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Optimization of Cellular Concrete Formulation with Aluminum Waste and Mineral Additions

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Abstract

The paper aims to study cellular concrete with a new approach of formulation without an autoclave, with the use of aluminum waste and incorporation of mineral additions into the sand and evaluate its physical and mechanical properties. In this experimental study, two types of cellular concrete are prepared, based on crushed and dune sand with the incorporation of 15% of the slag and 10% of pozzolana, as sand replacement. An experimental program was performed to determine the compressive strength at 28 days, the density and thermal conductivity of the confected cellular concrete. The obtained results showed that concretes prepared with crushed sand developed better mechanical resistance compared to the dune sand. It is also noted that the concretes containing the mineral additions provide a substantial increase in compressive strength in particular slag. Furthermore, cellular concretes with sand dunes offer better thermal conductivity, compared to those with crushed sand. The use of the additions reduces the Water/Binder (W/B) ratio and leads to a lower thermal conductivity regardless of the used sand nature. The outcome of the present study here in could present a modest contribution for the production of cellular concrete with local materials in particular dune sand, active mineral addition and aluminum waste. The physical and mechanical properties obtained from this new composition are estimated acceptable compared to those of the industry-prepared cellular concrete product.

Keywords: Cellular Concrete; Dune Sand; Crushed Sand; Mineral Addition; Resistance; Conductivity.

1. Introduction

In recent years, cellular concrete is widely used as it has the potential to be an alternative to ordinary concrete, it reduces dead loads on the structure and contributes to energy conservation and reduces production and labour costs during construction and transport [1] and also for the development of new raw materials of cement, foaming agents and fillers for specific applications of cellular concrete. Cellular concrete is generally defined as a lightweight product, also called lightweight cellular concrete or low-density concrete, composed of Portland cement, silica-cement, cement-pozzolana, lime-pozzolana or silica-lime [2, 3]. The main advantages of cellular concrete compared to conventional Portland cement concrete are weight reduction up to 80%; excellent acoustic and thermal isolation; high resistance to fire; lower costs in raw materials, easier pumping and application; and finally it does not need compacting, vibration or

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levelling [4]. It is either a cement paste or a mortar, classified as lightweight concrete, its construction applications as light and semi-structural material are becoming more frequent [5, 6].

Today, in order to design sustainable building materials, all the knowledge gathered on materials science as well as modern techniques can solve problems [7]. The hydrothermal synthesis of a calcium silicate binder obtained from a mixture of lime and silica [8, 9]. The alveolar appearance is induced by the addition of aluminum powder in the basic mixture, which leads to the release of hydrogen. The bubbling is accompanied by the formation of C3AH6 hydrates produced by reacting the aluminum hydroxide with the lime, leading to a sufficient firming of the dough to stabilize the shape of the expanding material. A curing treatment, usually a hydrothermal synthesis, then promotes the formation of tobermorite C5S6H5 (calcium silicate) by reaction of the lime on the silica. In their current range of density (400 to 600 kg/m^3), these materials have an acceptable compromise in terms of thermal insulation and mechanical performance, the thermal conductivity of such materials remains between 0.1-0.3 W/m.°K. The mechanical properties are sufficient to guarantee the use of constructive block concrete with a structural role on one or two-stage heights (compressive strength of 4 to 7 MPa) [9, 10].

With the contemporary concept of sustainable development, which is based on the main actions: social, economic and environmental, Scientific research, which is the driving force behind all development, is obliged to harmonize with this approach by meeting the economic and ecological requirements of this concept. This reflects the current trend of research into new building materials that meet techno-economic and environmental requirements such as cellular concrete and the valorization of local materials for the development of these high-performance materials, ecological and at the lowest cost.

Several recent studies have been conducted on the effect of the use of construction waste and industrial waste for the improvement of the performance of cellular concrete. The partial replacement of cement in the production of cellular concrete by the incorporation of both Silica Fumes (SF) and residual marble powder (WMP) considered as industrial waste characterized by severe environmental pollution and low recycling rate, was examined [11] to assess its effect on the mechanical properties and durability of cellular concrete Overall, the appropriate SF and WMP cement replacements have significantly improved the mechanical and durability properties of the aerated concrete, especially after sulphate acid attack and cellular concrete with 10% SF and 5-20% WMP had optimal mechanical properties and durability.

Fly ash was used to fill lightweight cellular concrete as the main mixture to promote complete technical applications; the reinforcement mechanism was studied concerning microstructures, including porosity and skeletal characteristics. Through examination and analysis the relationship between microscopic parameters and compressive strength, as well as wet bulk density and the mechanism of skeletal structure evolution, the results showed that the difference comes from the effects of ball and particle filling of fly ash before 28 days. Whereas after 28 days, the fly ash pozzolanic reaction and the cement hydration reaction mutually promote densification of the skeletal structure and the recommended fly ash content is about 25% [12]. An experimental cellular concrete study was conducted to assess the effect of fly ash by partially replacing cement from 0 to 50% and replacing river sand with quarry dust (0 to 50%) for various mixtures. The study concluded that the partial replacement of 30% of the fine sand and quarry dust combination produced better results compared to those of conventional foam concrete [13].

A new eco-cellular concrete has been developed with 100% waste [14]. Blast Furnace Slag (BFS) was the precursor, Rice Husk Ash (RHA) was used as a source of silica, biomass ash from Olive stone (OBA) as an alkaline source and recycled aluminium foil (AR) The functional characteristics of the materials were studied and compared with those established by the European standard and the Committee 523 of the American Concrete Institute (ACI). A density, compressive strength and thermal conductivity of 660 kg/m^3, 6.3 MPa and 0.20 W/m.°K respectively are obtained for the eco-cellular concrete studied. Another approach envisaged the use of lightweight cellular concrete incorporating more environmentally friendly alternatives. The cement was partially replaced by blast furnace slag. The purpose of this study was to provide a protective layer on a weak platform in a pavement structure. Three different densities of lightweight cellular concrete were considered. It consisted of 400, 475 and 600 kg/m^3, containing 80% Portland cement, 20% slag, water and pre-foam. It was determined that the material had sufficient compressive strength to apply the pavement at all densities considered. It was also found to have a higher stiffness than the typical granular material [15].

In this regard and for a positive contribution to sustainable development, the use of mineral additions in Algeria in the manufacture of concrete, in particular cellular concrete allows the recovery and recycling of materials that would otherwise have been sent to landfill, minimizes the consumption of natural raw material and helps reduce CO_2 emissions. These mineral additions are of natural origins such as the limestone and volcanic rock of the Beni-Saf pozzolana in Algeria, or of industrial origins, such as the blast furnace slag from the El Hadjar plant in Algeria which produces about 380 kg of slag per ton of cast iron, the annual production of pig iron is about one million tons [16]. And indeed, Algeria is known for its mountainous nature (source of limestone) in the north and by its sand dunes which occupy more than 60% of the surface of the country mainly, the desert area in the south.

In this respect, the idea of promoting the use of dune sand and the active addition of pozzolana and slag in the production of cellular concrete, the aim of which was to develop local resources, that appeared interesting from the economic and environmental point of view [17]. In addition to the recovery of waste aluminum powder, manufactured by the local company METANOF, which are used as a reactive agent for the expansion of cellular concrete, noting that the quality of aluminum affects the reaction of expansion. Indeed, the use of lightweight materials in construction, especially in the southern regions of Algeria ensures better thermal comfort of premises and contributes to the reduction of the housing energy consumption both in winter and summer.

In this context, we are making an attempt to use and valorize local materials for the manufacture of cellular concrete incorporated in the grain size skeleton of dune sand of the Oued-Souf region and crushed sand of the Bordj region. Mineral additions (Pozzolan, blast furnace slag) by partial substitution in the presence of slaked lime and aluminum powder as an expansive agent are used in the study. However, the presence of this material in a mixture implies the use of a higher water-binder ratio (W/B) which generates an increment in the water absorption of the final product [18]. The reason that could justify such use of the superplasticizer in our formulation. Generally, this admixture seems to improve the mechanical characteristics of a concrete; compactness is favoured at the expense of porosity, but if we aim to improve the thermal properties it is the intervention in the opposite direction that is coupled in the obtained product.

In front of the double challenges, it comes our experimental work to reach a compromise, while retaining good thermal characteristics and improving the mechanical behavior of cellular concretes by an intervention qualified as chemical rather than physical. The methodology used in this work is summarized in the flowchart presented in Figure 1.

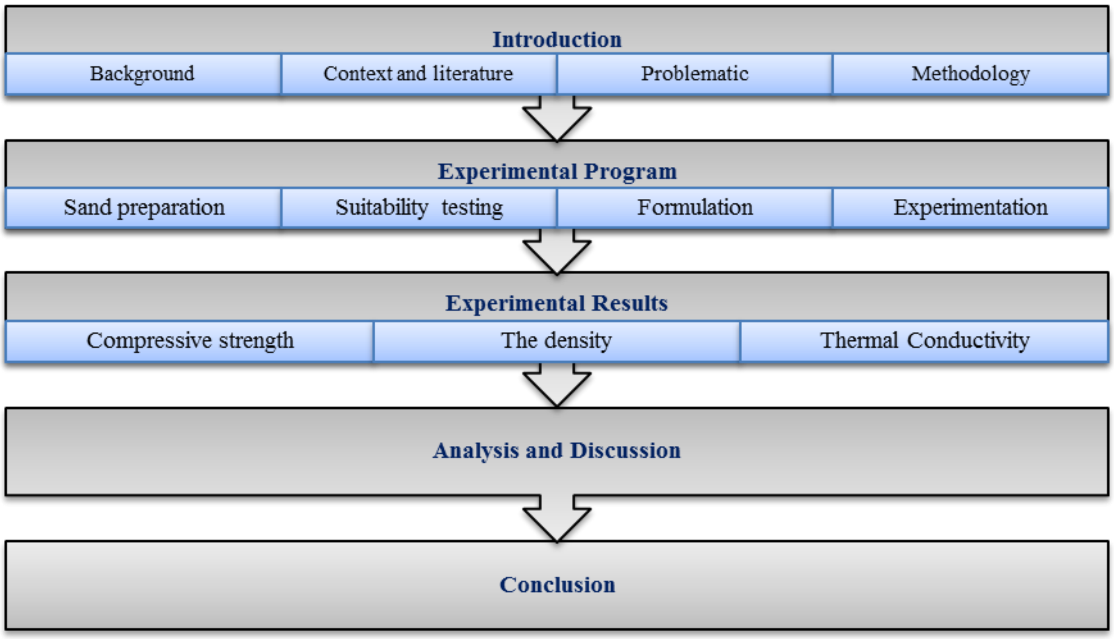

Figure 1. Flowchart of research methodology

2. Experimental Program

2.1. Materials

The present experiment used local materials.

- Cement is the main binder obtained from the Lafarge cement plant in the M'sila region (Algeria) in the eastern region of Algeria, its chemical composition is presented in Table 1.

Table 1. Chemical composition of the materials used

	SiO2	Al2O3	CaO	Fe_2O_3	MgO	SO_3	K_2O	CL	Na_2O
Cement	17.35	4.51	59.87	2.92	1.62	3.08	0.617	/	/
Pozzolana	37.26	15.37	17.01	10.55	3.06	0.38	1.33	0.012	0.41
Slag	35.52	8.88	26.11	2.81	2.58	1.50	1.26	0.047	0.67

- The granulated blast furnace slag by-product of El-Hadjar (Annaba- Algeria) steel complex shown in Figure 2, is used as an active mineral additive, its chemical composition is presented in Table 1.

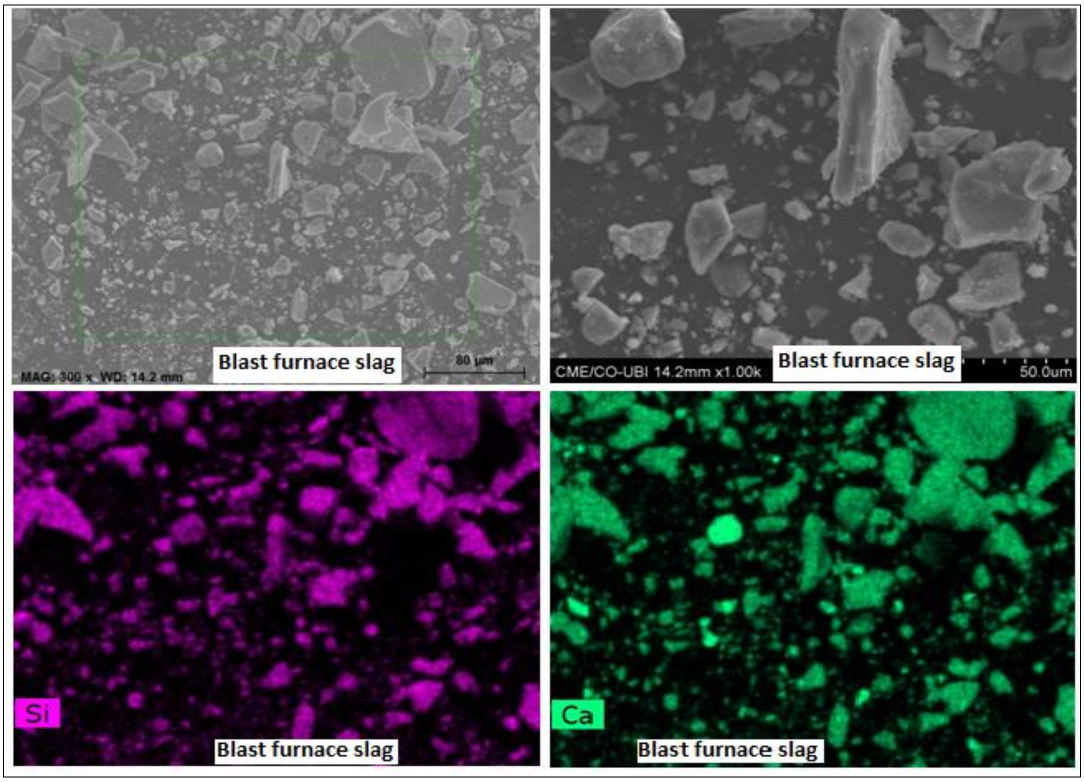

Figure 2. Scanning electron microscopy of the slag

- The natural crushed rock pozzolana from the Beni-Saf deposit (Ain T'emouchent-Algeria) shown in Figure 3, used as an active mineral additive, its chemical composition is presented in Table 1

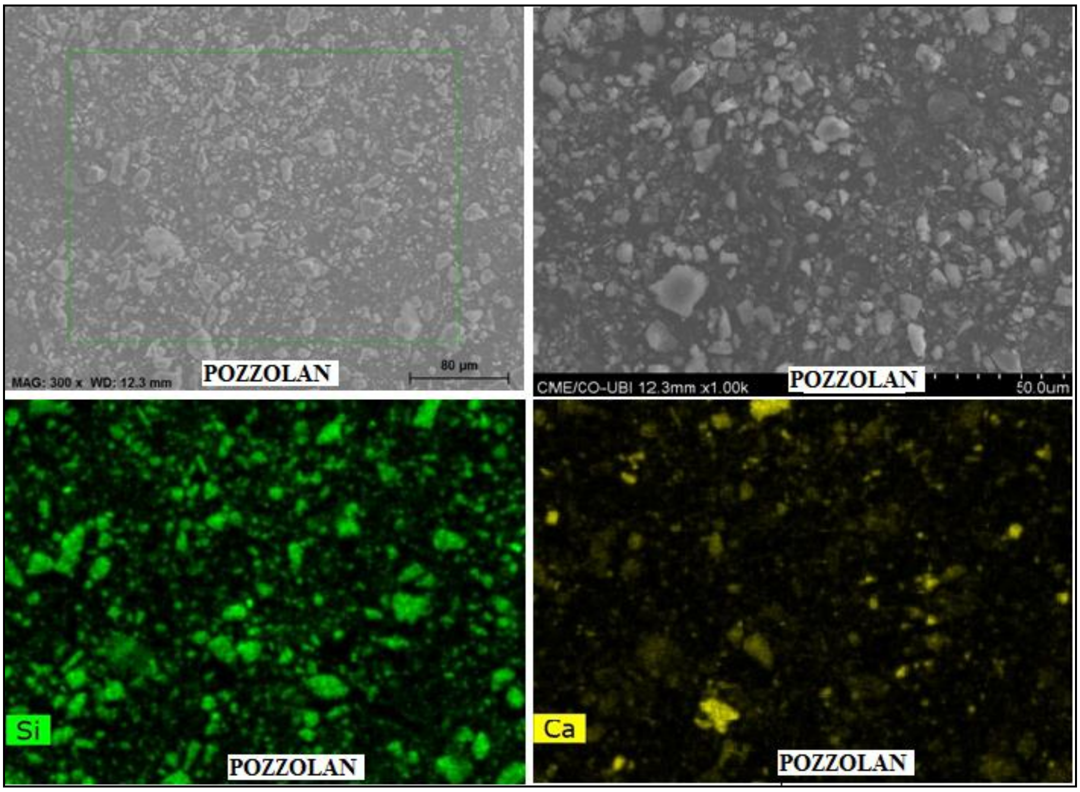

Figure 3. Scanning electron microscopy of the pozzolana

Figure 4 presents the important chemical ratio C/S and A/F of minerals used in cement, slag and pozzolana.

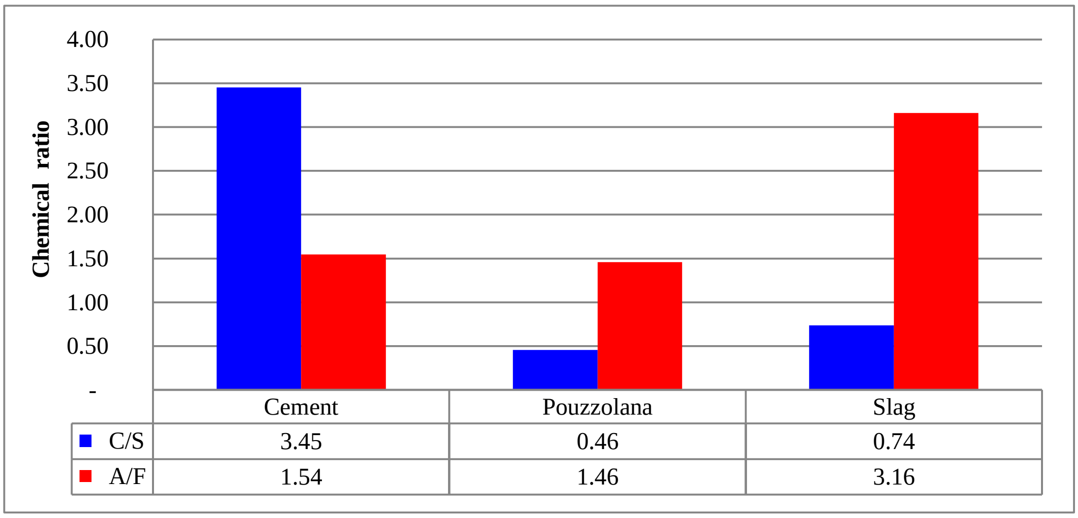

Figure 4. Chemical ratio (C/S and A/F) of materials used

The sands used for the production of cellular concrete are two types of different sizes, the first being sand dunes of the Oued Souf region and the second is crushed sand of the BBA region.

Table 2. The fine modulus and the Specific surface area of the materials used

Materials	Specific surface area (cm^2 /g)	Mf
Cement	3488	/
Pozzolana	3710	/
Slag	3630	/
Dune sand	/	2,36
Crushed sand	/	3,09

The fine modulus of the sands used and the Specific surface area of the cement and the mineral additions used are presented in Table 2 and the densities of materials used are shown in Figure 5.

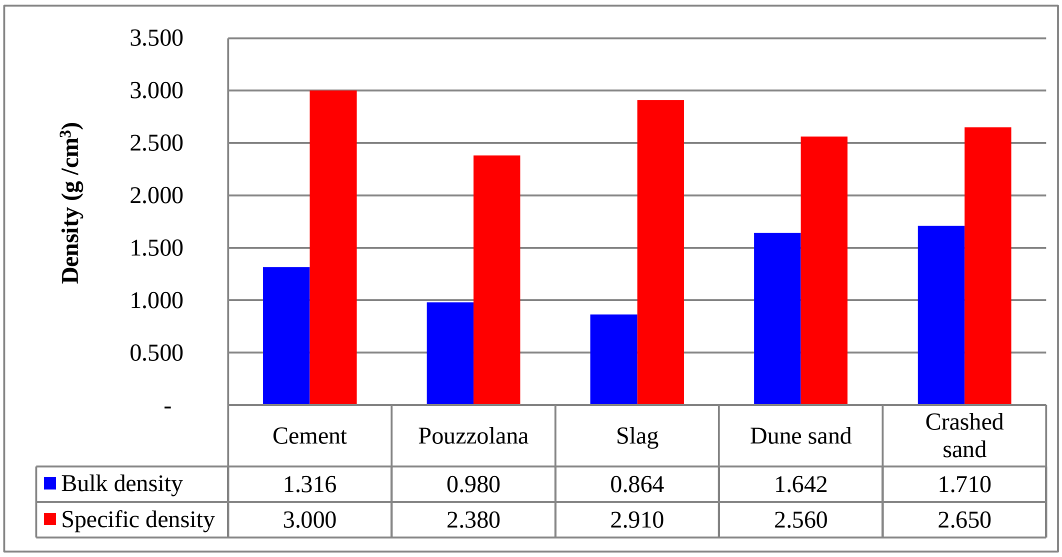

Figure 5. Densities of materials used

- The lime used is that of the lime conditioning company in eastern Saida region, which mainly consists of CaO lime 85%, with a density of 0.9 t/m^3, a fineness of 0 to 4 mm and a PH equal to 12.4.
- The local super-plasticizer admixture used in the study is manufactured by the company Granitex, with a dosage stopped after convenience tests on a mini cone at 1.8% relative to the weight of the cement, its characteristics are presented in Table 3.

Table 3. Characteristics of the super plasticizer used

	dry extract	Appearance	Color	PH	Density
Medaflow (30)	30	Liquid	Light Brown	6 – 6,5	1,07 ± 0,01

- Aluminum powder is an essential element used in many types of research for the development of this type of concrete [19] used as a reactive agent for the expansion of the concrete made up of 97% pure aluminum (Table 4), with a particle size distribution. Approximately 100 µm, produced as waste by the aluminum industry manufactured by the METANOF Company. One can note that the degree of reactivity of the aluminum affects the percentage used in the formulation and subsequently on the expansion reaction (Aluminum-chalk) and therefore the density of the finished product.

Table 4. Chemical analysis of aluminum powder

	AL	Zn	Fe	Pb	Cu	Cd	Mn
Aluminum powder	97.66	1.16	1.08	0.066	0.026	0.0082	0.0078

2.2. Sand Preparation Method

After washing and drying the sand in its natural state, the sand was sieved to sort it by different fractions, as indicated in Figure 6.

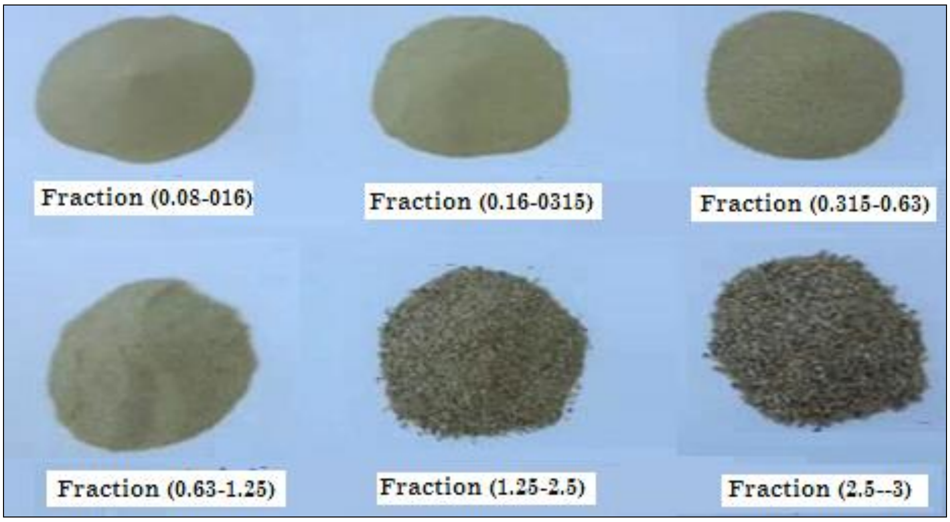

Figure 6. Different fractions of sand

For a second step, the sand is prepared according to the composition of standardized sand by replacing the finest fractions with mineral additions (slag and pozzolana) respectively with a rate of 10 and 15% as presented in Table 5.

Table 5. Composition of the two types of prepared sands

Fraction	Percent	Sand control	Sand with pozzolana	Sand with slag
0.08-0.16	10%	Sand	Pozzolana (10%)	Slag (10%)
0.16-0.315	15%	Sand	Sand	Sand (10%) + slag (05%)
0.315-0.63	30%	Sand	Sand	Sand
0.63-1.25	20%	Sand	Sand	Sand
1.25-2.5	15%	Sand	Sand	Sand
2.5-3	10%	Sable	Sable	Sable

(Dune sand and crashed sand)

2.3. Nomenclature of Cellular Concrete Mixtures

We have prepared 6 types of cellular concrete for each sand (dune and crashed sand) as presented in Table 6, 12 types of cellular concrete are tested for the two kinds of sands.

Table 6. The formulation of cellular concrete prepared (Nomenclature and designation of concrete type for the tow sands)

Name	Symbol
Cellular concrete control without additions and superplasticizer	CC
Cellular concrete with 15% slag in sand	Cslag
Cellular concrete with 10% pozzolana in sand	Cpz
Cellular concrete control with superplasticizer	CC(sp)
Cellular concrete with 15% slag in sand and superplasticizer	Cslag(sp)
Cellular concrete with 10% pozzolana in sand and superplasticizer	Cpz (sp)

2.4. The formulation of prepared cellular concrete

The formulation used (Table 7) takes into account the following considerations.

- Given the nature of the aluminum powder obtained from industrial waste, which affects its reactivity a high percentage of aluminum powder is required in the formulation, which influences the expansion reaction (Aluminum-lime) and the density of the finished product.
- A fairly high percentage of cement was used in the formulation in order to increase the mechanical resistance of the cellular concrete.

Table 7. The formulation of cellular concrete prepared

Vacuum	Cement	Lime	Blowing Agent
58%	18.5%	18.5%	5%

- The amount of water required (Table 8) is determined after several tests of convenience which aims at the preparation of cellular concrete with a volume containing about 42% of solid and 58% of vacuum.

Table 8. Composition of cellular concrete prepared for sand dune and crashed sand

Concrete type	Sand composition (%)			Superplasticizer (%)	W/B	
	Sand	Slag	Pozzolana		Dune Sand	Crushed Sand
CC	100	-	-	-	1.01	0.96
Cslag	85	15	-	-	1.03	0.97
Cpz	90	-	10	-	1.03	0.97
CC(sp)	100	-	-	1.8	0.93	0.86
Cslag(sp)	85	15	-	1.8	0.96	0.89
Cpz(sp)	90	-	10	1.8	0.96	0.89

Figure 7 shows that the addition of pozzolana and slag, require a higher water demand for normal consistency compared to control. This is consistent with the consistency test which shows an additive need for water for these additions [20].

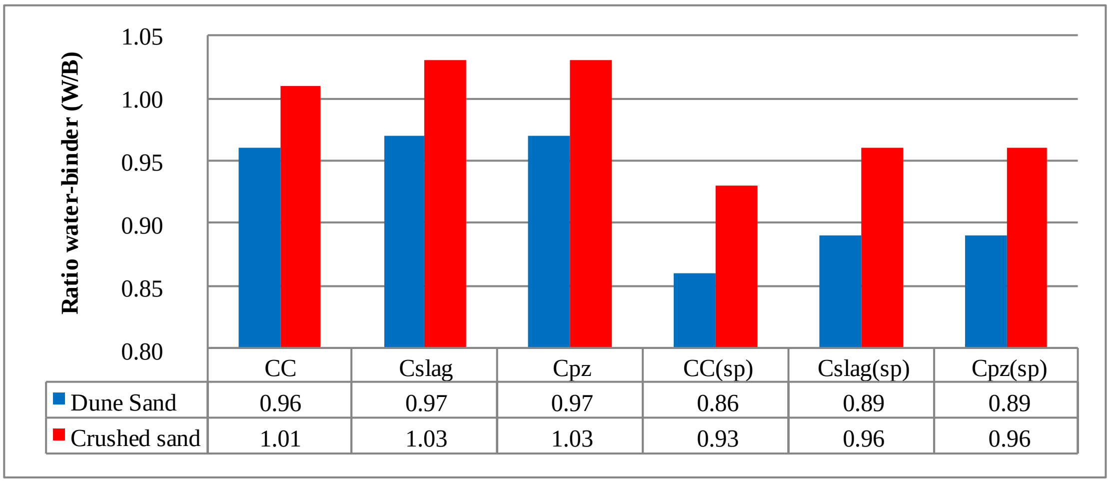

Figure 7. Ratio water-binder of different cellular concretes types studied

2.5. Preparation of mixtures

The tests carried out were carried out on cubic-shaped mortars (10×10×10 cm) based on different sand compositions with an addition rate of 15% for the slag and 10% for tfcihe pozzolana, by substitution of the sand to improve the hydration power of the cement in the presence of lime, whose compositions and the nomenclature of mixtures are summarized in Table 8.

2.6. Testing

- *Compressive strength (crush test) [NA EN12390-3]*

The compression test is carried out on standard cubic specimens (10×10×10 cm).

- *Conductivity measurement*

The purpose and method of measurement.

The CT METRE, an easily transportable device, was developed to accurately assess, the thermal characteristics of several materials, such as bricks, rocks, earth, cellular concrete resins or complex products, etc.

The operating principle consists of measuring the temperature rise felt by the sensor using a combination of a heating element and a temperature sensor (both combined in the same probe), placed in the middle of the cut test tube, during a specified heating period, depending on the material to be tested and the type of probe used [21].

3. Results and Discussion

3.1. Compressive Strength

The different experimental results of compressive strength are presented in Table 9, according to the tests carried out on cellular concrete following the procedures applied to concrete and mortars [21]. Analysis of the results obtained and illustrated in the histogram (Figure 8) showed that sand-based concretes containing active mineral additions, in particular blast furnace slag, offer the best compressive strength compared to sand-based control cellular concrete.

This highlighted the positive contribution of incorporation of additions into the sand due to its physical infill effect and chemical effect due to the chemical reactivity of additions [22]. In addition, these results are consistent with a similar recent study [23] that has been conducted on the incorporation of active additions such as slag and pozzolana into the particle size skeleton of sand (active sand) for mortar and which has proven the effect of additions in improving the compressive strength of the mortar. The benefits of using industrial waste to replace natural sand and cement in lightweight concrete are also discussed. The benefits of using industrial waste to replace natural sand and cement in lightweight concrete are also discussed in a study that presented the use of fly ash and blast furnace slag to replace 100% sand in concrete cellular [24]. The results of this study have proved that a foamed concrete uses fly ash and blast furnace slag can replace traditional concrete in construction as well as replacing clay bricks. This will not only improve concrete strength but also reduce costs as well as protect the environment.

Table 9. Results of compressive strengths of formulated concrete

Concrete type	The average compressive strength at 28 days (MPa)	
	Dune sand	Crushed sand
CC	0,67	3,09
Cslag	1,34	8,10
Cpz	1 ,16	6,31
CC(sp)	0.93	4,32
Cslag(sp)	1.45	9,55
Cpz(sp)	1.40	8,83

On the other hand, the nature of the sand influences the mechanical resistance through the shape, grain size and particle size distribution, although the crushed sand offers better resistances than those of the sand dune of Oued-Souf which develops resistances that remain far from acceptable compared to those of manufactured cellular concrete. More than the results obtained for the compressive strength at 28 days confirm that the use of the superplasticizer increases the mechanical strength in comparison with the concrete without admixture [25].

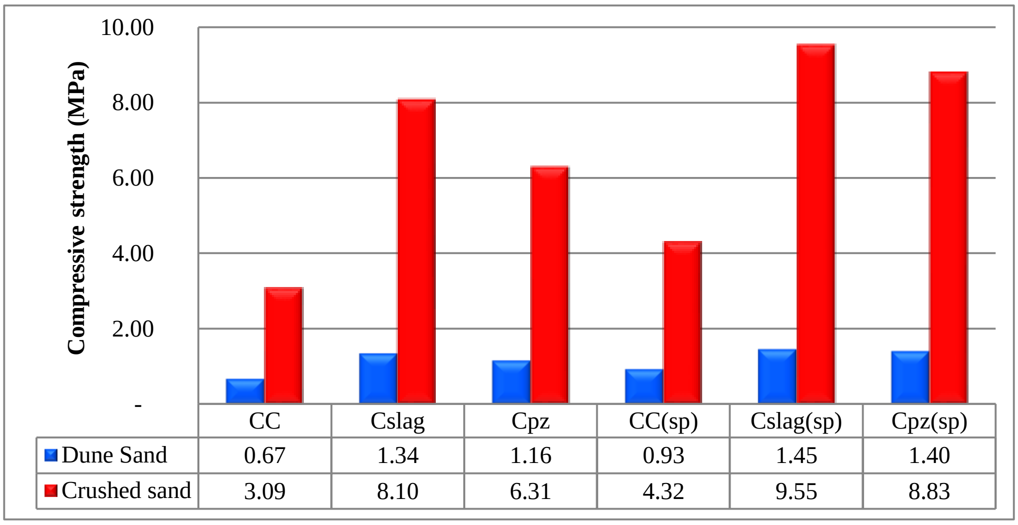

Figure 8. Compressive strength of different cellular concretes types studied at 28 days

3.2. The Density

According to the results obtained and presented in Table 10, it is noted that the densities of the crushed sand-based cellular concrete are greater than those of the sand-based concretes of Oued-Souf. This difference is due to the different nature of the two types of sand as well as their different particle size distribution and the shape of the grains and the microstructure developed pending hardening, on the other hand, the incorporated active additions influence the microstructure physically by filling and stacking and chemically by their reactivity and determination of hydrates and their structuring.

Table 10. The bulk density results of concretes based on the two types of sands

Concrete type	Bulk density (kg/m^3)	
	Dune sand	Crushed sand
CC	780	865
Cslag	842	841
Cpz	850	795
CC(sp)	855	785
Cslag(sp)	765	870
Cpz(sp)	830	892

Figure 9, shows that the decrease in the density of the cellular concretes both types of sand. The densities of the elaborated cellular concretes are acceptable in comparison with the industrially fabricated cellular concrete.

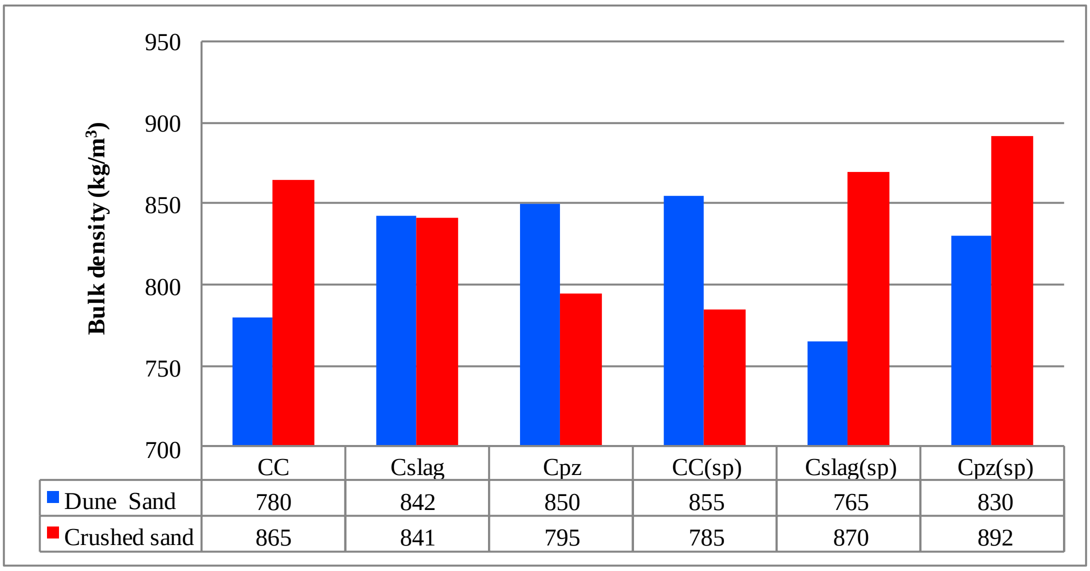

Figure 9. Bulk Density of different cellular concretes types studied

As for the hard relationship between the mechanical properties and the density of cellular concrete, [26] indicated that the compressive strength decreases exponentially with the reduced density in foamed concretes [26]. Nevertheless, it should be highlighted that such property depends of a lot of factors, the element form and size, the foam production method, the load path, the age, the water content, the characteristics of mixture elements and the curing process [27, 28]. Kearsley also noted that for dry densities between 500 and 1000 kg/m^3 the compressive strength is reduced when the bubble diameter increases. For the densities above 1000 kg/m^3, the paste Composition is what controls the strength [28].

A similar experimental study of the properties of cellular concretes with a protein-based foam agent, containing fly ash (FA) as binder and blast furnace granulated slag (GBS) as fine aggregate was discussed to assess porosity, density and, compressive strength and thermal conductivity. The results showed that an increase in the water-binder ratio (W/B) due to a decrease in the binder content leads to an increase in the porosity of the foam concretes, which consequently leads to a decrease in bulk density, which is consistent in our case with crushed sand-based cellular concrete unlike dune sand which does not agree with this result [29].

Table 11. Thermal conductivity of concretes based on both types of sand

Concrete type	Thermal conductivity λ in (W/m.°K)	
	Dune Sand	**Crushed sand**
CC	0.392	0.393
Cslag	0.403	0.482
Cpz	0.454	0.500
CC(sp)	0.508	0.512
Cslag(sp)	0.464	0.450
Cpz(sp)	0.418	0.500

3.3. Thermal Conductivity

The results obtained (Table 11) and illustrated as a histogram in Figure 10, show that the thermal conductivity of cellular concrete based on crushed sand in particular that containing active mineral additions, is higher than that of Oued-Souf sand even after the use of the adjuvant, Noting that thermal conductivity decreases each time the density is low, which is the case for previous research that has shown that thermal conductivity is proportional to density [30].

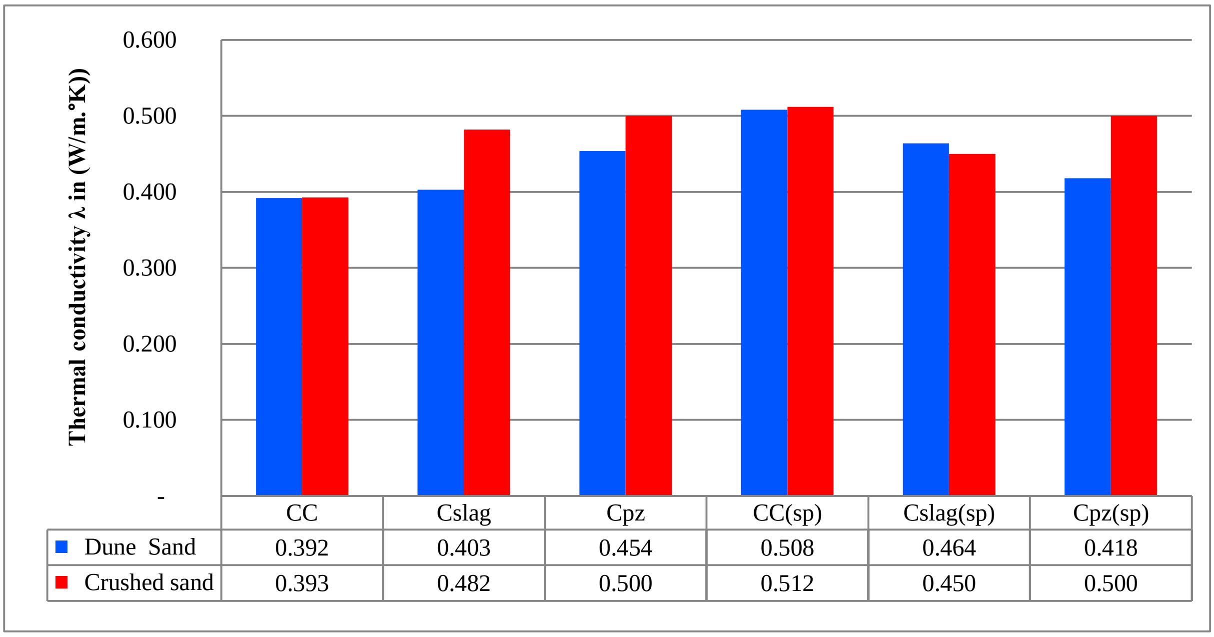

Figure 10. The thermal conductivity λ of different cellular concretes types studied

The thermo acoustic isolation and the fire resistance are intrinsic properties of foamed concretes that are related to the porosity as well [31]. The foamed concrete has sound absorption rates 10 times higher than the conventional concrete and its thermal conductivities is closer to 0.66 W/m.°K [27].

4. Conclusions

This study is based on the development of cellular concrete and the examination of its thermal, physical and mechanical properties. The preparation of this concrete is based on two types of sand (dune and crushed sand) used separately with the incorporation of active mineral additives by substitution of fine sand fractions. The research aims at two objectives, the feasibility of using local materials to produce acceptable and efficient cellular concretes, the second to evaluate the influence of sand prepared with active mineral additives on thermal, physical and mechanical properties of cellular concretes prepared. The results obtained allow us to draw the following conclusions;

The development of cellular concrete with new materials or with the treatment of existing materials allows very important modifications of physical, chemical and microstructural properties. Hence the substitution of very fine fractions of prepared sand by active mineral additions considerably affects the microstructural construction and development of the porous structure due to the chemical effect related to the reactivity of the additions and the process hydration on the formation and arrangement of hydrates and by the physical effect of stacking and nucleation. Incorporation of mineral additions into the particle size skeleton of sand, in particular slag, positively influences compactness and results in a considerable increase in mechanical strength compared to control cellular concrete with sand without mineral additions.

As for the nature of the sand, it is noted that the cellular concrete with crushed sand develops a better mechanical resistance than the cellular concrete with dune sand and preserves even lower densities than the control concrete, on the other hand, concrete with dune sand that develops densities higher than those of control concrete. Noting that the super-plasticizer further improves the compactness and densities of dune sand concretes compared to those with crushed sand. Concerning thermal conductivity, the effect of mineral additions and the nature of sand remains insignificant as the control of cellular concrete remains better in terms of thermal conductivity. However, dune sand makes it possible to produce cellular concretes with a better thermal conductivity compared to crushed sand and the use of mineral additions reduced the ratio W/B which directly influences the density regardless of the type of sand used. Finally, the recovery of aluminum waste by its use as an expansion agent in the formulation of cellular concrete can be beneficial even if it uses at a relatively high rate.

5. Declarations

5.1. Author Contributions

Conceptualization, B.M.S., A.N., and L.B.; writing—original draft preparation, B.M.S., A.N., and L.B.; writing—review and editing, B.M.S., A.N., and L.B. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in article.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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