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Modelling of heat transfer through permanent formwork panels exposed to high temperatures

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HIGHLIGHTS

- Modelling of heat transfer through permanent formwork panels exposed to high temperatures.
- The model can be easily implemented as external subroutine in Abaqus FE software.
- Comparison between the experimental and numerical results.

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ABSTRACT

A small-scale fire test was performed on a wood-cement panel intended as a permanent formwork. The tested panel was subjected on one side to a uniform heat flux of about 6 kW/m^2. Measurements of the temperature profiles were recorded with thermocouples embedded in the sample. The density and its variation with temperature were obtained by taking weight measurements. The thermal conductivity of the wood-cement composite at room temperature was determined using the hot plate method. Its variation with temperature and that of the specific heat were determined using analytical and numerical approaches. Using the obtained data, a pyrolysis model, implemented in Abaqus, was developed to simulate the effect of heat in the panel. The validation of the model is carried out by simulating charring tests. The model provided reasonable predictions for the thickness of the charred layer and the temperatures profiles across the depth of the panel. The model can supplement the testing of small laboratory samples to characterise the fire performance of these panels, and hence help establish their certification for use in sustainable construction.

1. Introduction

The building industry is particularly energy-intensive. It is a major greenhouse gas emitter and consumer of natural resources. Buildings consume large amounts of energy and account for a quarter of carbon dioxide emissions [1–4]. It is clear that the declared environmental targets cannot be met without dramatically reducing the environmental impact of buildings and infrastructure construction [2]. It is not surprising therefore that the construction and infrastructure industry has been identified as one of the priority targets to fulfil the objectives of sustainable development.

To ensure user comfort, and reduce the environmental impact, the construction sector must innovate; hence the interest of developing eco-building [5–9]. This new design paradigm aims to build comfortable buildings with low environmental costs. Sustainable buildings are designed to meet the four criteria: (1) an ecological criterion to minimise greenhouse gas emissions throughout the life of the building, and reducing the use of non-renewable resources; (2) a health criterion aimed at improving the well-being of the occupants; (3) a user comfort criterion; and (4) an economic criterion to ensure the optimisation of the cost of the building over its service life.

To achieve sustainability in the building industry, the materials used must therefore become more efficient and meet the specific criteria. In this aspect, bio-sourced materials combined with a cementitious matrix offer an interesting alternative to traditional construction materials. They are inexpensive to produce, and environmentally friendly. Their multiscale porosity results in a low hygro-thermal transfer ability as well as an excellent capacity to absorb sounds [10–15]. The wood-cement panels used as permanent formwork elements, as illustrated in Fig. 1, are a perfect example. These panels serve two purposes: (1) through mechanical

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Fig. 1. Wood cement panels as permanent formwork.

strength, they ensure the function of the formwork; and (2) by remaining in place to form the inner and outer façades of the building, they provide thermal and acoustic comfort through their hygro-thermal transfer and sound absorbing properties, and the can be easily rendered.

A major hurdle to the development of the use of wood-concrete panels in construction is their perceived combustibility, which raises questions about their fire safety. Indeed, the flammability of cladding panels, particularly in high-rise buildings, poses a serious safety issue. Fig. 2 shows a facade panel of the Grenfell tower in London exposed to a real fire on the 14th June 2017, which, unfortunately, left more than 80 dead. The use of wood cement panels could constitute a solution because the cementitious matrix provides a protection to the wood particles. However, their use in construction will remain marginal until the fire safety issue is resolved.

To ensure the safety of occupants and maintain the structural integrity of a building in the presence of a real fire, fire protection is a major requirement in the design of buildings [16–18]. The fire resistance of a building is a measure of its ability to withstand the effects of fire in one or more ways: resistance to collapse, limiting the spreading of fire, and so on... The longer the fire resistance time, the better its performance. In recent years, the construction sector has become increasingly interested in the use of waste from the timber industry because of the contribution of organic materials to the regulation of indoor climate [19–33]. In addition, the use of these materials promotes the recovery of waste and industrial co-products, which improves the environmental balance. However, a major hurdle to the generalisation of their use is their perceived combustibility, which raises questions about their fire safety. The aim of this study is the characterisation of the behaviour of these materials under fire for use as permanent formwork. This study develops for important points: (1) Experimental work: The values of the density at high temperature and the thermal conductivity at room temperature are measured; (2) Analytical work: Generalisation to 2D (and 3D) of a one dimensional pyrolysis model originally developed in literature. Moreover, the thermal properties at high temperatures are estimated using a mixture approach; (3) Finite Element (FE) modelling: Implementation of the thermal law as a user subroutine Umatht in Abaqus software; and (4) Validation step: Predictions of the FE model are compared to the experiment results.

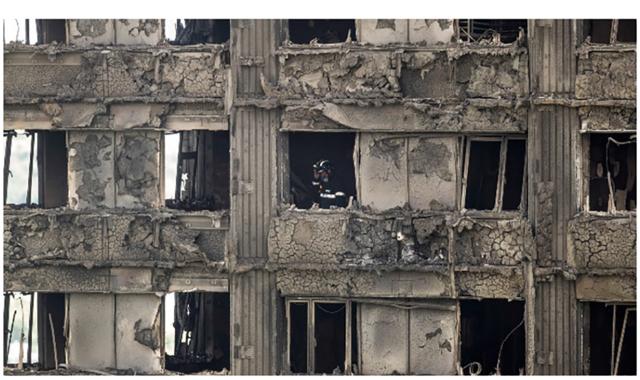

Fig. 2. Facade of the Grenfell tower in the aftermath of the fire.

Indeed, there is very little data available the fire behaviour of these composite panels, and most of it is empirical. Because they are often used as lining materials and have no structural role, there are virtually no design methods available, which limit their commercial use. The methodology presented is inspired from the EC5 [34] regulation for timber structures. To improve the fire resistance of the wood-cement composite material, it is necessary to study the variation of its thermo-physical properties such as thermal conductivity, specific heat and density with temperature, and observe its thermal degradation during exposure to fire. In this work, different and complementary approaches (experimental, analytical and numerical) are used to analyse the fire performance of wood-cement panels. The fire test is performed in the laboratory on small specimens exposed to a radiating heat of about 1600 W. A heat transfer analysis is carried out using a finite element model including the three modes of heat transfer (radiation, convection and conduction) to simulate the fire tests. To calibrate the constants of the thermal model, the results of the simulations are compared with the experiment.

2. Experimental characterization of the thermal properties of the wood-cement material

The thermal behaviour of the wood-cement composite material depends on the constituents, the morphology, and to the interactions between the different types of transfers existing in the material. The wood chips came from the waste generated by the timber industry. They are from the spruce species, which belongs to the category of softwood. Portland cement type CEM II/A-L 42.5 R was used. The cement's Blaine fineness was about 0.41 m^2/g, and its relative specific gravity was around 3.07; more details are given in Ref. [1].

Like all lightweight concretes, the material developed here contains a large proportion of air voids. The still air trapped in the voids is a very poor conductor of heat, thus conferring to the material excellent insulation properties. The dry conductivity of the final material is less than 0.54 W/(m.K), which represents the conductivity of the binder (cement) alone. The presence of moisture in the material influences the value of the thermal conductivity. This point, however, is beyond the scope of this study. Hence, only the thermal behaviour of the dry material will be described in this section using experimental data obtained on the variations of the density, thermal conductivity and specific heat at elevated temperatures.

2.1. Mass degradation

Charring tests were carried out on specimens measuring 35 $\times$ 200 $\times$ 75 mm. The test sample is exposed to a ceramic radiating panel consisting of 4 flat emitters of 12 $\times$ 12 cm. The total power of the panel is approximately 1600 W (4 $\times$ 400 W). The specimen is placed vertically 5 cm away from the heating plate. The maximum flow imposed is 6 kW/m^2. Five thermocouples are placed at