Conclusion

By using black liquor as a superplasticizer, it is possible to control the slump of fresh concrete, which means, that the place ability of concrete might be improved. The concrete with black liquor was denser, which means that the durability improved.

Ultimately, the main benefits of this study are to show the possibility of avoiding the danger represented by the enormous quantities of black liquor thrown into rivers and transforming this liquid waste into an efficient ingredient for cementitious materials. The most important points we can take away from this study are as follows:

After treatment, black liquor is a common plasticizing admixture for mortar and concrete. It has a relatively high lignin content and is superficially active.

- The cement paste consistency can be considerably decreased by the addition of 10% or more black liquor.
- Black liquor significantly reduces the initial setting time of cement, but has no impact on its final setting time.
- Black liquor dramatically improves mortar and concrete flow (usually by 4 to 8 cm of cone slump).
- Concrete with black liquor can have a much lower water content while maintaining the same workability as concrete without admixture (control).
- The mortar with the admixture and water reduction lost significantly less workability over time than did the mortar without the admixture.
- Despite the significant increase in workability, black liquor only marginally strengthened the concrete without lowering the water content.
- The graph in Figure 2 can be used to determine the dry matter content in black liquor and the dosage of liquor in the concrete and mortar.
- Black liquor significantly reduces the shrinkage of mortar, especially mortar with water reduction; this is important because it can lessen or eliminate the risk of cracks forming in concrete and mortar in the hot, dry climate of Algeria.
- Black liquor significantly increases the strength of concrete with water reduction (typically by 14 to 22%) at 28 days, by 17 to 26% at 7 days, and by up to 21% at 60 days.

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