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Evaluation of the properties of a new circular building composite material to upcycle building wastes

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Abstract. A new circular composite material for building applications is developed, made of two secondary raw materials coming from waste recycling: fibers and sand. Hydraulic lime is added as a binder. This new composite targets a low environmental impact thanks to benefits of upcycling buildings waste, low energy production process, lifetime up to 60 years and of a high potential of reversibility, reuse and upcycling. The research focused on mechanical and physical properties, as well as analysis of the microstructure by X-ray 3D microtomography and in-situ compression testing. The mechanical and physical test results show good and unexpected properties: a density of 390 to 1300 kg/m³; a compressive strength between 0.2 and 2.2 MPa, a bending strength of 0.1 to 1.9 MPa and a thermal conductivity of 0.06 to 0.14 W/mK. Further research will focus on circular construction and environmental aspects. Three applications are envisioned, according the standards of the building sector.

1. Context

The environmental context is profoundly impacting the evolution of the building sector. New materials - more sustainable, bio-based, less energy-consuming, reusable or recyclable - and new construction methods - more circular, adaptable and reversible - are being increasingly developed, with the aim of limiting grey energy, CO_2 emissions and waste generation of the sector [1, 2, 3].

Despite this, the building sector is still the second largest waste generator in Europe with only a few of these valorised and without robust recycling chains, except for inert construction wastes, which are mainly downcycled into road aggregates [4, 5].

In this context, there is a real opportunity to recycle wastes as secondary raw materials to produce new building materials. The objective of the research is therefore to upcycle building wastes by developing a new class of building composite materials that will meet technical performances – according the standards of the building sector - and environmental performances such as to minimize the energy footprint of the material thanks to a high volume fraction of recycled materials, a low energy production process and a high potential of reuse, recovery or recycling in the production, construction and dismantling stages, as shown on Figure 1.

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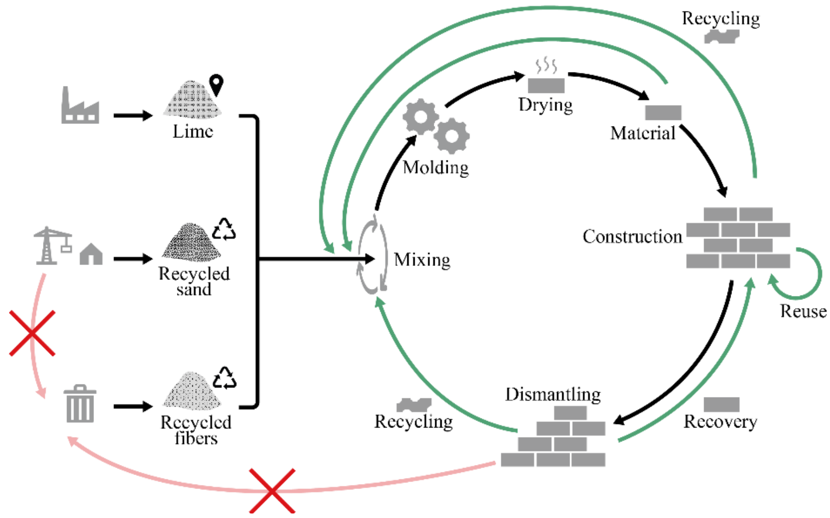


Figure 1. Life cycle of the new material: to avoid the generation of new waste, the material comes from recycled secondary materials or wastes, except for hydraulic lime. Inert and insulation wastes are directly recycled in the production chain. The building material is also reusable and recoverable (directly on site). If it is damaged, it can be crushed and reintegrated into the production chain.

2. Materials and methods

A preliminary research has proved the energy-efficiency of the process and revealed good mechanical, thermal and fire resistance properties for materials containing a volume fraction of paper wastes between 15 and 70% - using as fibers to bring lightness and insulating properties to the material - and mixed with river sand and hydraulic lime [6, 7].

2.1. Materials

The research focuses on the use of recycled waste from the building sector as secondary raw material. For this purpose, the fibers used come from abundant insulation waste from production or recycling centre: paper fibers, glasswool and rockwool. A second objective is to replace the river sand with a recycled sand from crushed inert building wastes that are currently to weakly exploited. The hydraulic lime is the only virgin raw material, used as binder. Lime is produced locally in Belgium and its production process is less energy consuming compared with cement.

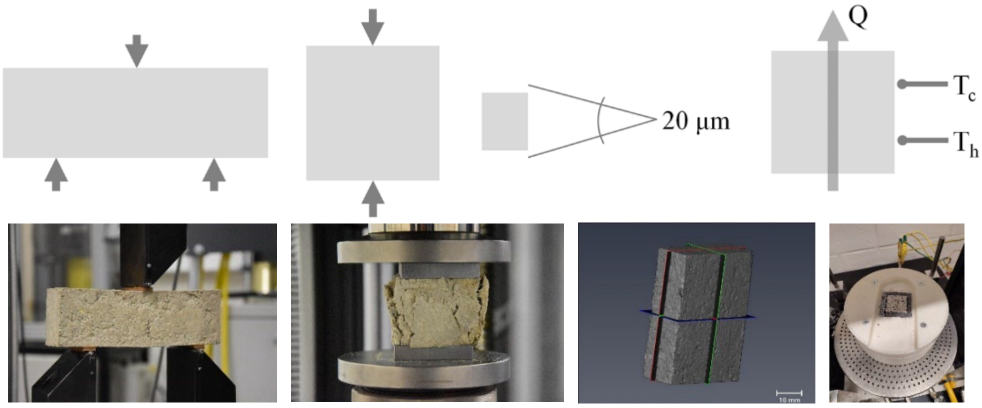
2.2. Samples manufacturing

In order to characterize the physical and mechanical properties of this new material, samples were produced by crushing and mixing the fibers with the sand, lime and water, followed by moulding and naturally air-drying. Six compositions with two different volume fractions of fibers (20 and 45%) were manufactured: one composition for each of the three fibers and each type of sand. All these samples allow comparing the influence of the different secondary raw materials on the new material's characteristics (Figure 2).

(a) (b) (c)

Figure 2. Samples containing (a) paper fibers, (b) glasswool fibers, (c) rockwool fibers, with hydraulic lime and river sand (on the left of each picture) or recycled sand (on the right)

2.3. Determination of the properties
Several experimental tests were carried out, as shown in Figure 3, to determine the physical and mechanical properties of these different compositions. The three-point bending tests were carried out on samples close to the dimensions of a masonry brick. The uniaxial compression test was performed on cubic samples. These two tests rely on the measured force and displacement which are then converted into stress and strain. The thermal conductivity was assessed by placing a small cubic sample between a hot plate and a cold plate, with thermocouples to determine the heat flow through the sample (the latter values are only indicative as the setup contains measurement errors).



(a) (b) (c) (d)

Figure 3. Different experimental methods: (a) bending, (b) compression, (c) 3D microtomography, (d) thermal conductivity.

3. Results
3.1. Thermal conductivity
The influence of the different volume fraction and nature of the fibers and types of sand on the thermal conductivity has been determined as shown in Table 1. Samples containing more fibers (45%) have a lower thermal conductivity, between 0.06 and 0.09 W/mK and therefore better insulating properties. The thermal properties of the materials are directly linked to the density. The samples with a higher fiber volume fraction contain also higher amount of porosity that forms between the fibers.

Table 1. Density and thermal conductivity.

Compositions	Fibers vol. fraction %	Density Kg/m³	Thermal conductivity W/mK
Paper fibers + river sand	20	821	0.095
	45	500	0.067
Paper fibers + recycled sand	20	812	0.088
	45	497	0.094
Glass wool + river sand	20	689	0.086
	45	392	0.059
Glass wool + recycled sand	20	603	0.079
	45	433	0.057
Rock wool + river sand	20	1213	0.143
	45	790	0.075
Rock wool + recycled sand	20	1303	0.121
	45	846	0.078
Aerated concrete [8, 9]		300 – 900	0.090 – 0.520
Lime-hemp [10, 11]		340 – 500	0.071

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3.2. *Bending test*

The density, volume fraction and nature of the fibers also influence the mechanical properties of the samples. The denser the material, the better its bending strength. Samples with 20% fiber content achieve maximum stresses of 0.45 to 1.87 MPa, while those with 45% fibers content are between 0.14 and 0.46 MPa (Table 2). The influence of the nature of the fibers and the sand will be presented in the discussion.

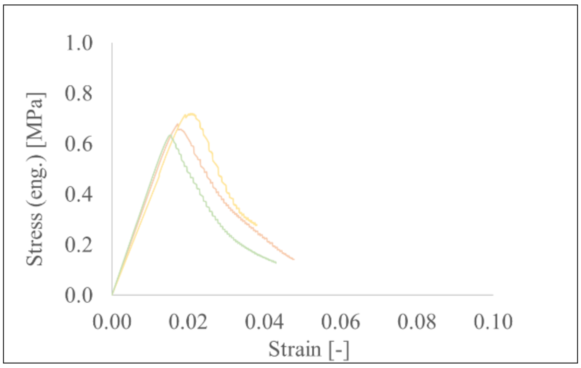

Figure 4. Bending behaviour: stress/strain response of 3 samples of the composition containing 20% paper fibers + recycled sand + lime.

Table 2. Bending properties.

Compositions	Fibers vol. fraction %	Max. force N	Max. stress MPa	Max. strain -	Young's modulus MPa
Paper fibers + river sand	20	874	0.73	0.05	38.84
	45	260	0.22	0.06	9.57
Paper fibers + recycled sand	20	813	0.68	0.04	41.30
	45	244	0.20	0.04	6.65
Glass wool + river sand	20	544	0.45	0.09	9.69
	45	184	0.15	0.17	1.09
Glass wool + recycled sand	20	670	0.56	0.11	10.53
	45	173	0.14	0.10	2.27
Rock wool + river sand	20	2026	1.69	0.05	79.90
	45	434	0.36	0.05	9.08
Rock wool + recycled sand	20	2243	1.87	0.05	92.01
	45	556	0.46	0.04	15.52
Aerated concrete [8, 9]			0.70 – 1.30		
Lime-hemp [10, 11]			0.23		

Compression test

The same conclusion can be made regarding the compressive strength of the material, with a maximum stress of 0.59 to 2.16 MPa for 20% fibers and 0.15 to 0.49 MPa for 45% fibers (Table 3).

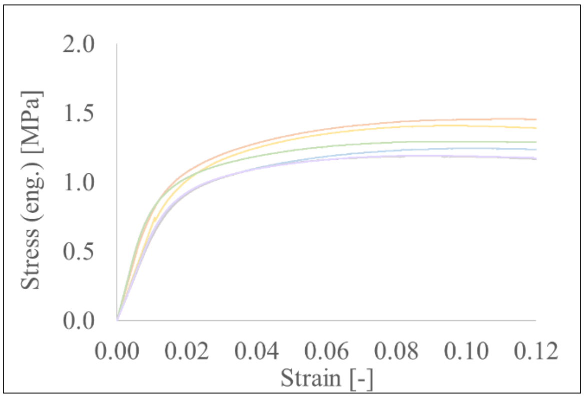

Figure 5. Compressive strength: stress/strain curve of 6 samples of the composition containing 20% paper fibers + recycled sand + lime.

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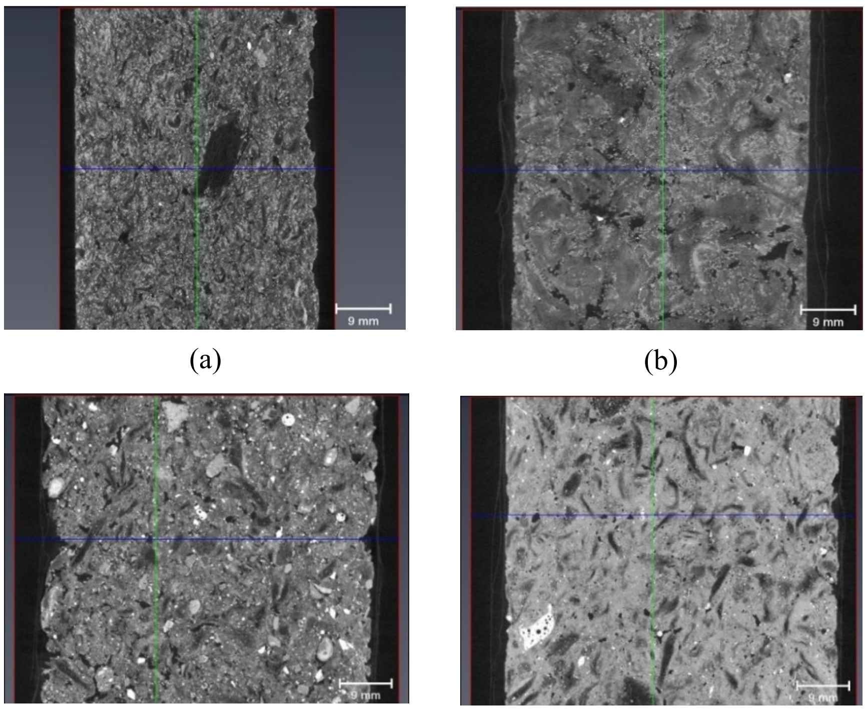
Table 3. Compression properties.

Compositions	Fibers vol. fraction %	Max. force N	Max. stress MPa	Max. strain -	Young's modulus MPa	Elastic limit MPa
Paper fibers + river sand	20	4377	1.22	0.11	67.74	0.88
	45	1454	0.40	0.12	12.58	0.28
Paper fibers + recycled sand	20	4669	1.30	0.10	73.62	0.81
	45	1284	0.36	0.11	9.17	0.23
Glass wool + river sand	20	2203	0.61	0.09	22.87	0.52
	45	528	0.15	0.11	3.13	0.11
Glass wool + recycled sand	20	2130	0.59	0.09	19.30	0.50
	45	730	0.20	0.10	7.76	0.13
Rock wool + river sand	20	7780	2.16	0.06	95.91	2.15
	45	1536	0.43	0.07	12.08	0.37
Rock wool + recycled sand	20	6903	1.92	0.11	69.59	1.34
	45	1760	0.49	0.08	22.86	0.38
Aerated concrete [8, 9]			1.20 – 4		1400 – 2900	0.60 – 1.10
Lime-hemp [10, 11]			0.22 – 0.35		50 – 100	

3.3. 3D Microtomography

The scans generated by 3D microtomography are used to characterize the material's microstructure. The samples are relatively homogeneous. However, from time to time, a cluster of fibers forms and affects the overall mechanical strength. The scans also show that the grain size of the recycled sand (Figure 6d) is more random than the river sand (Figure a, b, c), without any influence on the mechanical and thermal properties.



(a) (b) (c) (d)

Figure 6. Scans of **s**amples containing (a) paper fibers + river sand, (b) glass wool + river sand, (c) rock wool + river sand, (d) rock wool + recycled sand

4. Discussion

The characterisation testing campaign demonstrated that fibers and sand selection has a marked influence on the material's mechanical and thermal properties.

Firstly, samples with glasswool, having a lower density, also have a lower thermal conductivity and therefore better insulating capacity. However, they present the worst mechanical strength, both in bending and compression. Samples with rockwool have a much higher strength but poorer thermal properties. Samples with paper fibers lie in between the two.

There is a small influence coming from recycled sand compared to river sand. Recycled sand shows a tendency to improve the thermal and mechanical properties of the material. The low thermal conductivity is explained by a larger porosity. The use of recycled sand allows increasing the proportion of recycled raw materials in the composition which reduces the material's environmental impact.

The properties extracted from the new materials were compared to existing building materials available on the market with the conclusion that the material can be classified between cellular concrete and lime-hemp blocks in terms of mechanical strength and thermal conductivity. Moreover, it presents the significant additional advantage of being made from recycled raw materials, in contrast to these two materials which require natural resources for their manufacturing.

5. Conclusion

On the basis of these first results, three building applications were proposed: a partition panel, a dry screed slab and a self-supporting block, with mechanical and physical properties according the standards of the building sector [7]. These applications will be studied to respond to the environmental challenges of the building sector with reversible assemblies and connections to offer a high potential of reuse or recycling, as shown on Figure 1. Further research will focus on construction and environmental aspects such as the applications at 1/1 scale, a life cycle analysis and a material passport for the manufacturer.

This research provides a response to the environmental and economic challenges of the building sector by developing a balanced eco-circular composite material with an energy-efficient manufacturing process, good physical and mechanical performances, depending on the targeted applications, and environmental performances, while being reversible and recyclable as part of a circular economy scheme [7].

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