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New circular building composite material to upcycle building wastes

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New circular building composite material to upcycle building wastes

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Abstract. A new class of sustainable building composite materials is developed, made out of recycled fibers waste, of sand from crushing inert waste and of lime. The fibers come from abundant and available bio-based or mineral fibers such as cellulose, glass wool, or rock wool. The crushing sand comes from inert building waste and is used instead of river sand which is a resource under shortage. Lime is, like the other two constituents, available locally. The targeted performance is minimizing the environmental footprint compared to the current building materials available on the market in terms of CO_2 emissions and grey energy consumption over the entire life cycle. Additional specific objectives are a lifetime up to 60 years, the incorporation of at least 75% recycled or end-of-cycle materials and a high potential of further reuse or recycling. These performances must be optimized under all the structural, thermal and durability constraints of specific building applications. A test campaign has proved the energy-efficient nature of the processing and excellent potential in terms of insulation, fire resistance and mechanical strength, for materials containing a rate of paper fibers larger than 50%.

1. Context

The building sector is both energy and natural resources intensive as well as one of the most emitting industrial sectors in terms of waste and greenhouse gases. This accounts for the full life cycle including all the processing steps of the building materials. In addition, the valorization and recycling chains are not well developed, except for inert waste from constructions, which is today mainly downcycled into aggregates for road foundation and not reintroduced into material production processes [1]. New building technologies relying on a more sustainable use of natural resources are encouraged by the European Union [2]. These involve (i) green building concepts which are more sustainable and responsible, (ii) circular economy concepts that extend the lifespan and cycles of materials, and studies on reversibility, reuse and adaptability and (iii) the development of new building materials from bio-based raw materials with less energy-consuming production [3, 4, 5]. An increasing amount of materials is also based on wastes from other industrial sectors. However, materials directly made from recycling building waste have still not widely flourished. Considering the annual waste amount produced by this sector in Belgium - more than 10 million tons of building and demolition inert wastes produced each year [6] - and the development of new recycling chains (inert materials, paper, etc.), there is a real opportunity to develop and use these wastes as resources for the building sector.

The objective of this research is to develop a new class of sustainable building composite materials based on recycled fiber wastes, crushing sand and lime. The constituents, the composition and the manufacturing process will be described in detail in the second part of the paper. The objective is to create a balanced material that combines technical and environmental performances including circular aspects. The targeted performance is to minimize the environmental footprint compared to the other current building materials available on the market in terms of CO_2 emissions and grey energy consumption over the entire life cycle. Additional specific objectives are a lifetime up to 60 years, the incorporation of at least 75% recycled or end-of-cycle materials and a high potential of reuse or recycling. Obviously, these performances must be optimized while meeting all the constraints of the applications. Therefore, several building applications with reversible assemblies and connections will be studied in order to offer a high potential of reuse or recycling. These applications in the form of internal or external finishing panels and dry screed boards, will take advantage of the good performance of the material.

A first experimental test campaign has proved the energy-efficient nature of the processing and the good potential in terms of insulation, fire resistance and mechanical strength, for materials containing a volume fraction of paper fibers larger than 50% [7]. The first tests and first results will be discussed in the third part of the paper. The actual research methodology, discussed in the fourth section, is set under the umbrella of the rational materials selection approach, and relies on the characterization of the very heterogenous microstructures and properties, and on the modelling targeting high environmental performance indices under technical architectural constraints [8, 9].

This paper aims at presenting and discussing the methodology, the properties of the raw materials and briefly analysing the origin of the good performances with respect to the constituents and microstructure.

2. New composite material

As introduced above, the construction sector produces a lot of waste, which should today be seen as a huge deposit of available raw materials gold mine as primary resource to manufacture new materials. This process, called upcycling, allows the upgrade of wastes by transformation into a new high-quality composite material. The upcycling, as well as the reuse of building elements and materials is one of the UE targeted objectives in terms of circular economy [2].

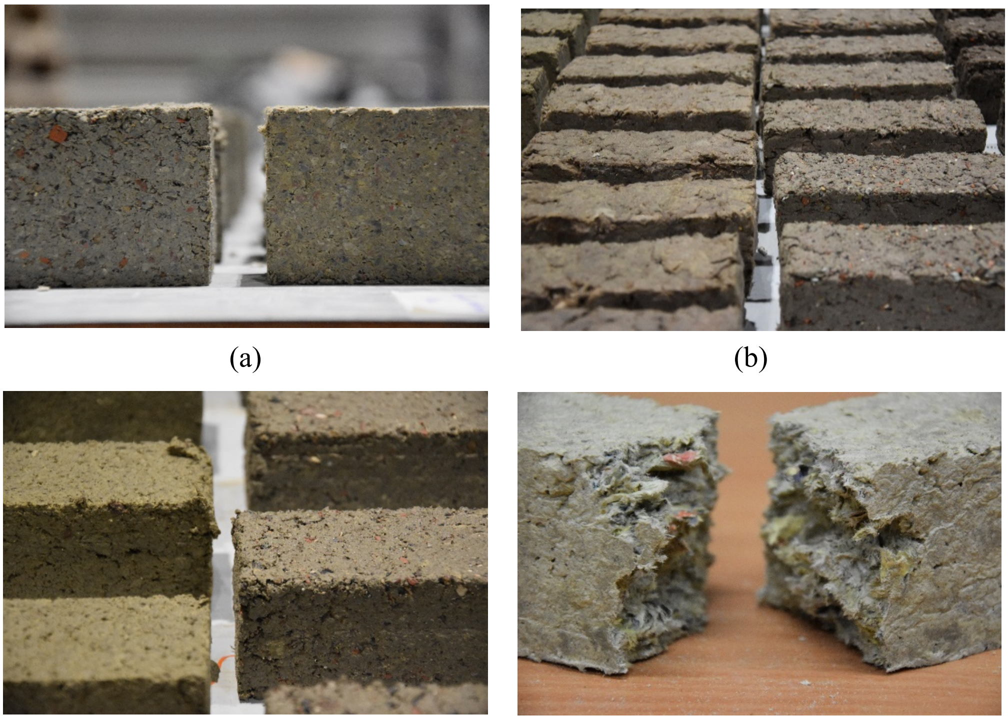
2.1. Constituents

This new material is a "composite" since it is made up of several constituents each providing different technical properties to the material.

Fiber wastes constitute the main component and therefore the largest part of the material. These fibers come from bio-based or mineral fibers such as cellulose, glass wool, rock wool or even inert waste of paper and cardboard. This type of fibers represents a large quantity of available wastes since it is widely used in the construction market in Europe, generally as insulating material and their implementation involves 5% of falls on average. In addition, there are not a lot of recycling channels for this type of waste yet so they can be considered as available and abundant resources. Even paper, which can undergo only a limited number of recycling steps (due to fiber degradation) before it becomes an inert waste. In fact, around 4.5 million tons of paper and cardboard wastes are produced each year in Belgium and only 63% are recycled. The main advantage of these fibers is that they provide insulating capabilities to the material thermal conductivity with potential mechanical impact as well as hygroscopic behaviour.

Sand is the second component, which is also a recycled resource. The selected sand comes from crushing inert building waste, such as bricks, concrete, cement, ceramics or even porcelain which are crushed, washed and screened to form sand with the same properties as the yellow river sand usually used in construction. There is a real opportunity to use crushing sand instead of river sand because yellow sand is a resource under shortage as well as because the building sector produces a huge amount of waste

every year which is still too weakly exploited. As explained above, this sand is downcycled for road construction. By incorporating it into the composition of a new material, it will be upcycled. The sand gives mechanical resistance to the material.
The third and final component is lime which acts as a binder for the material. Lime is used instead of cement for its lower environmental impact. Indeed, it produces less grey energy during manufacture and during transport since it is a local resource in Belgium.



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

Figure 1. Samples containing in addition to sand and lime: (a) cellulose wastes, (b) glass wool wastes, (c) rock wool waste, (d) paper wastes.

2.2. Processing

Another essential element to consider when developing building materials is the manufacturing process which has a direct impact on the environmental footprint in terms of CO_2 production and grey energy consumption. The goal here is to make this process as energy efficient as possible.

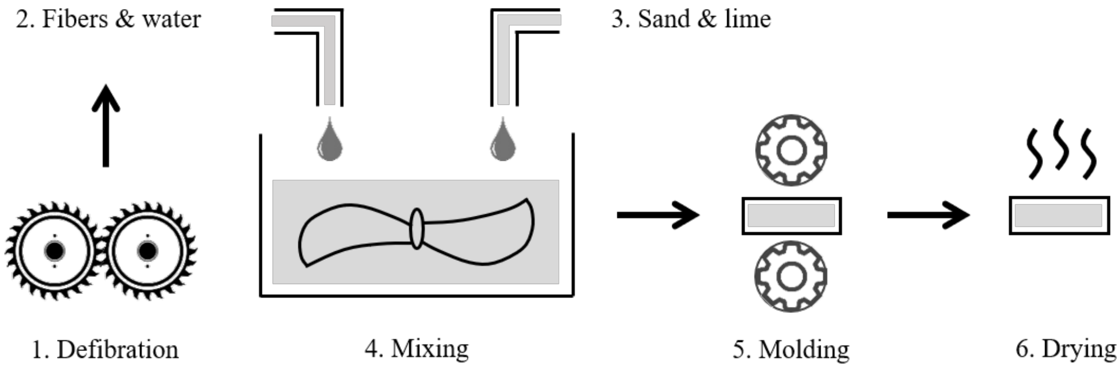


Figure 2. Energy efficient manufacturing process of the new composite.

As shown in Figure 2, the fibers are first crushed or defibrated to the desired size, then they are mixed with water, to which the crushed sand and lime are added. Thus, the mixture can be moulded and pressed. The material is then stored to dry naturally, avoiding any thermal cycle.
The manufacturing process for this new composite requires very low energy demand thanks to the use of physical and non-chemical transformations, to the simplicity of the production steps and to a natural drying without heating.

3. Experimental test campaign

A first test campaign [7] has demonstrated the potential of this new composite material and and highlighted the need of further research. Only the composition made of waste paper fibers - sand - lime was studied during this campaign. As paper allows only a limited number of recycling operations, the objective was to use paper wastes at the end of their life as fibers, which has become inert waste.

3.1. Experimental conditions

Samples are produced with a variation of the composition and of the processing conditions (temperature, pressure, humidity, etc.). The properties are then evaluated, without efforts at this stage to understand the origin of the measured properties.
In this case, several proportions have been studied, always keeping the same composition (paper - sand - lime). The paper content varied in six proportions from 40 to 90% wet paper. The proportion of lime and sand was kept identical. Several experimental tests were carried out in order to determine the main properties of the different samples such as water absorption, resistance to fire, bending, compression and creep and thermal conductivity.

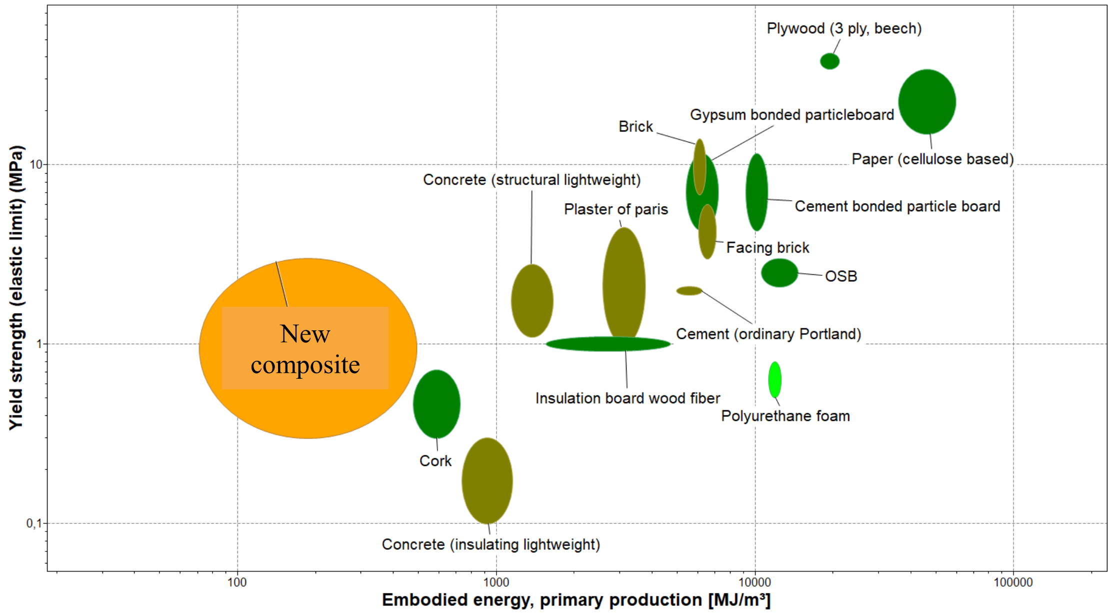
3.2. Main results

The results of the experimental tests show that samples containing more paper have a lower thermal conductivity on the order of 0.05 W/mK and therefore better insulating properties. The higher insulation properties conjugate with a lower environmental impact as a result of a higher proportion of recycled materials. However, the mechanical performances moderately decrease (in bending and compression).
The main properties have been compared to various existing materials on the building market such as cellular concrete or lime-hemp. The comparison of the main properties to these materials shows superior mechanical strength (above 1.5 MPa in compression), combined, such as in lime-hemp, with a low thermal conductivity and a very good fire resistance. The material has the additional advantage of being made from recycled raw materials, which helps the conservation of natural resources and recover waste.
This first test campaign provides the window of composition in which the next step of the study will concentrate, involving also introduction of other types of fibers as mentioned above (as cellulose, glass wool, rock wool).

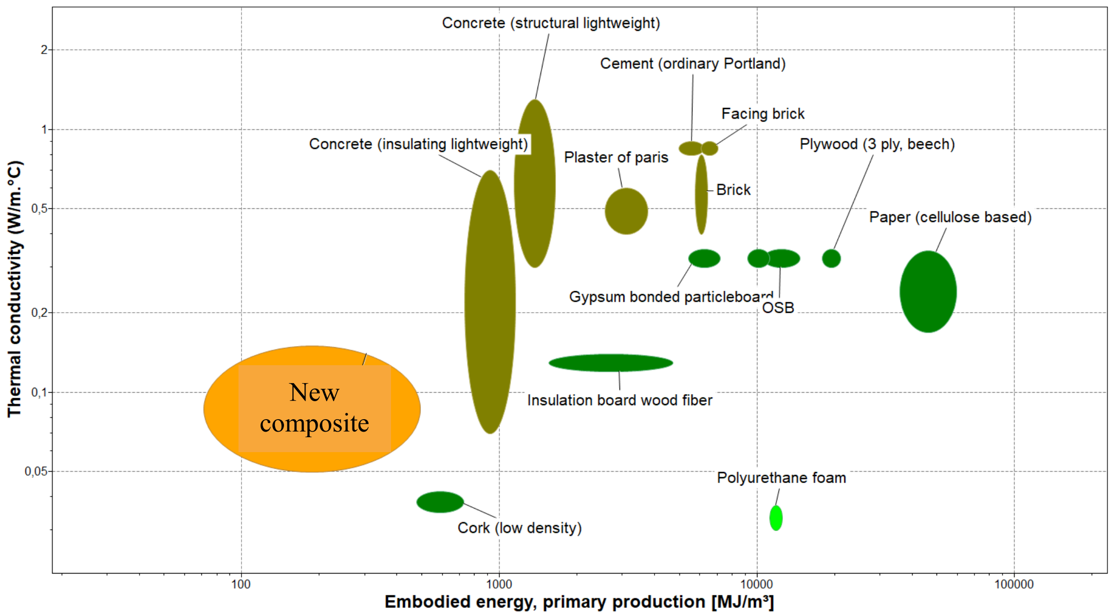
4. Material selection analysis

Materials science paradigm is based on the triangle “elaboration - microstructure - properties”. The objective is to understand the link between the properties of materials through an analysis of the microstructure which is itself the result of the processing history. This approach is carried out using high-performance characterization tools and models associated with numerical simulation methods. This is the approach that is pursued in this research. Nevertheless, it is supplemented also by a rational materials approach to guide towards optimum systems.

This approach consists in using specifications which vary according to each given application and which specify the objective to maximize accounting for a series of constraints and free variables. Then the objective is expressed in the form of performance indices. These indices are evaluated for each material in order to determine the best options, i.e. the one that optimizes the desired performance, for example using a selection chart. This approach also allows the identification of gaps in the property chart such as given in Figure 3. Such a chart positions the different material classes with respect to another for two properties or performance indicators. This rational selection approach naturally extends to eco-selection by working with eco-indicators such as the carbon or energy production linked to the life cycle of the material that must be minimized, depending on the constraints of the application (thermal, mechanical, etc.) [8] The method allows combining the technical performances with environmental and circular performances.



(a)



(b)

Figure 3. Estimated position of the new composite compared to conventional building materials, in a material property map providing the grey energy performance versus (a) yield strength or (b) thermal conductivity, from the Edupack software.

Based on the first test campaign, new circular composite has been positioned into two materials selection charts shown in Figure 3. Two maps are provided in terms of (a) the grey energy necessary for its production as a function of the yield strength on the first chart and (b) of the thermal conductivity on the second chart. Compared to known building materials (such as concrete, cement, brick, wood, insulation), these two charts show that the new class of composites fills a hole. It produces less grey energy than existing materials while having interesting technical properties. Very similar chart can be produced for the CO_2 emission, looking quite similar as a result of the generally strong connection between energy and greenhouse gas production. This shown the interest in applying such approach of eco-selection of materials in order to fill gaps on chart towards more sustainable materials.

5. Conclusion

This research provides a response to the environmental and economic challenges of the construction sector by developing a balanced eco-circular composite material composed of a high amount of upcycled waste based on an energy-efficient manufacturing process. A first test campaign indicates a series of favourable physical performances depending on the targeted applications (mechanical, thermal, acoustic and water resistance) and environmental performances, while being reversible and recyclable as part of a circular economy scheme.

Acknowledgements

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