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Thermal and mechanical performances of cement-based mortars reinforced with vegetable synthetic sponge wastes and silica fume

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Abstract

Appropriate sand for construction is getting scarce in many countries leading to a growing interest in the use of wastes from several origins in mortar and concrete production. This paper investigates the performances of mortar containing the industrial wastes of vegetable synthetic sponges (VSS) as natural sand replacement. After preparation, different amounts of VSS particles (up to 20 wt% of sand replacement) were incorporated in the cementitious matrix containing 20 % of silica fume by weight of cement. The use of silica fume improved the cement-aggregate interface leading to reduce the porosity and to increase consequently the mechanical strength. The replacement of the natural sand with VSS improved the thermal performance of the studied composites by causing a decrease of thermal conductivity up to 63% for 20 wt% of sand replacement by VSS. The thermal diffusivity of composites decreased and the specific heat capacity increased. The combination of VSS and silica fume in cementitious materials can largely improve the post-cracking extension and fracture energy, even if the compression strength is reduced. The study showed that the use of

vegetable synthetic sponge wastes provides good potential to answer a major challenge: reducing environmental impact of this material while providing a new use with optimum technical properties, as found with 8 wt% of VSS.

Keywords: mortar, vegetable synthetic sponge wastes, sand replacement, thermal conductivity, mechanical performances, circular economy

1. Introduction

Large amounts of industrial and postconsumer wastes are generated each year causing environmental problems. The reuse and revalorization of wastes in building industry is a sustainable solution which can reduce the environmental impact of this sector and resource depletion. Sustainability supports using the wastes and renewable resources as a replacement of raw materials, such as sand, gravel, fibres and cement [1].

The production of concrete, the most widely used building material [2], uses 8-12 million tons of natural aggregate annually [3-4]. Fine aggregate (sand) is a main constituent of concrete and have significant effect on the workability, shrinkage, weight, strength and durability of concrete [5]. Appropriate natural sand for construction is in scarcity in several countries [6]. In order to find suitable solutions of this problem, several researches have been conducted concerning the use of wastes of several origins as sand replacement material in mortar and concrete production [7-11].

The use of vegetable particles as building material aggregates has grown greatly [12] because it achieves the sustainability goals, since they are low-cost, renewable and biodegradable. Agricultural by-products were studied for their use as sand partial or full replacement. The results showed that some of them, such as olive ash and rice husk ash, improved the thermal properties. Almost all the agricultural wastes reduced mechanical strength and mass density

[6]. Panesar and Shindman [13] examined the effect of the replacement of aggregates by waste cork on the properties of mortar and concrete. They found that the increase of the cork size increases the porosity and decreases the compressive strength. Optimum transport and mechanical properties was obtained with finer cork sizes. However, due to their high rapid chloride ion permeability, the studied concrete-cork composites may have limited durability if they are exposed to the outdoor environment.

The properties of concrete containing rice husk waste as sand replacement were investigated by Sisman et al. [14]. It was found that the thermal conductivity and the compressive strength of concrete mixtures decreased with the amount of rice husk. The thermal conductivity and the compressive strength losses reached 14% and 10%, respectively with 30 vol% of rice husk. According to the authors, the use of rice husk makes it possible to produce low-cost and lightweight concretes which satisfy insulation and mechanical requirements.

In spite of their advantages, the bio-aggregate based composites utilization in construction is still low because of the large variability of biosourced materials and the conservative nature of the industry [15]. Moreover, referring to a state-of-the-art of Amziane et al. [16], the chemical interactions that can take place between the bio-aggregates and mineral binders can strongly impact the properties of the building materials containing them such as: setting time, hydration mechanisms, mechanical properties, durability [16]. The studies in this field being few, Amziane et al. [16] proposed the transposition of the available data on wood-based concrete to the bio-aggregate composites.

Many studies linked the limited industrial production of cement-based composites reinforced with natural fibres to the long term durability problem [16-22]. This problem is related among others to the degradation of the natural fibres in alkaline matrix and the mineralization of fibres [17, 21]. A review of the chemical interactions and the methods to improve the durability can be found in [16] and [18].

The aim of this study was to use locally available industrial wastes of VSS as sand replacement in order to produce new lightweight materials for sustainable building purposes. Research on the utilization of VSS in mortar or concrete production has not yet been conducted. In this research natural sand was partially replaced with particles of VSS wastes at levels of 5 %, 8%, 10 %, 15 % and 20 %, by weight. Taking into account the benefits of silica fume 20% by weight of cement was added to the cementitious matrix. The addition of silica fume in concrete can increase the bond strength between cement paste and aggregate by making the interfacial zone denser, the strength of the concrete at the same water cement ratio, the durability by reducing permeability and refining pore structure [23-26]. The combination of VSS wastes and silica fume, with optimized formulations, can thus make it possible the production of construction materials for both structural and isolation purposes. The physical, thermal and mechanical performances of the produced materials were investigated and compared to the reference mortar and to the requirements of the construction materials.

2. Materials and Methods

2.1 Materials

Industrial wastes from vegetable synthetic sponges (VSS) were used in this study. VSS are made from wood pulp to which cotton, flax and hemp fibres are added to reinforce the strength. Salt crystals are also added to make the porous holes in the cellulose sponge.

These wastes were cut in pieces of approximately 10x10 cm in a wood chopper, and then they were at the same time washed and ground in a wet centrifugal grinder. The wet grinding process removes salt from the wastes of VSS. The obtained particles were filtered and then oven dried at 50°C for 24h. Fig. 1 shows the particles from wastes of VSS used as natural

sand replacement. The bulk densities of natural sand and VSS wastes are respectively 1713 kg.m^{-3} and 32 kg.m^{-3} .

CEM I 42.5 R Portland cement and silica fume (SC) (Elkem Microsilica 971) were used in production of mortar specimens. Table 1 gives the chemical and physical properties of the used materials.



Fig. 1. Wastes of VSS after grinding, washing and drying.

Table 1. Properties of used materials.

Composition (%)	Cement	Silica fume
Chemical composition		
SiO ₂	20.8	98-98.4
Al ₂ O ₃	4.6	0.3-0.2
Fe ₂ O ₃	2.4	0.1-0.01
CaO	63.8	0.3-0.2
MgO	2.0	0.2-0.1
SO ₃	2.4	0.3-0.1

Na ₂ O	0.11	0.2-0.15
K ₂ O	0.9	0.3-0.20
Insoluble materials	0.6	-
Physical properties		
Loss on ignition	1.7	0.8-0.5
Bulk density (kg.m ⁻³)	3130	250-350

2.2 Mixing and casting procedure

Six mortar mixtures were studied. The sand was substituted with the VSS particles at ratios of 0% (VSS-0), 5% (VSS-5), 8% (VSS-8), 10% (VSS-10), 15% (VSS-15), and 20% (VSS-20) by weight (of sand and VSS). The VSS-0 mortar corresponds to the control mortar without substitution of the natural sand. A constant water-to-cement weight ratio of 0.5 was used in all mixtures. Silica fume at 20% by weight of cement was added in the mixes in order to improve the strength of the composites and their durability which can be affected by the incorporation of the VSS particles in substitution to sand. In order to highlight clearly the effect of adding vegetable synthetic sponge wastes in the material, the admixture is superplasticiser free because of its effect on the workability.

The mix proportions were designed in order to investigate the effect of VSS particles on mechanical strength and thermal conductivity of mortars. The main objective was to explore the potential benefits of the developed materials for both structural and non-structural applications (premade blocks for load-bearing or non load-bearing applications, surface coating, insulating screed fill, etc). Several preliminary tests were performed in order to

determine the mix proportions and the mixing and casting method suitable for the VSS wastes. The mix proportions are reported in Table 2.

In order to take into account the water absorption capacity of the recycled VSS particles, they were first prewettted and mixed in approximately 30 wt % of water. Cement, sand and silica fume at 20 % by weight of cement were dry mixed in a concrete mixer, and then the remaining water was added and mixed at low speed until complete homogeneity. The soaked VSS particles were finally added progressively to the mixture to avoid agglomeration. The mixing was continued at high-speed until the obtaining of a homogenous mixture.

The mortar was moulded and casted in $40 \times 40 \times 160$ mm standard moulds (Fig. 2a). During the casting process, mortar was compacted using press (Fig. 2b) at a compacting stress of 3 MPa. All specimens were demoulded after 24 h and then placed in a storage room ($T=20^{\circ}\text{C}$ and $\text{RH}=50\%$) during 3 months.



(a)



(b)

Fig. 2. (a) Moulds and (b) press used in this study.

Table 2. Mix proportions.

Mix	Identification	Cement (g)	Sand (g)	VSS as sand replacement

				(g)
VSS-0	Control	500	1000	0
VSS-5	5 %	500	950	50
VSS-8	8 %	500	920	80
VSS-10	10 %	500	900	100
VSS-15	15 %	500	850	150
VSS-20	20 %	500	800	200

2.3 Methods

2.3.1 Scanning electron microscope observations

The microstructure of raw wastes of VSS, VSS particles used as sand replacement, and produced mortars were examined using a JEOL 6301F scanning electron microscope (SEM).

2.3.2 Thermophysical characterization

The Hot Disk Thermal Constants Analyzer (TPS2500, Hot Disk AB, Gothenburg, Sweden) was used for thermal conductivity and thermal diffusivity measurements. This method uses a Kapton sensor as a source of heat and temperature sensor. In practice, the probe is very often sandwiched between two identical samples (Fig. 3). An alternative is to place the probe between the sample studied and an insulator with known thermal characteristics. A complete description of the method can be found in the literature [27-28].

During Hot Disk experiments, the first step is to determine the best parameters to obtain optimal results on the various samples tested. These key parameters that require prior optimization are the size of the probe, the duration of the experiment, the size of the sample and the power delivered by the probe. The experimental conditions are described in details in [29].

In this study, a Kapton sensor 5465 and the anisotropic method were used. The measurement settings are presented in Table 3.

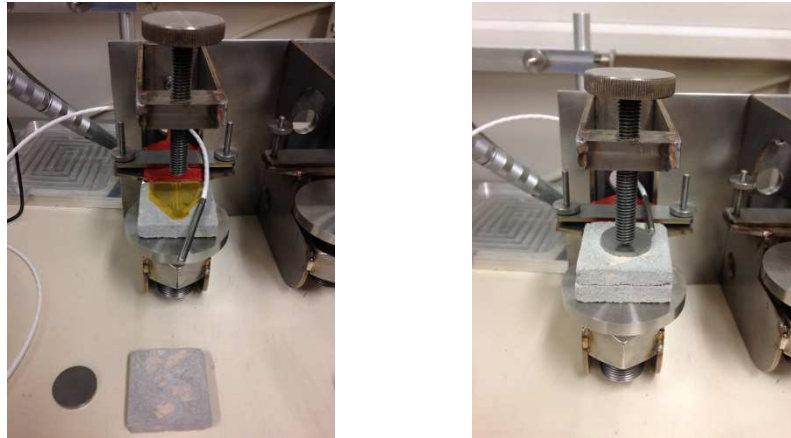


Fig. 3. Photo of Hot Disk probe.

Table 3. Measurement settings.

Sample	Power (mW) (During 10 s)
VSS-0	150
VSS-5	90
VSS-8	70
VSS-10	60
VSS-15	50
VSS-20	45

2.3.3 Mechanical characterization

Compressive and flexural tests were carried out on $40 \times 40 \times 160$ mm mortar specimens (Fig. 4) 3 months after the casting using CONTROLS PILOT4 C300kN. First the three-points

bending test (Fig. 5) was performed and then the compression tests according to ASTM C109.

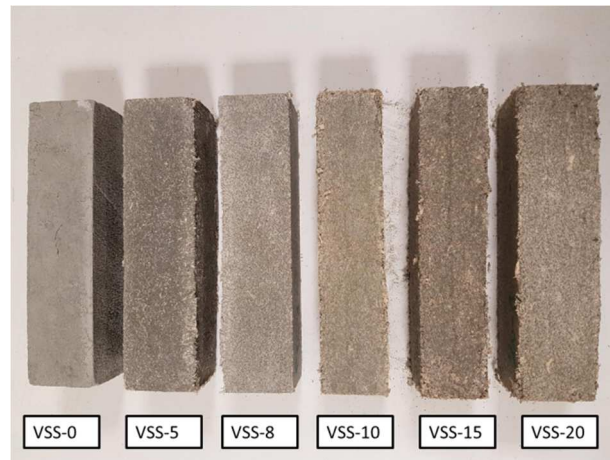


Fig. 4. Mortar specimens with variable proportions of VSS particles, as referenced in Table 2.



Fig. 5. Flexural test.

2.3.4 Density and open porosity

The density of mortars was obtained from the measurement of dry sample mass and sample sizes. The water accessible porosity measurement is in accordance with NF P18-459 [30].

The method consists in placing samples under vacuum which can force water to penetrate into large pores (diameter > 100 nm). In the first phase of the test, mortar samples are placed under vacuum at 30 mbar during 4 hours in order to eliminate the air present inside the pores.

Directly after, the glass containers were filled with water to signal the start of the second phase and as a result samples were immersed in water under a constant pressure of 30 mbar for 44 hours. After 48 hours of such curing (4 h under vacuum then 44 h immersed), samples were removed and dried in an oven at a constant temperature of 105°C. The weight was recorded every 24 hours until reaching mass stabilization (less than 0.05% of mass variation).

The porosity measurements were carried out 3 months after the casting as in the case of mechanical tests.

3. Results and discussion

3.1 Microstructure

The morphological analyses of the VSS wastes before and after processing are shown in Fig. 6. From Fig. 6a and Fig. 6b a highly porous structure of raw wastes of VSS can be observed. After grinding, washing and drying, the porous structure was destroyed and one can see agglomerates of natural fibres (cellulose, cotton, hemp, flax) (Fig. 6 c) and detail of individual natural fibre such as flax (Fig. 6 d).

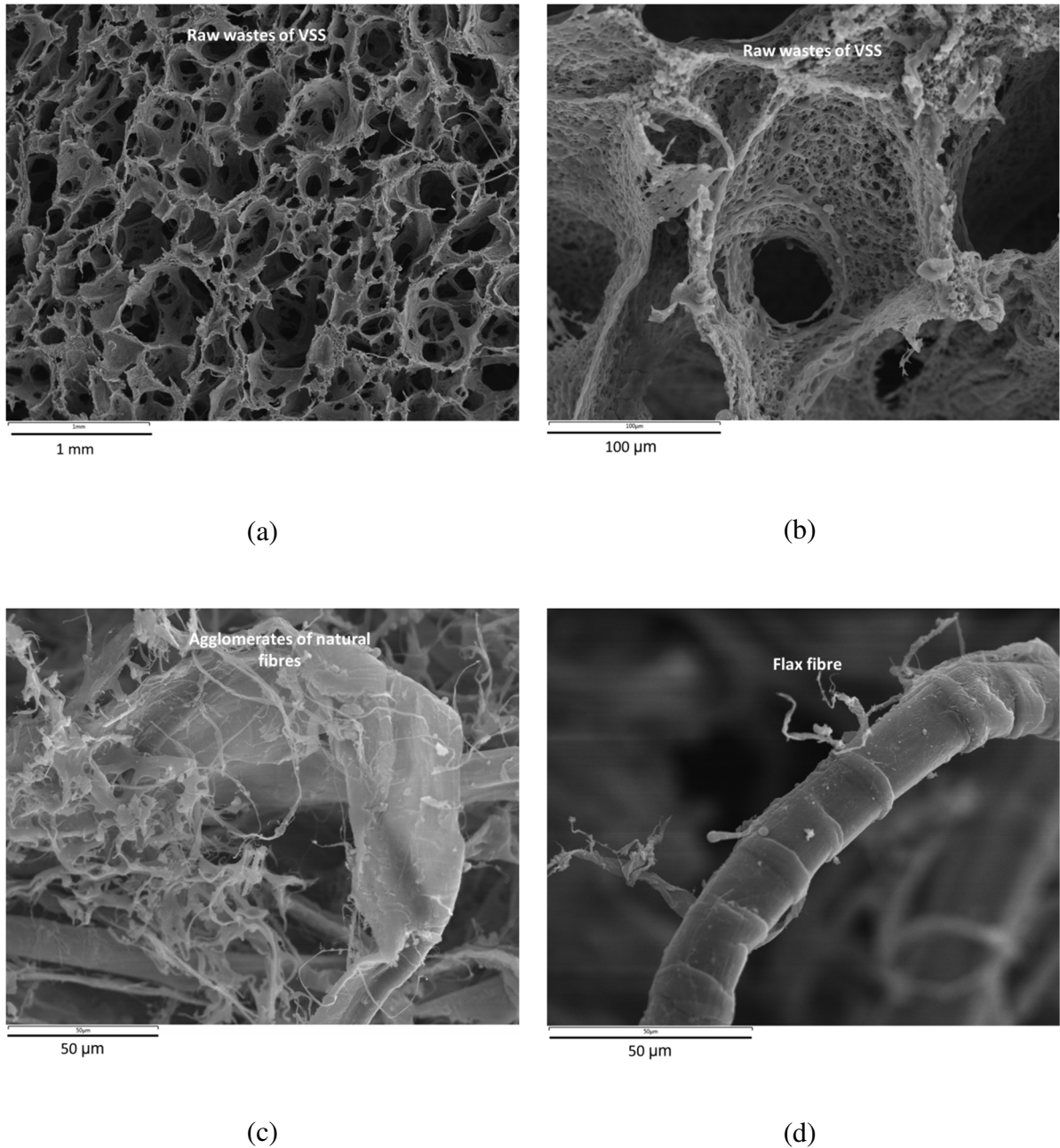
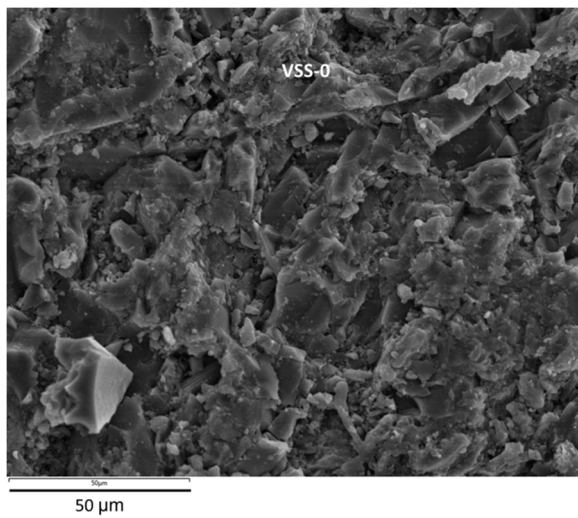


Fig. 6. SEM photos of (a) and (b) raw wastes of VSS, (c) agglomerates of natural fibres (cellulose, cotton, hemp, flax) and (d) detail of individual natural fibre.

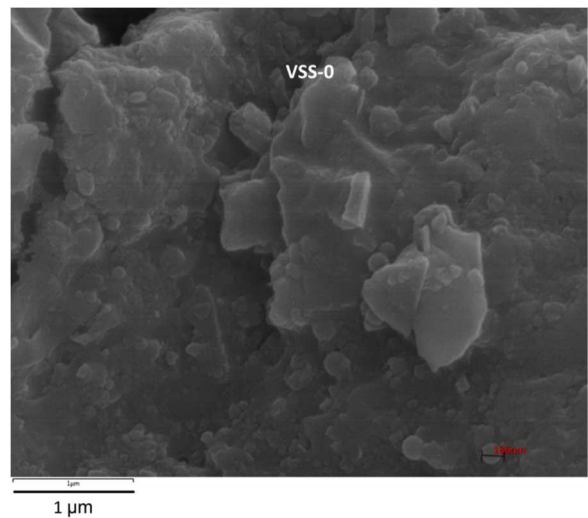
The microstructure of the reference mortar (Fig. 7a) shows that the paste structure is homogeneous without distinct interfacial transition zones. Indeed, the addition of the silica fume resulted in a dense microstructure which can be seen at high enlargement (Fig. 7b).

Silica fume (Fig. 7c), owing to its size, is known to act as filler improving the cement-aggregate interface [31].

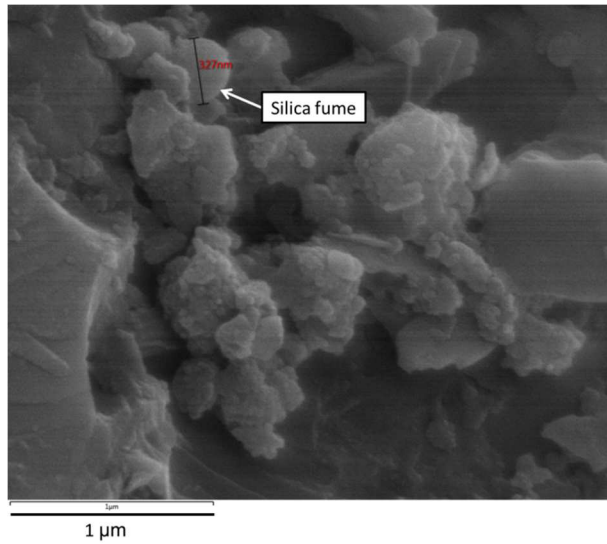
Fig. 8a shows the VSS particles/matrix adherence for 5% VSS particles as sand replacement. VSS particles seem to be well dispersed in the cement matrix as can be observed in Fig. 8b. In addition, the aggregates are sufficiently embedded by hydrated cement particles. When the replacement level exceeds 8% the hydrated cement particles are not sufficient to embed all the VSS particles (Figs. 9a and 9b). There is thus a threshold replacement value above which the microstructure of the material is more complex than the inclusion-matrix type.



(a)

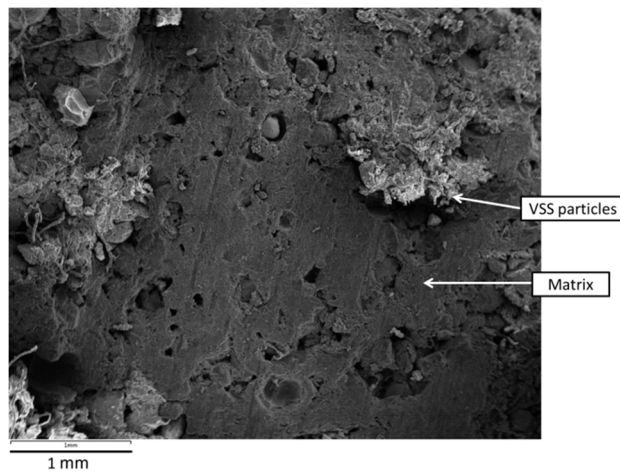


(b)

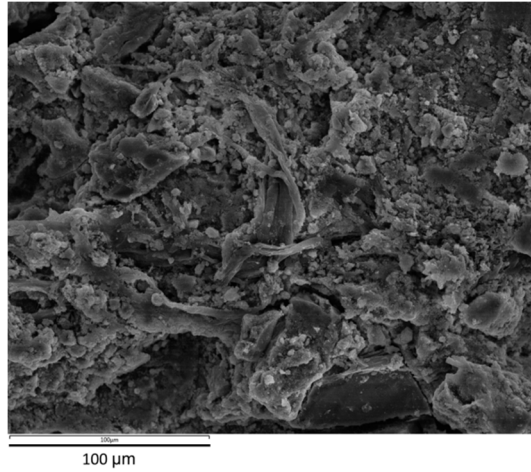


(c)

Fig. 7. SEM photos of reference mortar VSS-0 showing (a) and (b) homogenous and dense microstructure and (c) silica fume particle of 327 nm.

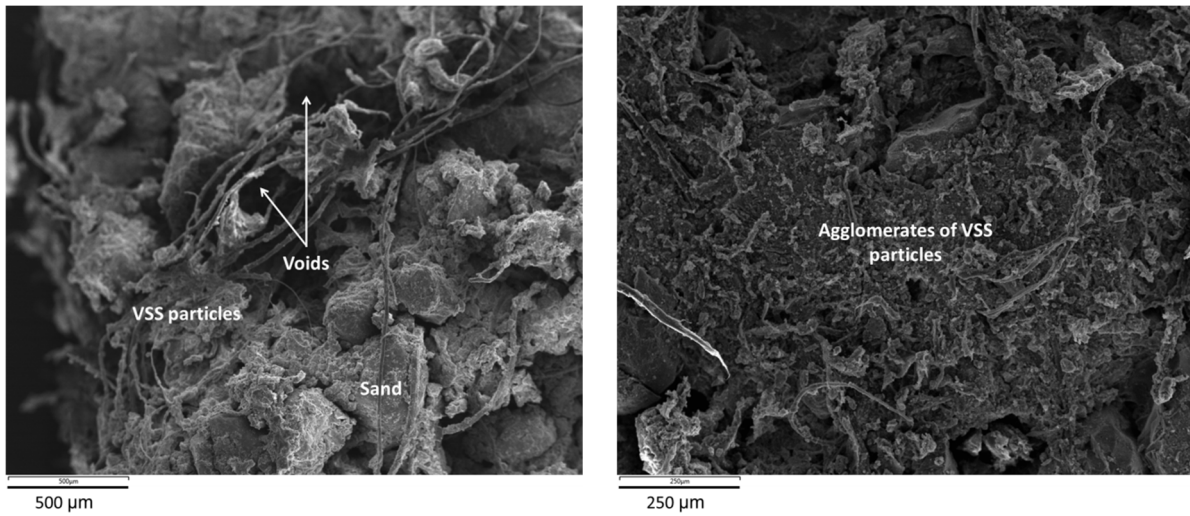


(a) Interface between the VSS particles and the cement matrix.



(b) Homogeneous distribution of the VSS particles in the matrix.

Fig. 8. SEM micrographs of VSS-5.



(a)

(b)

Fig. 9. SEM micrographs of VSS-15 (a) and VSS-20 (b).

3.2 Density

Fig. 10 presents the densities of the VSS mortar specimens with different sand replacement levels. It varies from 1170 kg.m^{-3} to 2074 kg.m^{-3} . The incorporation of VSS particles reduced

the density of the mortar as the VSS particles are more porous and thus lighter than sand. The VSS-based-mortars could be classified as lightweight aggregate mortars in which the density is less than 2000 kg.m^{-3} [14].

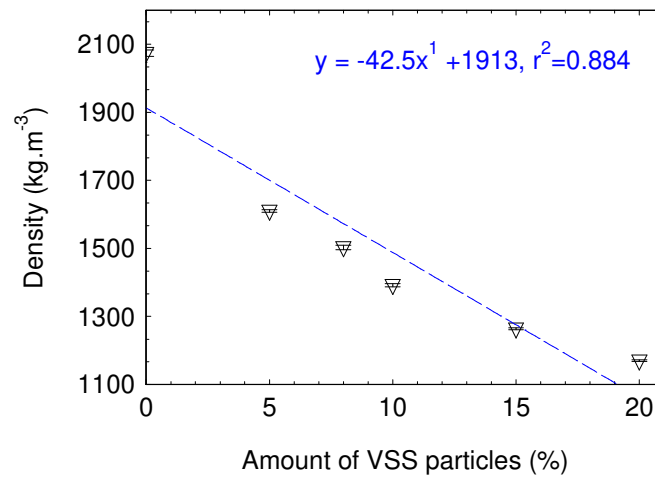


Fig. 10. Evolution of the mortar density vs. the wt% of the sand replacement by VSS particles.

3.3 Thermal conductivity

Fig. 11 presents the variation of thermal conductivity of the produced mortars vs. density (Fig. 11a) and vs. sand replacement level (Fig. 11b). In Fig. 11, the average of 5 values is reported with a standard deviation ranging from 0.001 to $0.004 \text{ W.m}^{-1}.\text{K}^{-1}$. One can see that the thermal conductivity increased with the density. This can be related to the increase in the porosity which includes both the porosity of the VSS particles and the porosity of the matrix or the VSS-matrix interactions [32]. Furthermore the thermal conductivity decreased by increasing the incorporation of VSS particles instead of sand due to a low thermal conductivity of the VSS. Similar results are found on wood aggregate based composites [32-33], hemp concrete [16], date palm wood concrete [34].

Thermal conductivity depends, among others, on formulation, production method, temperature, moisture content, etc [16, 35]. According to Asadi et al. [36], thermal

conductivity of lightweight concrete (LWC) is in the range of 0.2-1.9 W.m⁻¹.K⁻¹. Our values are in the same range as those found in the literature. The thermal conductivity of the reference specimen (without sand replacement) is about 1.01 W.m⁻¹.K⁻¹. The replacement of the natural sand with VSS improved the thermal performance of the studied mortars by causing a reduction up to 63% at a replacement level of 20% by weight (in addition to the 6% decrease in thermal conductivity resulted from the addition of silica fume as reported in [37]). Based on the experimental reports (185 experimental test results) available in the literature, Asadi et al. [36] proposed the equation (1) to evaluate the thermal conductivity of concrete (k) for density (ρ) varying from 150 kg.m⁻³ to 2350 kg.m⁻³:

$$k = 0.0625e^{0.0015\rho} \quad (1)$$

They compared Eq. (1) to the one proposed by ACI committee for LWC (Eq. 2) [38] and found good fitting between them for densities lower than 1500 kg.m⁻³ [36]:

$$k = 0.0864e^{0.00125\rho} \quad (2)$$

The experimental values of thermal conductivity obtained for the VSS-lightweight mortars produced in this study were compared to the predicted values using the Eq. (1) and the ACI committee equation (2). Fig. 12 indicated that except slightly higher value obtained for mortar with 15 % VSS, the experimental results correspond well to the predicted ones for mortar densities less than 1500 kg.m⁻³.

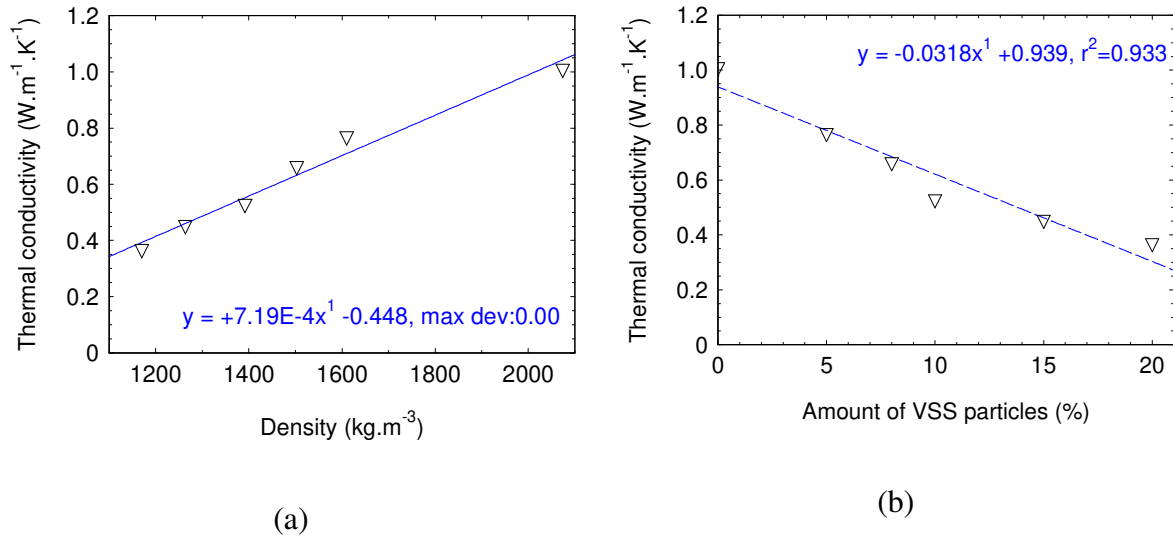


Fig. 11. (a) Thermal conductivity of mortars vs. their density and (b) thermal conductivity vs. the wt% of the sand replacement by VSS particles.

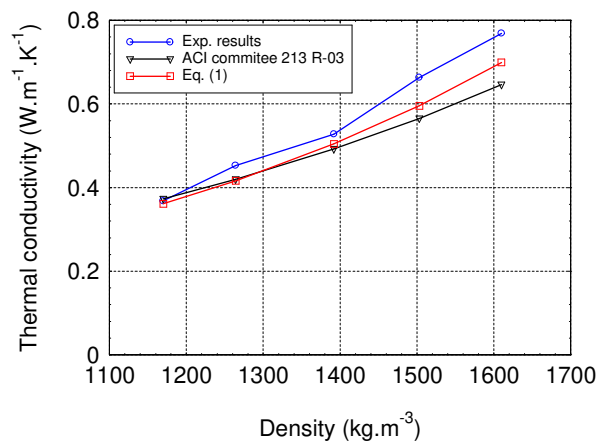


Fig. 12. Comparison between the experimental and the estimated values of the thermal conductivity of the produced VSS lightweight mortars.

3.4 Thermal diffusivity

Fig. 13 presents the variation of thermal diffusivity of produced mortars according to sand replacement level with VSS particles. In Fig. 13, the average of 5 values is reported with a standard deviation ranging from 0.001 mm².s⁻¹ to 0.004 mm².s⁻¹. Substituting sand with VSS particles decreased thermal diffusivity of mortars in correlation with decrease in thermal

conductivity. Values decreased from $0.917 \text{ mm}^2.\text{s}^{-1}$ for the VSS-0 mortar to $0.335 \text{ mm}^2.\text{s}^{-1}$ for the VSS-20 which is equal to a reduction of about 63%. The values of the thermal diffusivity were used to calculate the specific heat capacity of the samples which is in the range of 530-938 $\text{J}.\text{kg}^{-1}.\text{K}^{-1}$.

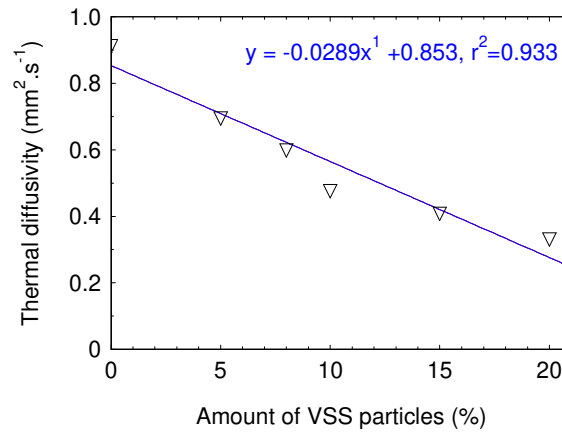


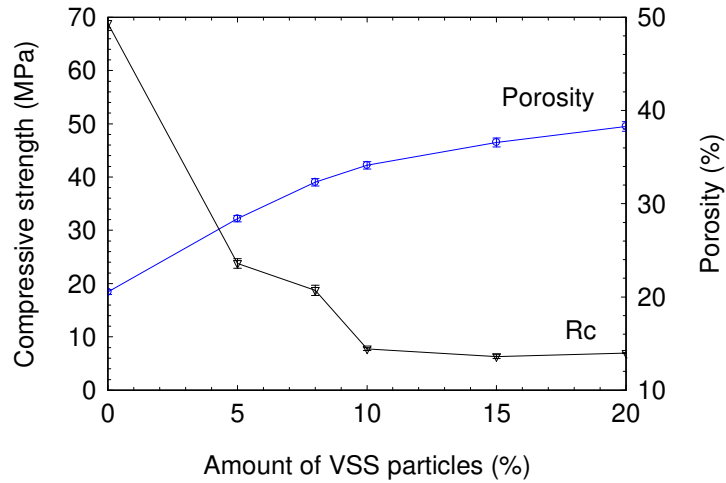
Fig. 13. Variation of the thermal diffusivity of mortars vs. the wt% of the sand replacement by VSS particles.

3.5 Mechanical strength

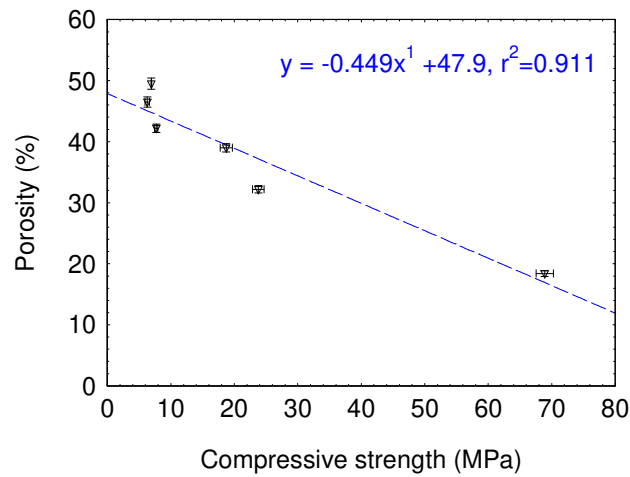
3.5.1 Compressive strength

The mechanical behavior of mortars is influenced by many factors such as curing conditions, age, kind and content of binder. The compressive test results and the porosity of the studied mortars are plotted in Fig. 14a (each point is an average of three tests). The VSS-based mortars had much lower compressive strength compared to the reference mortar. A compressive strength respectively of 23 MPa and 18 MPa can be achieved for 5 wt% and 8 wt% of sand replacement. Increasing sand substitution with VSS particles leads to a compressive strength reduction up to 90 % for the mixes containing 15 wt% and 20 wt% of VSS. The decreased compressive strength can be linked to the increase of the porosity as a result of VSS particles incorporation and the poor VSS/matrix adhesion. Fig. 14b shows the relationship between the compressive strength and the porosity accessible to water of the

studied mortars. The compressive strength decreases when the porosity increases. This shows a direct relationship between them, which is in agreement with literature results [34, 39]. The VSS particles have lower mechanical strength as compared to sand which can also contribute to the decrease in the compressive strength of the VSS mortars.



(a)



(b)

Fig. 14. (a) Compressive strength Rc (in black) and porosity (in blue) vs. the wt% of VSS particles and (b) Porosity of specimens vs compressive strength.

3.5.2 Flexural strength

The obtained results are presented in Fig. 15. Each point is an average of four tests. The studied mortars achieved flexural strength varying from 7.3 MPa to 2.4 MPa. Therefore they can be used in structural applications such as prefabricated blocks for load-bearing walls according to the BS6073 requirements [42].

Amongst the VSS-based mortars, the highest flexural strength value of 5.6 MPa was obtained for 8 wt% of sand replacement by VSS. The decrease of the flexural strength with VSS particles incorporation was lesser than that of the compression strength. The fibres as a constituent of VSS could enhance the flexural strength and the ductility of the matrix in which they are incorporated. This is related to the fibre properties which make it as bridge over cracking [43] as highlighted in Fig. 16.

The failure mode of specimens during the bending tests changes according to the wt% of VSS (Fig. 16). For the reference case, the failure of the specimens is sudden and regular. However, by increasing the wt% of VSS, the fracture toughness becomes higher. The post-cracking behaviour can be improved by VSS particles incorporation. This finding is highlighted for the specimens containing 20 wt% VSS that reach quite higher values of flexural strength. The fracture energy of mortar can thus be increased with the added VSS particles. Such improvement of the flexural strength and toughness at high VSS content is also probably related to the change of the microstructure morphology as observed in Fig. 9 (and commented at the end of section 3.1).

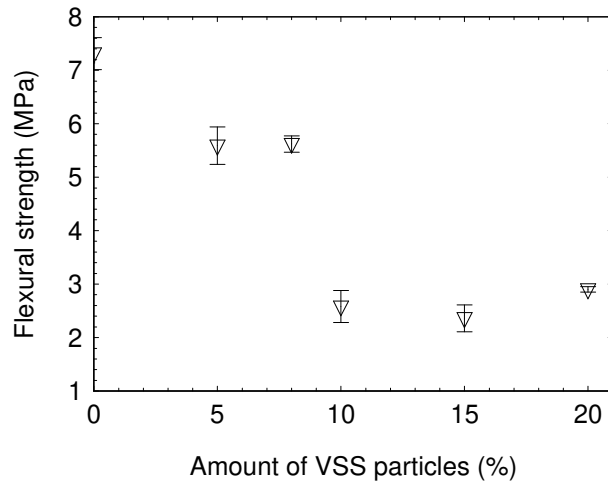


Fig. 15. The influence of sand replacement on the flexural strength.

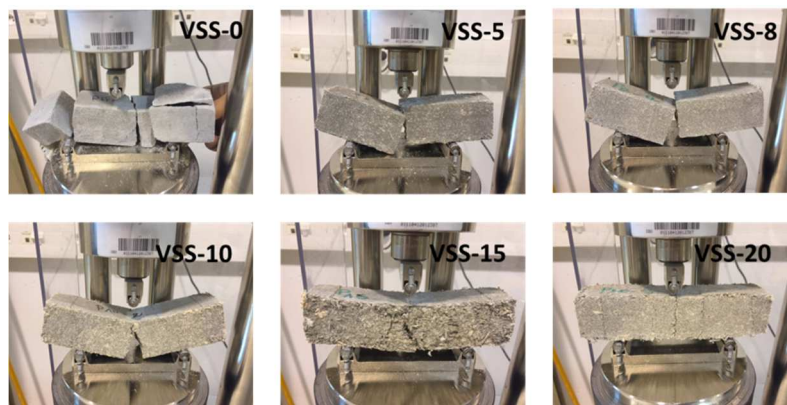


Fig. 16. The failure mode of specimens during the bending tests.

3.6 Mechanical and thermal performances

Table 4 summarizes the values of density, thermal conductivity and compressive strength of the produced VSS lightweight mortars. The comparison of these values with the Rilem functional classifications of lightweight concrete (Table 5) [40] showed that they can be ranged both in class (I) (for 5 wt% sand replacement) and class (II) (for the other materials). An optimum of thermal insulation and mechanical performance can be achieved for 8 wt% of sand replacement with VSS particles (Fig. 17). Although recycling VSS wastes in mortars reduces the compressive strength, till 8 wt% the produced materials have sufficient mechanical strength for use in structural applications such as prefabricated blocks for load-

bearing walls with improved thermal insulation properties leading to save energy. The mortars produced with more VSS wastes have interesting thermal insulation properties and can be used for both non-structural and structural applications such as non-load bearing walls, surface coating and insulating screed fill.

There are no published results concerning the use of VSS wastes in mortars or concrete to make comparison with our results. Moreover, the physical and mechanical properties of materials are influenced by the manufacturing process which varies from one study to another. The Table 6 compares the properties of mortars developed in this study with different cement based composites containing vegetable wastes of various origins as sand replacement reported in the literature.

Table 4. Properties of produced VSS lightweight mortars.

Lightweight mortar	Density (kg.m ⁻³)	Thermal conductivity (W.m ⁻¹ .K ⁻¹)	Compressive strength (MPa)
VSS-5	1610 ± 7	0.769 ± 0.004	23.8 ± 1.8
VSS-8	1503 ± 13	0.663 ± 0.002	18.7 ± 1.9
VSS-10	1392 ± 9	0.528 ± 0.001	7.7 ± 0.5
VSS-15	1264 ± 6	0.453 ± 0.003	6.3 ± 0.7
VSS-20	1170 ± 5	0.368 ± 0.004	6.9 ± 0.1

Table 5. Classification of lightweight concrete (RILEM, 1987) [40].

Properties	Class and type		
	Classe I Structural	Classe II Structural/Insulating	Classe III Insulating
Compressive	>15	>3.5	>0.5

strength (MPa)			
Thermal conductivity (W.m ⁻¹ .K ⁻¹)	-	<0.75	<0.30
Approximate density (kg.m ⁻³)	1600-2000	<1600	<1450

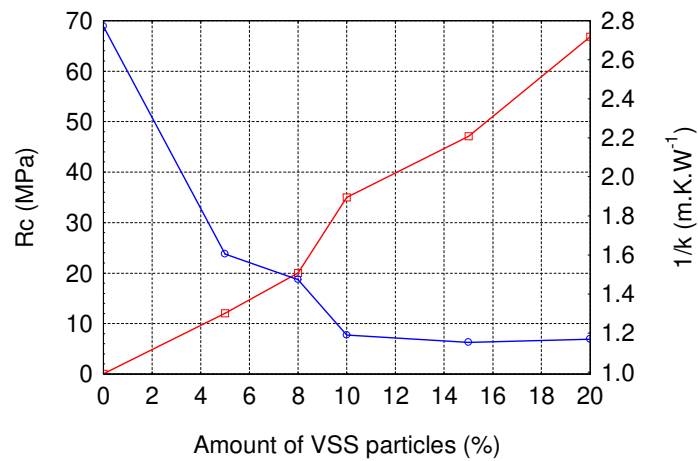


Fig 17. Compressive strength R_c (in blue) and $1/k$ (in red) vs. the wt% of VSS particles.

Table 6. Comparison of density, compressive strength and thermal conductivity of VSS mortars with different cement-composites containing vegetable wastes of various origins as sand replacement reported in the literature.

Waste type	Density (kg.m ⁻³)	R_c (MPa)	k (W.m ⁻¹ .K ⁻¹)	Reference
Rice husk	2268	37.5	1.535	[14]
	1797	17.6	0.71	
Cork	2382	65.5	-	[13]

	1773	10.2	-	
Corn stalk	1657	20.8	0.643	[41]
	1083	7.0	0.192	
Sugarcane bagasse ash	2379.85	27.98	-	[8]
VSS-8	1503 ± 13	18.7 ± 1.9	0.663 ± 0.002	This study
VSS-20	1170 ± 5	6.9 ± 0.1	0.368 ± 0.004	This study

Conclusions

In this study, the thermal and mechanical performances of cement-based mortars containing vegetable synthetic sponge wastes and silica fume had been meticulously evaluated. The use of both those two components in concrete or mortar with optimum content could achieve a good balance between their thermal and mechanical performances. Indeed, because of its size, silica fume is known with its filling effect improving the cement-aggregate interface leading to reduce the porosity and to increase consequently the mechanical strength. On the other hand, the replacement of the natural sand with VSS improved the thermal properties of the studied composites by causing a decrease in the thermal conductivity up to 63% for 20 wt% of sand replacement by VSS. These experimental results led to the following conclusions:

- The incorporation of VSS and silica fume in cementitious materials can largely improve the post-cracking extension and fracture energy, even if the mechanical

performances are reduced. For the application of these materials as a cover layer in buildings, the most interesting property to enhance is the breaking strength.

- The VSS incorporation can improve thermal resistivity of cementitious materials for surface covering of structure construction. Indeed, the results show that substituting sand with VSS particles decreased thermal diffusivity of composites and increased specific heat capacity.
- For ideal use of VSS in cementitious materials, the results show that an optimum of thermal insulation and mechanical performances can be achieved for 8 wt% of sand replacement with VSS particles.
- Finally, the use of vegetable synthetic sponge wastes in surface covering of buildings and structures can facilitate their recycling. This technical innovation of using VSS in construction may answer a major challenge: reducing environmental impact of this material while providing a new use with optimum technical properties. The hygroscopic properties, durability of the VSS mortars (chloride penetration, freeze/thaw, carbonation) and LCA are considered in future investigation.

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