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Synergistic and Antagonistic Effects of Agro-Industrial by-Products and Sewage Sludge on Mortar Properties

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ABSTRACT

The construction industry, particularly the cementitious materials sector, faces major environmental and economic challenges. Cement production, an essential component of mortars and concretes, generates considerable CO_2 emissions and consumes significant natural resources. Simultaneously, many industries produce waste and by-products whose management is problematic. In this context, the valorization of these industrial wastes in construction materials appears as a promising solution, combining reduced environmental impact and resource optimization. This study is part of this dynamic, exploring the potential of two types of industrial waste: sugar industry by-products (sugar scum and molasses) and sewage treatment plant sludge. The main objective is to evaluate the technical feasibility of their incorporation into mortars as partial cement replacement while analyzing their impact on the physical and mechanical properties of the final material. These materials are incorporated at rates ranging from 0% to 20% as cement substitutes. A series of standardized tests are conducted to evaluate the compressive and flexural strengths of mortars at different ages (7, 14, and 28 days). Through this study, we seek to identify optimal dosages that maintain acceptable performance while maximizing the incorporation of these wastes. The results show that sugar scum, at moderate dosages of 5-10%, presents the best potential with limited impact on mechanical properties. Molasses and sewage sludge, on the other hand, lead to more marked decreases in strength, requiring additional optimization strategies.

1. INTRODUCTION

The construction industry is confronted with significant environmental challenges, particularly due to its extensive utilization of cement, the production of which is responsible for approximately 8% of global CO_2 emissions [1]. Concurrently, the effective management of industrial waste is a pivotal concern for a multitude of sectors, including the food industry and wastewater treatment. In this context, the valorization of these wastes in construction materials represents a promising solution that is aligned with the principles of the circular economy and sustainable development [2].

This study focuses on two types of industrial waste: sugar industry by-products (sugar scum and molasses) and sewage treatment plant sludge. The sugar industry annually generates significant quantities of by-products, whose valorization remains a challenge [3]. Similarly, the management of sewage sludge, whose production continues to increase with urbanization, poses significant environmental and economic problems [4].

The incorporation of these wastes into cementitious materials has been the subject of several previous studies. For example, Frías et al. [5] showed that sugarcane bagasse ash could improve certain properties of mortars. Regarding sewage sludge, Yagüe et al. [6] observed that its incorporation at low dosage could be achieved without significantly compromising the mechanical properties of mortars.

Our research aims to deepen these works by conducting a systematic study of the incorporation of these two types of waste into mortars. The principal objective is to assess the impact of the materials on the physical and mechanical properties of mortars, with a particular focus on compressive and flexural strengths. The substitution rates of cement vary from 0% to 20%, thereby enabling the identification of optimal dosages.

This approach not only evaluates the potential of each waste but also highlights the similarities and differences in their behavior within the cement matrix. The stakes are multiple: environmental, by reducing cement consumption and valorizing waste; economic, by finding new outlets for these by-products; and technical, by developing eco-materials with satisfactory properties [7].

2. EXPERIMENT DETAILS

2.1 Characteristics of materials used

In conducting the tests, we used materials that were both locally available and widely used, the characteristics of which had been determined through experimentation at the Civil Engineering and Hydraulics Laboratory (LGCH) of the University of 8 May 1945 Guelma, as shown in Tables 1-5 [8].

Table 1. Sand characteristics

	The Sand Equivalent		Absorption Coefficient	Volumetric Mass	
Characteristics	Visual sand equivalent (%)	Sand equivalent with the piston (%)	(%)	Apparent (g/cm^3)	Absolute (g/cm^3)
	85.21	85.29	2.05	2.63	2.87

Table 2. Mechanical characteristics of gravel

Characteristics of Gravel	5/15	15/25
Coefficient of Los angeles %	24	29
Micro-deval coefficient %	20	22
Apparent density	1.58	1.57
Absolute density	2.75	2.58

Table 3. Physical characteristics of cement

Characteristics	Cement
	CPJ-CEM II-A 42.5
Absolute density	03.10
Apparent density	01.12
Specific surface area	3702

Table 4. Results of mechanical tests on cement

Designation	2 Days	7 Days	28 Days
Flexural tensile strength (MPa)	03.20	04.45	07.01
Compressive strength (Mpa)	14.10	33.48	48.60
Tensile load (KN)	04.40	01.30	02.70
Compressive load (KN)	53.45	45.10	52.25

Table 5. Chemical characteristics of cement

Designation	CaO	Al_2O_3	Fe_2O_3	SiO_2	MgO	Na_2O
Results in %	64.02	05.12	03.30	22.05	01.25	0.12
Designation	**K_2O**	**Cl^-**	**SO_3**	**CaO Free**	**PAF**	**RI**
Results in %	00.52	0.005	01.84	01.40	01.40	02.56

2.1.1 Sand

The sand used is dune sand from the Tebessa's region (Oum Ali) and is notably clean, with a complete lack of fine clay particles. This absence may result in insufficient plasticity in the concrete, necessitating an adjustment by increasing the water content to compensate.

2.2.2 Gravel

The gravel used in this study was obtained from the El Fateh (El Fedjoudje-GUELMA) crushing quarry and comprised fractions of 5/15 and 15/25 of the total gravel.

The gravel employed in the investigation of concrete was subjected to a series of mechanical tests in a laboratory setting.

An impact resistance test (Los Angeles test) was conducted to assess the ability of the gravel sample to resist fragmentation by impact. This test is in accordance with the NF18-573 standard.

Wear Resistance Test: The objective of this test is to measure the quantity of elements smaller than 1.6mm, by subjecting the material to the wear of standardized balls in the Micro-Deval machine.

The results obtained are presented in Table 2.

(a) In accordance with the Los Angeles Coefficient procedure, the threshold is established at 40%. It can be concluded that the gravel in question, which has a Los Angeles Coefficient of less than 40, can be used for hydraulic concrete.

b) The NF P18-572 standard sets the threshold at 35%. If the Micro-Deval Coefficient is less than 35%, which is the case for the gravel in question, The gravel is therefore deemed acceptable for use in concrete.

c) The results shown in the table indicate that $F = 10.36\% \leq 30\%$. It can therefore be concluded that the gravel in question is suitable for use in the production of concrete of an acceptable quality.

2.1.3 Cement

The cement employed is a CPJ-CEMII/A 42.5 grade, obtained from the Hadjar Soud cement plant in the Skikda region of Algeria. This grey cement, which complies with the Algerian standard NA 442/2000, has been formulated for use in high-performance concrete applications and is particularly suited to engineering projects such as bridges, viaducts, and tunnels.

2.1.4 The water used

The water used for mixing was obtained from a tap at a temperature of 28°C and subsequently subjected to chemical analysis (see Table 6). The results substantiate that the product in question complies with all the criteria set forth in the NF P18-404 standards.

The water sample obtained from the laboratory tank has been found to comply with the NF EN 1008 standard (07/2003) for use in concrete mixing.

Table 6. Chemical analysis of the mixing water

Parameter	Result	Unit	Observation
T	28	°C	
PH	7.50	--	
Cl	0.10	Mg/l	Water of good chemical quality
TDS	297	Mg/l	
Conductivity	541	Us/cm	
Salinity	0.20	--	

2.1.5 Admixture

The admixture employed is a high-range water-reducing superplasticizer (in Table 7), designated "SIKAPLASTE 40PRO," which complies with the NF EN934-2 standard and is manufactured by SIKA.

Table 7. A chemical analysis of the admixture

Parameters	Result	Unit	Observation
Density	1.06 ± 0.01	l/m^3	
PH	4.5 ± 1	--	
Dry extract	29 ± 1.5	%	/
Equivalent sodium oxide	≤ 1	%	
Chloride ion content	≤ 0.1	%	

It is classified as a high-range water-reducing superplasticizer [9].

2.1.6 Sugar scum

Sugar scum (in Figure 1), also referred to as sugar refining residue, is a by-product generated during the refining process of sugar cane or sugar beet. During the process of sugar crystallization, the removal of fine particles and impurities from the main mass of sugar crystals is an inherent consequence of the procedure.

This residual material contains fibers, wax, gums, and other organic compounds, thus forming a foam or scum rich in organic matter. The scum used in our work is recovered from the Sora sugar refinery in the Wilaya of Guelma.

Figure 1. Sugar scum used

2.1.7 Molasses

Sugar molasses (Figure 2) is a viscous, dark by-product obtained following the extraction of crystallized sugar from the juice of sugar cane or sugar beet. It is a thick syrup rich in residual sugars, such as sucrose, glucose, and fructose, as well as mineral salts and other organic compounds. The molasses used is recovered from the Cevital refinery in the wilaya of Bejaia.

Figure 2. Molasses used

2.1.8 Sewage sludge

The sewage sludge (Table 8) employed in this study was obtained from the wastewater treatment plant of the city of Guelma, situated in the Héliopolis region in proximity to the Oued Seybouse. The facility is located approximately 1 km north of the city on the right bank of the valley developed by Oued Seybouse. The facility commenced operations on 18 February 2008, with a treatment capacity of approximately 32,000 m³/day during periods of low precipitation and 43,000 m³/day during periods of higher precipitation. The plant is constructed on a plot of 7.8 hectares of agricultural land with a capacity of 200,000 population equivalents. The treatment method employed is the free culture process, otherwise known as 'activated sludge'. The preparation process comprises the following steps:

-Spreading of fresh sludge in the open air for drying, approximately 2 to 3 days (Figure 3).

- Grinding of the dry sludge.
- Sieving of the ground sludge.

The results of the chemical analysis of the sludge were provided by the Guelma wastewater treatment plant.

Table 8. Chemical characteristics of the sludge

Parameters	Methods	Results	Units
Cadmium	ISO 8288	7.5	Mg/kg
Chromium	NF EN 1233	30	Mg/kg
Copper	ISO 8288	102	Mg/kg
Nickel	ISO 8288	36	Mg/kg
Zinc	ISO 8288	395	Mg/kg

Figure 3. Dry sludge

3. COMPOSITIONS

The tests are carried out on a mortar with a standard composition of cement, sand, and water. The tested specimens are 4×4×16 cm^3 in dimensions.

From this base mortar (Table 9), we substituted a part of the cement with variable proportions of 0%, 5%, 10%, 15%, and 20% of scum, molasses alone, combined, and sludge, as shown in Figure 4.

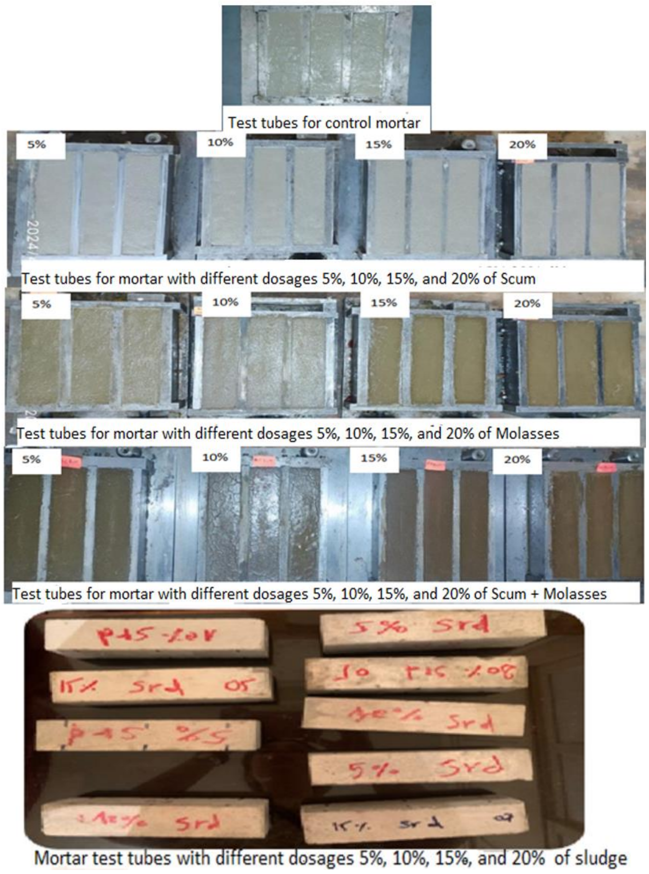

Figure 4. Tested specimens

Table 9. Compositions of different mortars

% \ Mass (kg/m³)	Sand	Water	Admixture	Scum	Molasses	Sludge	Cement
0%	1350	2475	9	/	/	/	450
5% (Scum)	1350	2475	9	22.5	/	/	427.5
10% (Scum)	1350	2475	9	45	/	/	405
15% (Scum)	1350	2475	9	67.5	/	/	382.5
20% (Scum)	1350	2475	9	90	/	/	360
5% (Molasses)	1350	2475	9	/	22.5	/	427.5
10% (Molasses)	1350	2475	9	/	45	/	405
15% (Molasses)	1350	2475	9	/	67.5	/	382.5
20% (Molasses)	1350	2475	9	/	90	/	360
5% (Écume &Molasses)	1350	2475	9	22.5	22.5	/	405
10% (Écume &Molasses)	1350	2475	9	45	45	/	360
15% (Écume &Molasses)	1350	2475	9	67.5	67.5	/	315
20% (Écume &Molasses)	1350	2475	9	90	90	/	270
5% (Sludge)	1350	2475	9	/	/	22.5	405
10% (Sludge)	1350	2475	9	/	/	45	360
15% (Sludge)	1350	2475	9	/	/	67.5	315
20% (Sludge)	1350	2475	9	/	/	90	270

4. TESTS ON HARDENED MORTAR

4.1 Three-point bending test: Standard NF EN 1015-11

The bending test measures the breaking strength of a material. This test is performed on mortar specimens placed between three support points. A force is applied at a constant speed to the central point with an increasing force until rupture shown in Figure 5.

The test was carried out on prismatic specimens (4×4×16) stored in open air.

The tests were conducted on mortars at 7, 14, and 28 days. The flexural tensile strength was calculated using the following formula:

$$R_f = \frac{1{,}5FL}{B^3} \quad (1)$$

where,

R_f: Flexural tensile strength in MPa;

F: Applied load at rupture in N;

L: Distance between supports (L = 12 cm);

B: Side of the square section of the specimen (B = 4 cm).

Figure 5. Flexural rupture mode

4.2 Compression test

The term "compressive strength" is used to describe the capacity of a material or structure to resist forces that act to reduce its dimensions through compression or crushing.

The test was carried out on the halves of the prismatic specimens obtained after the flexural tensile test. Figure 6 illustrates the compressive rupture mode.

Figure 6. Compressive rupture mode

5. RESULTS AND INTERPRETATION

5.1 Progression of the strength in the tested mortars

5.1.1 Three-point bending test

Figures 7-10 present the flexural strength values of mortars incorporating different dosages of sugar scum, molasses or a mixture of scum + molasses, and sludge, for specimens stored in open air and tested at 7, 14, and 28 days.

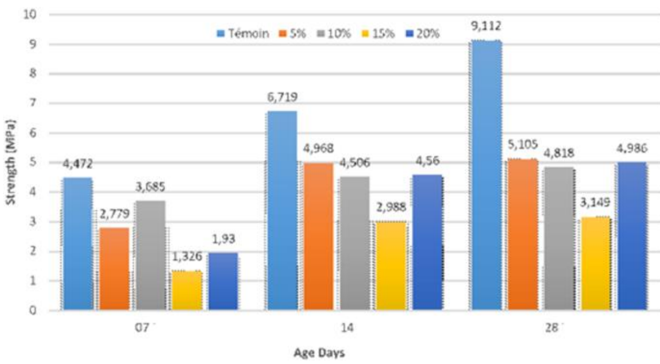

Figure 7. Variation of the flexural strength of mortar as a function of scum dosage alone

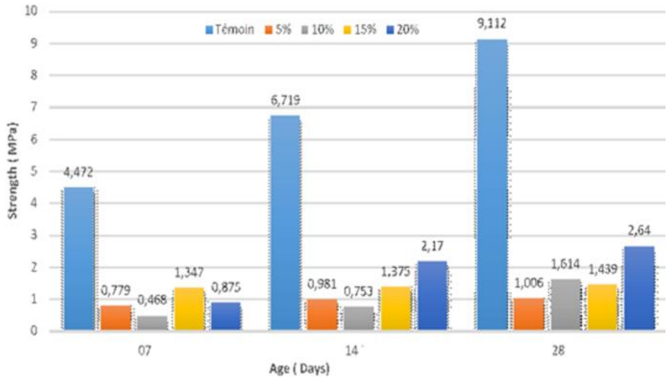

Figure 8. Variation of the flexural strength of mortar as a function of molasses dosage alone

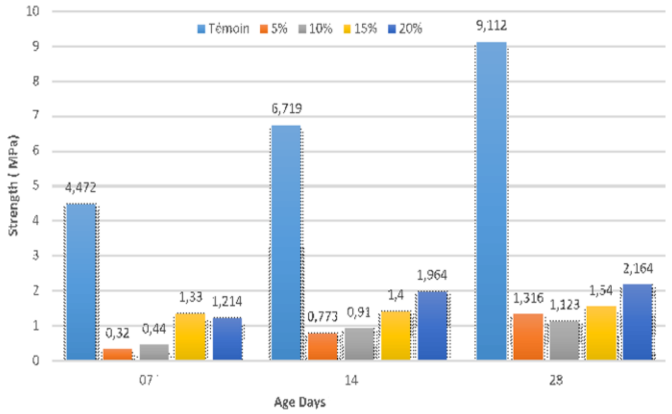

Figure 9. Variation in the flexural strength of mortar as a function of scum and molasses dosage

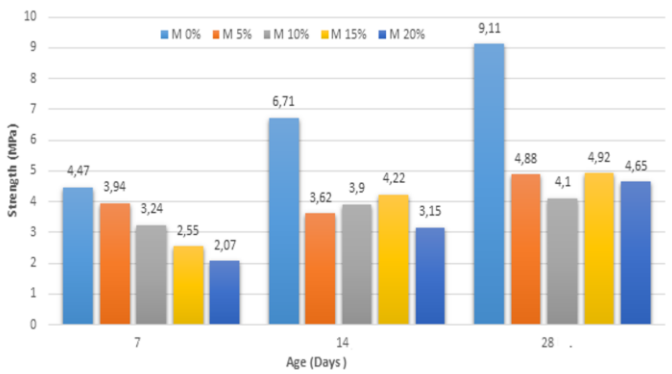

Figure 10. Variation of mortar's flexural strength with sludge dosage

<u>Analysis of flexural results:</u>

1. Scum alone:
- At 7 days, the addition of scum decreases the flexural strength compared to the control, and this decrease is more significant with increasing scum percentage.
- At 14 days, an improvement in flexural strength is observed compared to 7 days, but the values remain below the control.
- At 28 days, the flexural strength continues to increase but remains below the control, except for 20% scum which is similar to the control.

Therefore:
- Up to 10% scum, an initial decrease in strength is observed at 7 days, followed by a progressive improvement up to 28 days.
- At 15% and 20% scum, the strengths remain well below the control mortar, regardless of age.

2. Molasses alone:
- The addition of molasses significantly decreases the flexural strength at all ages and for all percentages, compared to the control.
- A slight increase in strength is observed with age, but the values remain very low compared to the control.

Therefore:
- For all dosages, the strengths are very low at 7 and 14 days, well below the control.
- A slight improvement is noted at 28 days, but the values remain low, except for 5% molasses.

3. Scum + Molasses:
- The mixture of scum and molasses also decreases the flexural strength compared to the control.
- A slight increase is observed with age, but the values remain below the control.

Therefore:
- As with scum alone, an initial decrease in strength is observed at 7 days.
- Between 7 and 28 days, the strengths increase but remain below the control for all dosages.

4. Sludge:
- The incorporation of sludge into the mortar results in a decrease in flexural strength compared to the control mortar. This strength decrease is more pronounced at early age (7 days) and for high sludge dosages.
- At 7 days, the strength losses compared to the control are approximately 12% for 5% sludge, 28% for 10%, 43% for 15%, and 54% for 20%.
- At 14 days, the respective decreases are 46% (5%), 42% (10%), 37% (15%), and 53% (20%).
- At 28 days, the strength decreases are lower: 46% for 5% sludge, 55% for 10%, 46% for 15%, and 49% for 20%.

Therefore:
- The control mortar without sludge addition (M 0%) presents the best flexural strengths at all ages: 4.47 MPa at 7 days, 6.71 MPa at 14 days, and 9.11 MPa at 28 days.

<u>Interpretation of flexural test results:</u>
- Sugar scum, rich in cellulosic fibers, seems to provide a progressive reinforcement effect to the cement matrix up to 10%, in accordance with other studies [10, 11].
- However, beyond 15%, the excess organic matter likely creates additional porosity and weakens the mortar [12].
- Molasses alone, rich in sugars, seems to have a very detrimental effect on the development of mortar flexural strengths, probably by disrupting the setting and hydration of the binder [13].
- The scum + molasses mixture appears to be less unfavorable than molasses alone but remains inferior to sugar scum for flexural strength gains.
- A progressive recovery of flexural strength is noted between 7 and 28 days for mortars with sludge, particularly for dosages of 15% and 20%.

In summary,
- The incorporation of sugar scum alone at moderate dosages (≤10%) allows for improvement in the flexural strength of mortars, probably due to a reinforcing effect of the fibers.
- Conversely, the addition of molasses alone leads to a very marked degradation of strengths, regardless of the

content.

- The scum + molasses mixture seems to attenuate the unfavorable effect of molasses alone but remains inferior to the gains provided by sugar scum.
- An optimal dosage of about 5 to 10% sugar scum seems most suitable for improving the flexural strength of mortars, in accordance with the literature on cellulosic additions.
- The addition of sludge harms the flexural performance of the mortar, particularly at an early age and for high dosages. However, a more marked strength recovery is observed at 28 days for mortars with 15 to 20% sludge.

This is attributable to the detrimental effects of sludge on the development of the cement structure [14-16].

5.1.2 Compression test

Figures 11-14 present the compressive strength values of mortars incorporating different dosages of sugar scum, molasses or a mixture of scum + molasses, and sludge, for specimens stored in open air and tested at 7, 14, and 28 days.

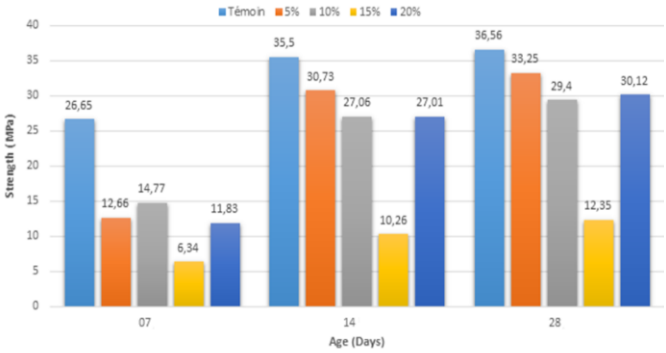

Figure 11. Variation of the flexural strength of mortar as a function of scum dosage

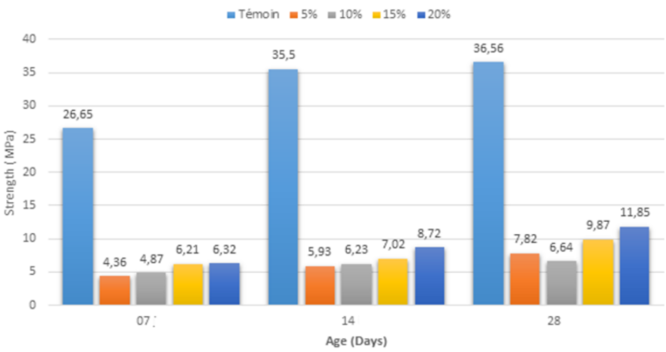

Figure 12. Variation of the compressive strength of mortar as a function of molasses dosage

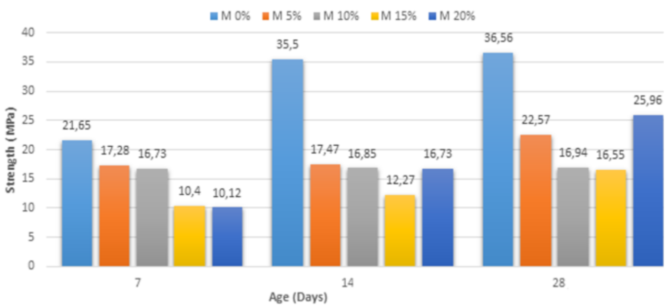

Figure 13. Variation of the compressive strength of mortar as a function of scum + molasses dosage

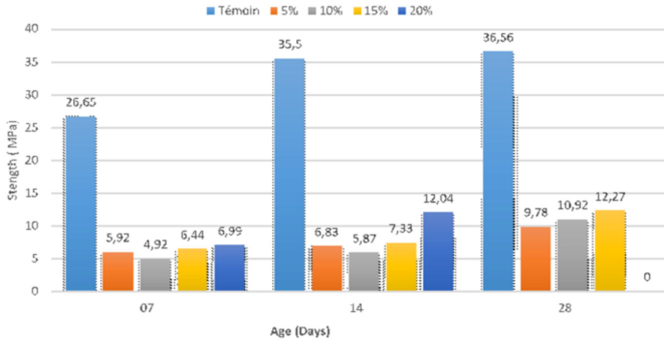

Figure 14. Variation of the compressive strength of mortar specimens as a function of sludge dosage

<u>Analysis of compression results:</u>

1. Sugar scum alone

- At 7 days, the addition of scum decreases the compressive strength compared to the control.
- At 14 days, the compressive strength improves for all scum percentages but remains below the control, except for 5% scum.
- At 28 days, the strength continues to increase but remains below the control for percentages higher than 5%.

Therefore:

- Up to 10% scum, a moderate decrease in compressive strengths is observed compared to the control mortar, in the order of 15-20% at 28 days.
- At 15% scum, the strengths drop significantly with decreases of 62% at 7 days and 66% at 28 days.
- 20% scum seems to be a limited dosage, with reduced losses of 18% at 28 days.

2. Molasses alone

- The addition of molasses considerably decreases the compressive strength at all ages and for all percentages, compared to the control.
- A slight increase is observed with age, but the values remain very low compared to the control.

Therefore:

- For all molasses dosages, the compressive strengths are greatly affected, particularly at early ages (7 and 14 days).
- At 28 days, the strength decreases remain significant: -73% for 5%, -70% for 10%, -66% for 15%, and -66% for 20%.

3. Scum + Molasses:

- The mixture of scum and molasses also decreases the compressive strength compared to the control.
- A slight increase is observed with age, but the values remain below the control for all percentages.

Therefore:

- The scum/molasses mixture also results in marked strength decreases compared to the control.
- The losses at 28 days are 79% for 5%, 82% for 10%, 73% for 15%, and 68% for 20%.

4. Sludge

- At 7 days, the strength drops by about 17% for a 5% sludge dosage, 34% for 10%, 39% for 15%, and 39% for 20% compared to the control mortar.
- At 14 days, the strength losses are around 51% for 5% sludge, 53% for 10%, 65% for 15%, and 53% for 20%.
- At 28 days, the respective decreases are about 38% for 5%, 54% for 10%, 55% for 15%, and 29% for 20%.

Therefore:

- The control mortar without sludge addition (0%) presents the highest strengths at all ages, reaching 36.56 MPa at 28 days.

- The addition of sludge results in a decrease in the compressive strength of the mortar compared to the control. This decrease is more significant as the sludge dosage increases.

- The mortar with 20% sludge seems to show a notable strength recovery between 14 and 28 days, reaching 25.96 MPa at 28 days.

<u>Interpretation of compression test results:</u>

- Sugar scum, rich in cellulosic fibers, seems to have a moderate effect on compressive strengths up to 10%, probably due to a reinforcing effect [17]. But beyond this, the organic excess creates porosities that significantly degrade the properties [12].

- Molasses, rich in soluble sugars, seem to significantly disrupt the hydration process and the structuring of the cement matrix, leading to heavy strength losses.

- The scum/molasses mixture seems to cumulate the adverse effects of both compounds, resulting in the highest strength decreases observed.

- Sludge: The incorporation of sludge in the mortar degrades its mechanical performance in compression, particularly at an early age and for high dosages. However, a 20% sludge dosage seems to allow the mortar to regain part of its strength in the longer term (28 days).

Therefore:

- The incorporation of sugar scum at moderate dosages (<10-15%) seems to be the least penalizing for the compressive strengths of mortars.

- The addition of molasses, alone or combined with scum, generates very marked decreases in compressive strengths, probably by severely disrupting hydration.

- A maximum dosage of about 10% sugar scum seems to be an acceptable compromise to limit compressive strength losses to 15-20%.

- The use of these sugar by-products in mortars will need to be finely controlled to avoid too significant degradations of mechanical properties.

- However, a 20% sludge dosage seems to allow the mortar to regain part of its strength in the longer term (28 days).

- These results are consistent with the literature on the incorporation of cellulosic fibers and organic additives rich in sugars, and the incorporation of sludge in cementitious matrices, due to the disruptive effects of these wastes on hydration and the formation of the cement matrix [14, 18].

Tests revealed contrasting behaviors depending on the type of substitution. Adding sugar foam alone at moderate dosages (≤10-15%) had only a limited impact on mechanical strengths, with a possible improvement in strength due to a reinforcement effect by the cellulosic fibers. However, beyond 15%, an excess of organic matter degraded performance. Conversely, incorporating molasses alone, rich in disruptive sugars, led to significant reductions in mechanical strengths and considerable increases in water absorption capacity and internal humidity, regardless of the content. These effects were amplified for foam + molasses mixtures, combining the adverse impacts of both substitutes.

In summary:

1. Flexural Strength: The trends observed for flexural strength generally follow those of compressive strength. The different behavior of foam compared to molasses and sludge could be explained by the specific nature and chemical composition of these additives, influencing their interaction with the cement matrix [2].

2. Compressive Strength: The moderate decrease in strength with foam up to 10% substitution is promising and comparable to the results obtained by Cordeiro et al. [3], with bagasse ash. However, the more marked decrease in molasses and sludge requires particular attention. The recovery in strength observed at 28 days for 20% sludge is interesting and could be related to late pozzolanic reactions, as suggested by Yagüe et al. [6].

6. CONCLUSIONS

This study on the incorporation of by-products from the sugar industry and sewage sludge into mortars has revealed promising results while highlighting some challenges. Sugar foam, at moderate dosages (5-10%), appears to be the most promising additive, with limited impact on mechanical properties. These results are in line with the work of Frías et al. [5], on bagasse ash, suggesting the potential of sugar industry by-products as mineral additions in cementitious materials.

Molasses and sewage sludge, although causing more marked decreases in mechanical strengths, show interesting behaviors, notably the long-term strength recovery observed for sludge. These observations are consistent with those of Yagüe et al. [6] and emphasize the importance of a long-term approach in evaluating these materials.

The results obtained pave the way for new formulations of eco-materials but require optimization strategies, particularly for molasses and sewage sludge. These strategies could include:

1. Pre-treatment of additives to improve their reactivity and reduce their negative impact on mechanical properties.

2. The use of ternary approaches, combining these additives with other more reactive mineral additions, as proposed by Mehta [2].

3. Optimization of curing conditions to promote the development of long-term properties.

In conclusion, this study demonstrates the potential for valorizing by-products from the sugar industry and sewage sludge in mortars, thus contributing to sustainable development goals in the construction industry. However, it also highlights the need for a balanced approach, taking into account not only environmental benefits but also the technical performance and durability of the resulting materials.

These results align with efforts to reduce the carbon footprint of the cement industry [1] and open up interesting prospects for the valorization of industrial waste. Further research is needed to optimize formulations, evaluate long-term performance, and study the economic feasibility of large-scale use of these additives in the production of sustainable construction materials.

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NOMENCLATURE

CO_2	Carbon dioxide
CaO	Calcium oxide (quicklime)
Al_2O_3	Aluminate
MgO	Magnesium oxide
Cl^-	Chloride
SO_2	Sulfur dioxide
Fe_2O_3	Ferric oxide
K_2O	Potassium oxide
SiO_2	Silicon dioxide
Na_2O	Sodium oxide
T	Temperature
CI	Chloride ion content
CPJ	Composite portland cement
TDS	Total dissolved solids, Mg/l
NA	Algerian norms
NF	French norms