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Thermal tests of a scaled down mock-up of CP5.2 packaging system: Post-test analysis

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ABSTRACT

In this study, the thermal performances of an Italian CP5.2 packaging system aimed at the transportation of bituminised wastes (i.e. engulfing fire of 800 °C for 30 min according to the IAEA regulation) are presented. Due to the high risk of auto-ignition of the bituminised wastes, that are stowed in the drums, in turn, immersed in the cement matrix of the CP 5.2, it was decided to test firstly a small scale mock-up. The mock up, containing only one drum with bituminised waste, was designed and built at the Department of Civil and Industrial Engineering (DICI) of the University of Pisa. The experimental test was carried out at Lab. Guerrini of the University of Pisa.

Results demonstrated that after half an hour of fire exposure at 800 °C, the temperature in the bituminised waste package is below that of auto-ignition of the bitumen. The obtained results allowed in addition to set up the test procedure to adopt for fire test of a full scale CP5.2 system.

Post test analysis, which was carried out by performing FEM analysis, is also presented and results compared to the experimental ones.

1. Introduction

The qualification of a packaging system for the transport of hazardous/radioactive materials (RAM or RW) must demonstrate the container fulfils the International standard requirements (IAEA, 2012; UNI, 2011; ENEA, 1987) and is able to provide protection to the human being and environment in any design conditions.

In this study the performance of a CP 5.2 containing drums with bituminised wastes will be presented. In particular the engulfing fire effects will be investigated experimentally and numerically (Lo Frano et al. 2011, 2018; Pugliese et al., 2010; Rains, 1999). The CP5.2 packaging is designed according to the activity and physical and chemical form of the waste material (e.g., raw solid wastes, wastes immobilized in cement or bitumen and compacted pellets immobilized by grouting).

In doing that, the thermo-mechanical response of a scaled down mock-up (1:6) of the CP5.2 packaging system, subjected to fire test, is investigated. In the following, the post-test analysis will be provided along with the discussion of the effects caused by the high thermal gradient generated by the fire exposure (800 °C for 30 min).

The integrity of packaging is crucial for a safe disposal, storage and transport of RAM/RW, for this reason manufactures has to demonstrate that packaging systems withstand all the loads, occurring in normal operation and accident conditions (Lo Frano et al., 2014; Rains, 1999), and satisfy safety requirements (i.e., confinement, containment, and radiation protection).

The relevance of the present study is due to the peculiarity of drums stored in the Italian CP5.2 packaging system. In fact, they contain RWs (low and intermediate level wastes) immobilized in bitumen; and, even if this treatment technique was used in the past today, all the issues that could evolve during normal and accident conditions are quite new in literature (due to the lack of the studies on this subject).

Moreover, an important aspect to consider is the highly risky associated with the possibility that bitumen vapors form and catch fire. Due to the flammability risk of the bitumen (having auto-ignition temperature of 250 °C), adequate test procedures were prepared and adopted as well as proper emergency actions planned. The small scale mock-up scheme of the CP 5.2 packaging system is given in Fig. 1.

To simulate the thermal behaviour of the mock up and determine its thermal performance a numerical model by ANSYS© was set up and implemented in a rather refined way, taking into account material properties and constitutive laws as well as all the heat transfer modes.

The accident conditions (IAEA, 2012) taken into account for the experimental test and the numerical simulation are:

1) exposure of a specimen for 30 min to a thermal environment that provides a heat flux at least equivalent to that of a hydrocarbon fuel-air fire in sufficiently quiescent ambient conditions to give a

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Nomenclature

CP	prismatic packaging system
DAS	Data Acquisition System
IAEA	International Atomic Energy Agency
RAM	Radioactive material
RW	Radioactive waste
TC	Thermocouple

minimum average flame emissivity coefficient of 0.9 and an average temperature of at least 800 °C, fully engulfing the specimen, with a surface absorptivity coefficient of 0.8 or that value the package demonstrated to possess if exposed to the fire specified.

2) cooling down of the specimen to an ambient temperature of 38 °C, which would be only subject to the solar insulation and to the design maximum rate of internal heat generation within the package by the radioactive contents for a sufficient period to ensure that temperatures in the specimen are everywhere decreasing and/or are approaching the initial steady state conditions.

The investigation, through experimental and numerical approaches, aims to demonstrate that the containment capacity of the packaging system is guaranteed, and to provide advice/recommendations concerning the design and testing (qualification process).

2. Description of the mock-up of the CP- 5.2 packaging

The prismatic container CP 5.2 has an external nominal volume of 5.2 m^3. The maximum external dimensions, taking into account closing mechanisms and any devices for the installation of vent systems, filters, etc., are: length = 2.5 m; width = 1.65 m; height = 1.25 m (Lo Frano et al., 2018). This packaging system stores six bituminised packages within and it is reinforced at the base in order to facilitate stacking and to limit the contact area and, therefore, the possible corrosion phenomena evolving at the interface. Furthermore, these reinforcements and/or stiffeners allow also to improve its mechanical strength.

Fig. 2 shows the mock-up representative of one sixth of the whole CP5.2 packaging; this shape guarantees the respect of the cement mortar thickness surrounding the bituminised wastes (similar to those of the entire CP5.2 storage configuration). This non-symmetric system (Fig. 2) has been entirely designed and built at the DICI of the

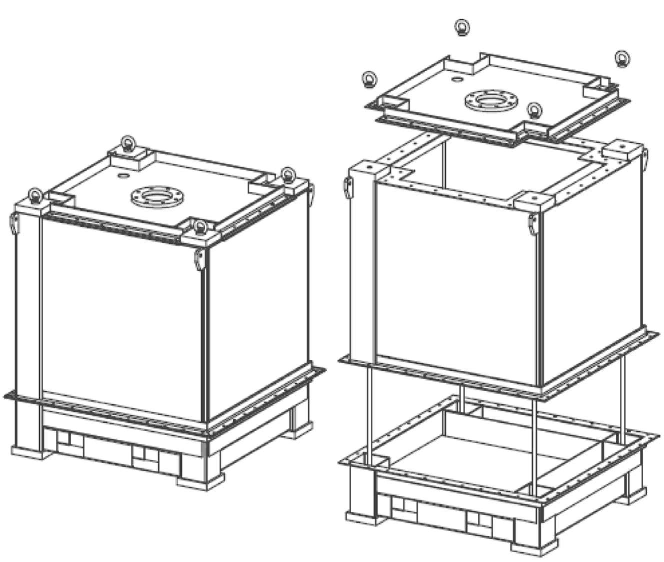


Fig. 1. Schematic representation of the experimental mock-up (1/6) of CP 5.2 packaging system; on the right side it is given a disassembled overview.

University of Pisa; its main dimensions are: about 1 × 1m and 1 m height.

Specifically, the mockup has a prismatic shape and is made of carbon steel properly coated. Inside, immersed in the cement matrix, it is stored one bituminised wastes package. The tightness is guaranteed by a suitable gasket and by the primary cover lid. Its main design characteristics, and geometrical and material properties are in agreement with the UNI 11196 (UNI, 2011), which represents the Italian reference standard.

To correctly represent the large-scale packaging behaviour, two of the four outside surfaces have been thermally insulated by means of 150 mm mineral wool, so to represent the adiabatic condition (null heat flux). In addition, a flange is present onto the cover lid; it allowed not only to grout cement inside the system but also behave as a filtering system during the test execution.

The mockup was equipped with four eyebolts for easier handling and lifting during the positioning on the slide of oven. Several thermocouples (TC), type K duly calibrated, were immersed in the cement paste and connected to the walls of the inner drum (T4, T5, TC7 and TC11 were located at the bottom of the bituminised package, while T3, TC12, TC13, TC14 and TC15 on the lateral surface of the bituminised package) and to the outer walls of the mock-up. The T1 = TC16, TC17, TC18 and TC20 were located on the packaging surface; the T2 = TC1, TC2, TC3, TC4, TC5, TC6, TC8, TC9, TC10 and TC19 at half thickness of the cement mortar.

The TCs allowed to measure the temperature distribution during the heating and the cooling phases, and to control the temperature of the oven and of the bitumen. Temperature values were acquired by an adequate data acquisition system. Fig. 3 shows the thermocouples disposition scheme.

The description of the experimental thermal test of CP5.2 is given in Lo Frano et al., (2018). Fig. 4 shows the instant of positioning of mock-up on the slide of the oven, before it would be tested at 800 °C for 30 min and after that, the simulacrum was handled for the cooling phase in air. In addition, the temperature regulation of the electric oven, during heating phase and test execution, was adequately controlled through a PID system (GEFRAN© GF Promer), avoiding in this way any problem of flame instability, which could have been encountered with real fire.

3. Numerical simulation of fire test

3.1. Thermal analysis formulation

The numerical model used for the post-test analysis is implemented in ANSYS©. It is based on a heat balance equation obtained from the principle of conservation of energy through which the code calculates nodal temperatures and other thermal quantities of interest.

The governing equations relate to the heat conduction mechanism. The heat equation, from the conservation of energy, is:

$$\nabla q = q_{gen} - \frac{de}{dt} \tag{1}$$

Eq. (1) provides the net heat conducted outwards, that is the sum of the volumetric heat generated (q_{gen}) and of the change in energy (e) stored within the structure. The change of the internal energy is thus related to the volume capability to store heat by increasing its own temperature; it is given by:

$$\frac{de}{dt} = \rho C_p \frac{du}{dt} \tag{2}$$

In Eq. (2), u is the temperature, ρ is the density of the material and C_p specific heat capacity of it. According to the Fourier's law, the rate of heat energy per unit area through a surface is proportional, through the thermal conductivity (k), to the negative temperature gradient across the surface:

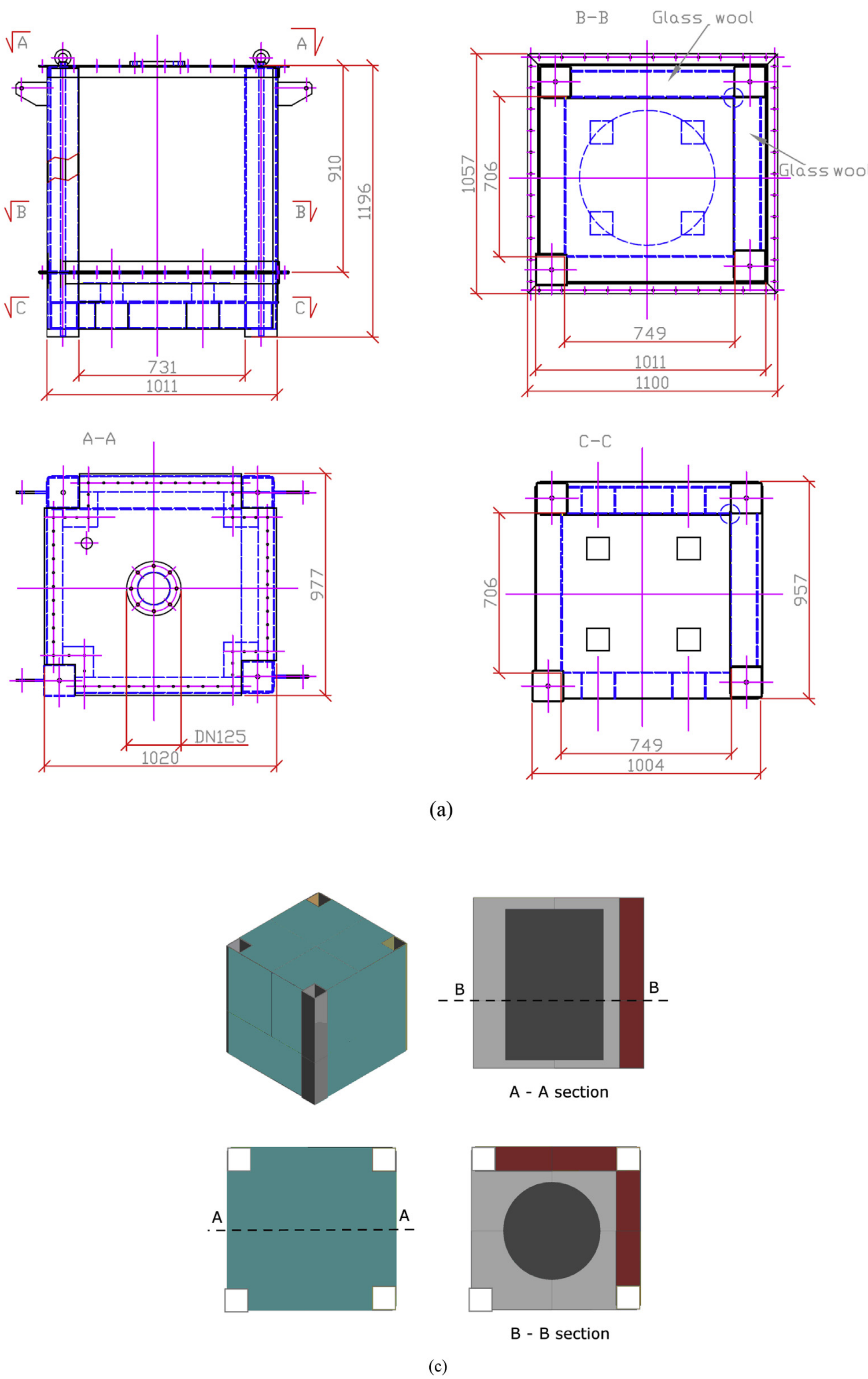


Fig. 2. (a) Drawings of the packaging mock-up. The isometric views of the 3D model of one-sixth of the CP-5.2, and the adiabatic surfaces in A-A and B-B sections (red colour) are shown respectively in figure (b) and (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$q = -k\nabla u \tag{3}$$

Finally, by substituting equations (3) and (2) in equation (1), we obtain the heat conduction equation:

$$\rho C_p \frac{du}{dt} - k\nabla(ku) = q_{gen} \tag{4}$$

By considering the procedure employed by ANSYS© for the solution of this equation in matrix form, it is possible to calculate at each time instant the temperature vector $\{u_n\}$ by solving the equations:

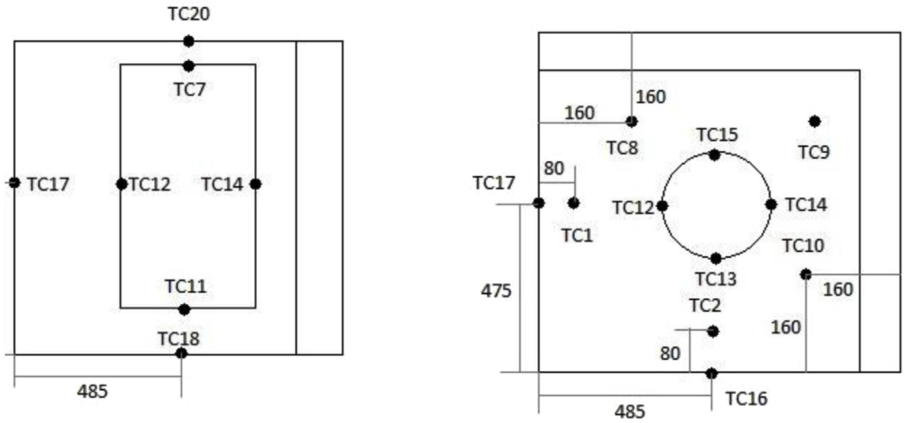


Fig. 3. Thermocouples position scheme.

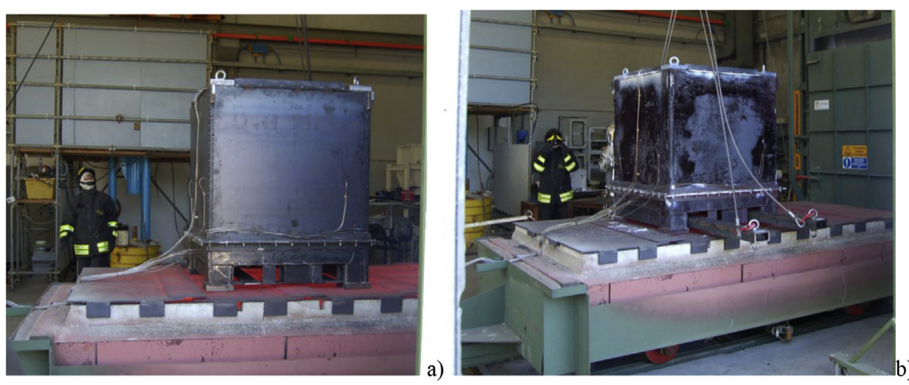


Fig. 4. Positioning of the mock-up on the slide of the oven before (a) and after fire test (b).

$$\begin{cases}\{u_{n+1}\} = \{u_n\} + (1-\theta)\Delta t\{\dot{u}_n\} + \theta\Delta t\{\dot{u}_{n+1}\} \\ [C]\{\dot{u}_{n+1}\} + [K]\{u_{n+1}\} = \{F\}\end{cases}$$

$$\Downarrow$$

$$\left(\frac{[C]}{\theta\Delta t} + [K]\right)\{u_{n+1}\} = \{F\} + [C]\left(\frac{1}{\theta\Delta t}u_n + \frac{1-\theta}{\theta}\right)\{\dot{u}_n\} \tag{5}$$

where θ is the transient integration parameter and is equal to 1 by default, Δt is the time step, $\{u_n\}$ and $\{\dot{u}_n\}$ are the nodal DOF values time rate of the nodal DOF values at time t_n.

The value of θ, known as Euler Parameter, must vary only between 0.5 and 1. In this range, the time integration algorithm is implicit and unconditionally stable.

When θ is equal to 0.5, the time integration strategy is referred to as Crank-Nicolson technique, while when it is equal to 1, the time integration strategy is referred to as Backward Euler technique. This is the default and most numerically stable setting since it eliminates spurious oscillations that may arise when severe nonlinearities or higher order (i.e., midside-noded) elements are present (it requires generally a smaller integration time step to achieve accuracy comparable to Crank-Nicolson).

3.2. Modelling and simulation

The numerical model of the mock-up is shown in Fig. 5. It is a 3-D FEM model with about 496333 type SOLID70 elements representing the bituminised RWs package, the cement mass, the overall packaging system with closure lid. This eight nodes element (with the temperature as single degree of freedom at each node) allows to simulate all the heat transfer modes (conductive, convective and radiation) inside the package and between the package and the surrounding oven environment.

For the numerical study, a mesh independence study was of course performed. The maximum mesh size of the implemented model was defined based on the module of Fourier for each mockup material (see Table 1), like:

$$\Delta t \geq \frac{(\Delta x)^2}{(M\alpha)} \tag{6}$$

α is the thermal diffusivity dependent on the time step, Δx the average element length and M is a coefficient ranging from 1 to 6.

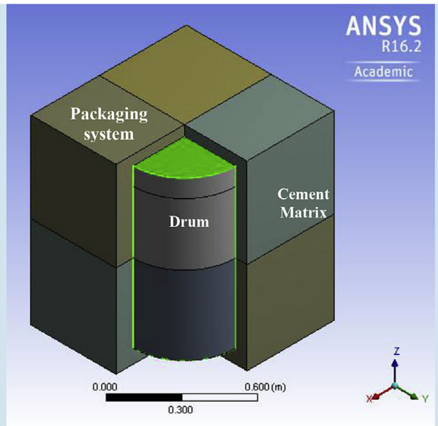
The bituminised wastes and the drum are represented respectively through a cylindrical solid and a thin cylindrical structure, with flat circular bottom and cover lid, surrounding the previous one. The cement matrix is reproduced by the external prism.

Some simplifications have been introduced in the modelling: the lower brackets were not represented while the cover lid was modelled like a simple plate. Moreover, structural parts as lifting trunnions, bolts and threads were not modelled since they have less influence on the temperature distribution. Further simplifications, such to neglect the external steel envelope and the external insulation on two of the four surfaces, were felt necessary to reduce the computational effort focusing mainly on the components that are significant for the thermal analysis.

The input materials properties are herein following indicated; specifically they are:

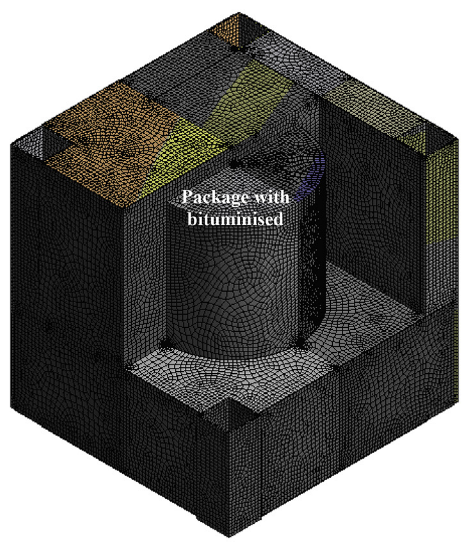
1) For the bitumen:

the density is 1423.3 kg/m^3, the specific heat 969.9 J/kg °C and thermal conductivity 3.036 W/m °C.



	Packaging system	Drum	Cement matrix
Height [mm]	780	880	1011
Length [mm]	-	-	868
Width [mm]	-	-	825
Radius [mm]	286	$r_{int} = 286$ $r_{ext} = 287$	-

(a)



(b)

Fig. 5. a, b. In the top figure (a) it is provided the 3D model of the experimental mock-up with its main constituents' dimensions, while in the below figure (b) it is shown the discretised FEM model.

Table 1
Module of Fourier for the three constitutive materials of the mock up.

Material	A (m^2/s)	Δx (m)	Δt (s)	$(\Delta x)^2/6\ \alpha$	Relation satisfied (Y/N)
Cement	3.5E-7	10E-3	60	47.6	Y
Bitumen	2.2E-6	20E-3	60	30.3	Y
Steel	1.77E-5	30E-3	60	8.5	Y

2) For the carbon steel:

the density is 7850 kg/m3, specific heat 434 J/kg °C and thermal conductivity 60.5 W/m °C.

3) For the cement matrix:

the density is 2300 kg/m^3; the specific heat behaviour, as function of temperature, is that plotted in Fig. 6.

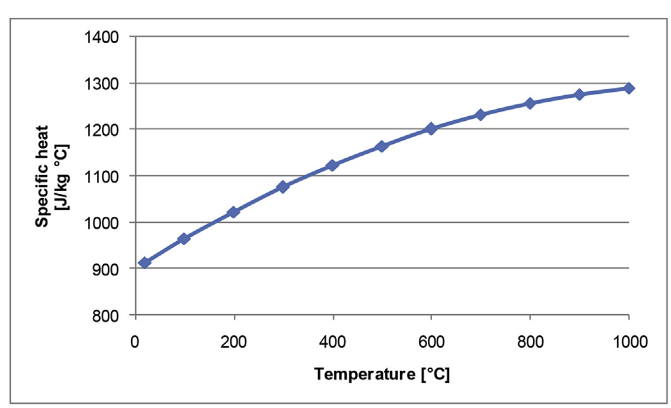


Fig. 6. Cement matrix specific heat vs. temperature.

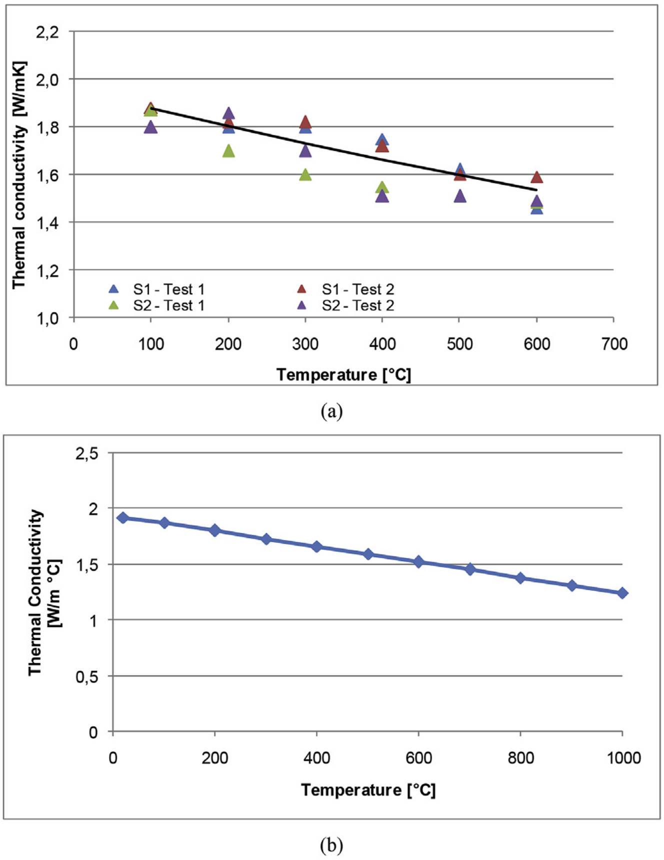


Fig. 7. a, b. Concrete thermal conductivity vs. temperature. In figure 7 a, it is represented the experimental trend of the thermal conductivity obtained performing experimental on different samples (namely S1 and S2).

The cement matrix thermal conductivity was furthermore experimentally measured by executing hot wire test at temperatures ranging from 100 to 600 °C on samples made of the same cement paste of that used for grouting the mock up (Lo Frano et al., 2017). Interpolating the so obtained data (Fig. 7 a), it was determined the behaviour of thermal conductivity (Fig. 7 b) used in the numerical simulations.

The engulfing fire exposure (fire test) has been simulated by

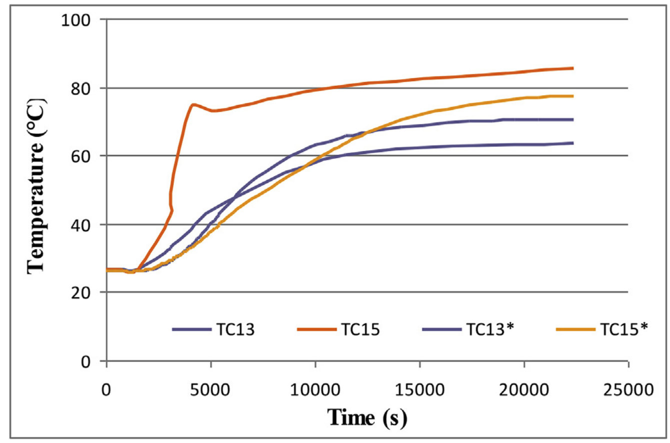


Fig. 9. Comparison of the temperatures located at the lateral surface of the bituminised package: the experimental measurements are provided by the TC13 and TC 15 plots, while the numerical trends are provided by those of TC13* and TC 15*.

imposing a temperature of 800 °C at the outer muck-up surfaces and assuming an equivalent convection coefficient equal to 230 W/m^2°C. This allowed to simulate the convection and the radiation between flames and container.

The convective heat input was included on the basis of still ambient air at 800 °C, in the accident condition, assuming also the absence of artificial cooling after the end of external heat input. Moreover, each radiating surface pair was defined by means of the emissivity (values equal to 0.8), the Stefan-Boltzmann constant (5.67e-8 W/m^{2}K^4) and the temperature offset.

In the numerical analysis we assumed also an initial uniform temperature distribution of 26 °C. To simulate the heating up (exposure for 30 min to about 800 °C) and the natural cooling down in air, (phases characterising the fire test), the temperatures measured by the thermocouples on the outer surfaces of mock up have been imposed as boundary conditions. These values are reported in Fig. 8.

4. Post test analysis of the experimental fire test

Analysing the numerical results, it is possible to observe that the temperatures' trends do not perfectly overlap each other's. This is first

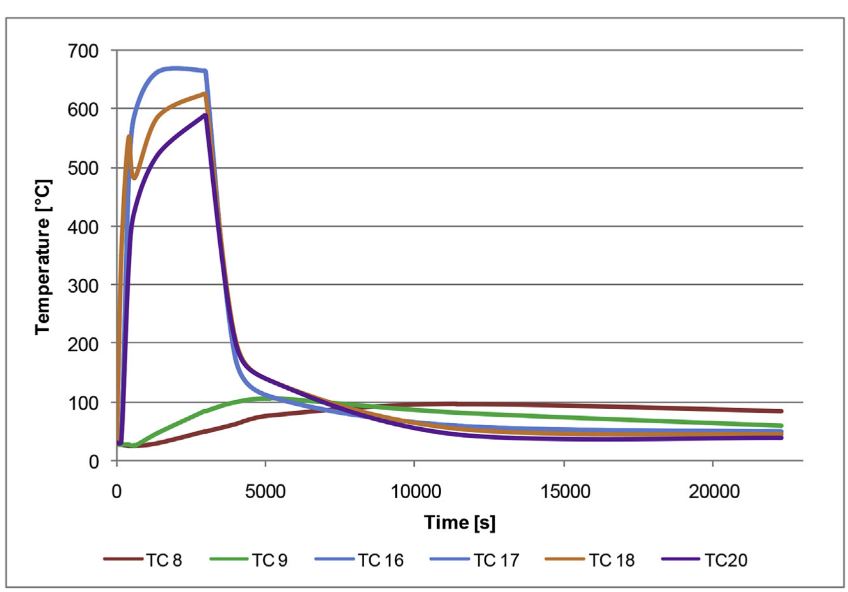


Fig. 8. Temperature behaviour used as boundary conditions for fire test simulation. TCs position complies with the thermocouples scheme given in Fig. 3.

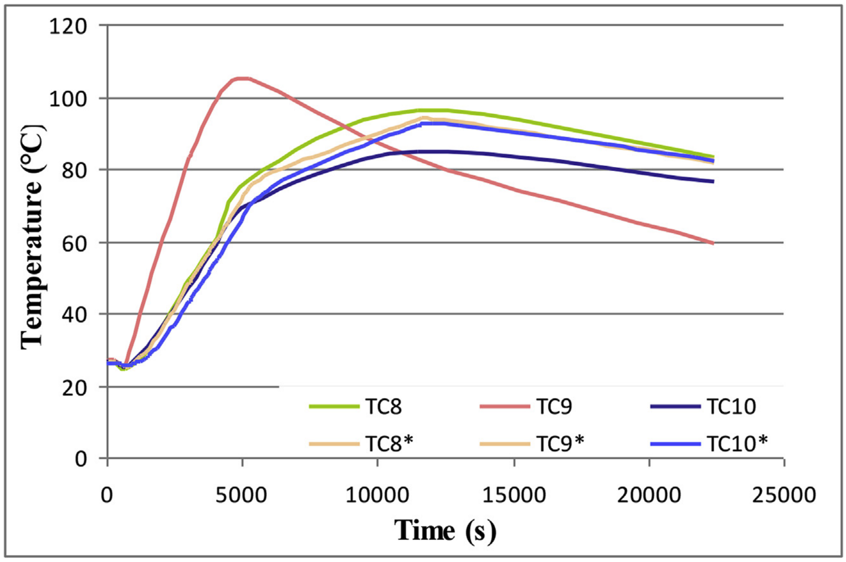


Fig. 10. Comparison of the temperatures on the mock-up outer surfaces.

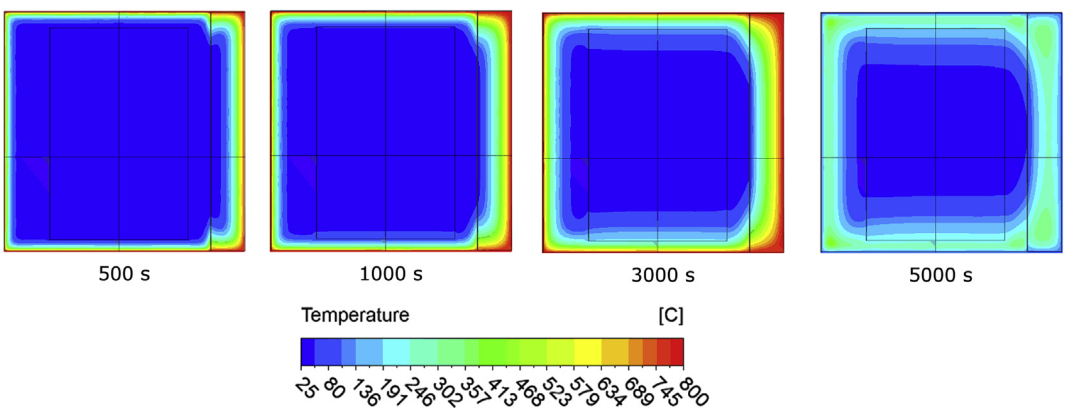


Fig. 11. Temperature distribution at the section A-A of mock-up.

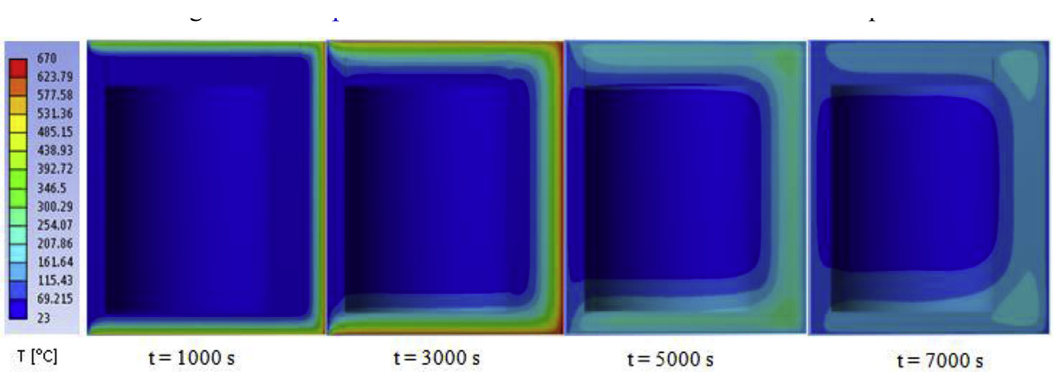


Fig. 12. Temperature distribution in the cement matrix at the axial section.

because the boundary conditions (temperatures) imposed on the overall surfaces and along edges of the numerical model derive from point measurements carried out (specific points of the mock-up corresponding to thermocouples positions) and thus do not represent perfectly the real temperature distribution.

In the following figures the obtained (numerical and experimental) results are given. The label with star identifies the numerical results. By analysing them, it is possible to note, in general, a quite good agreement despite some small discrepancies, mostly probably due to the above mentioned boundary conditions (i.e. temperatures) introduced in the numerical model and, in small extent, to the modelling the bitumen (the behaviour of the bitumen has been implemented as linear elastic because during the fire test its temperature did not ever overcome the limit temperature beyond which the phase change occurs).

Fig. 9 shows a discrepancy, that characterises mainly the initial phase of the fire test, between the values of TC15 and TC*15, that is probably due to the non-perfect thermal insulation (adiabatic wall condition) of mock up. TC13 and TC13* plots represent the behaviour of the temperature at not insulated mock-up surfaces (see the border of the grey part of sect. B mock-up in the previous Fig. 2 c). By comparing

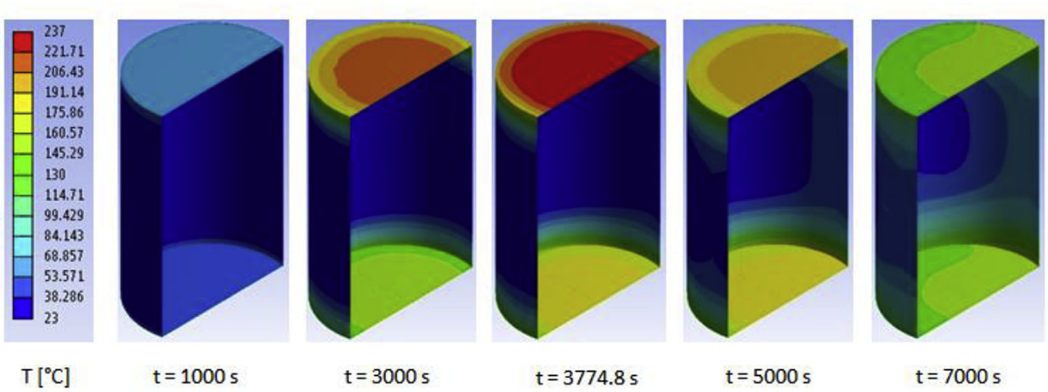


Fig. 13. Axial distribution of the temperature in the drum.

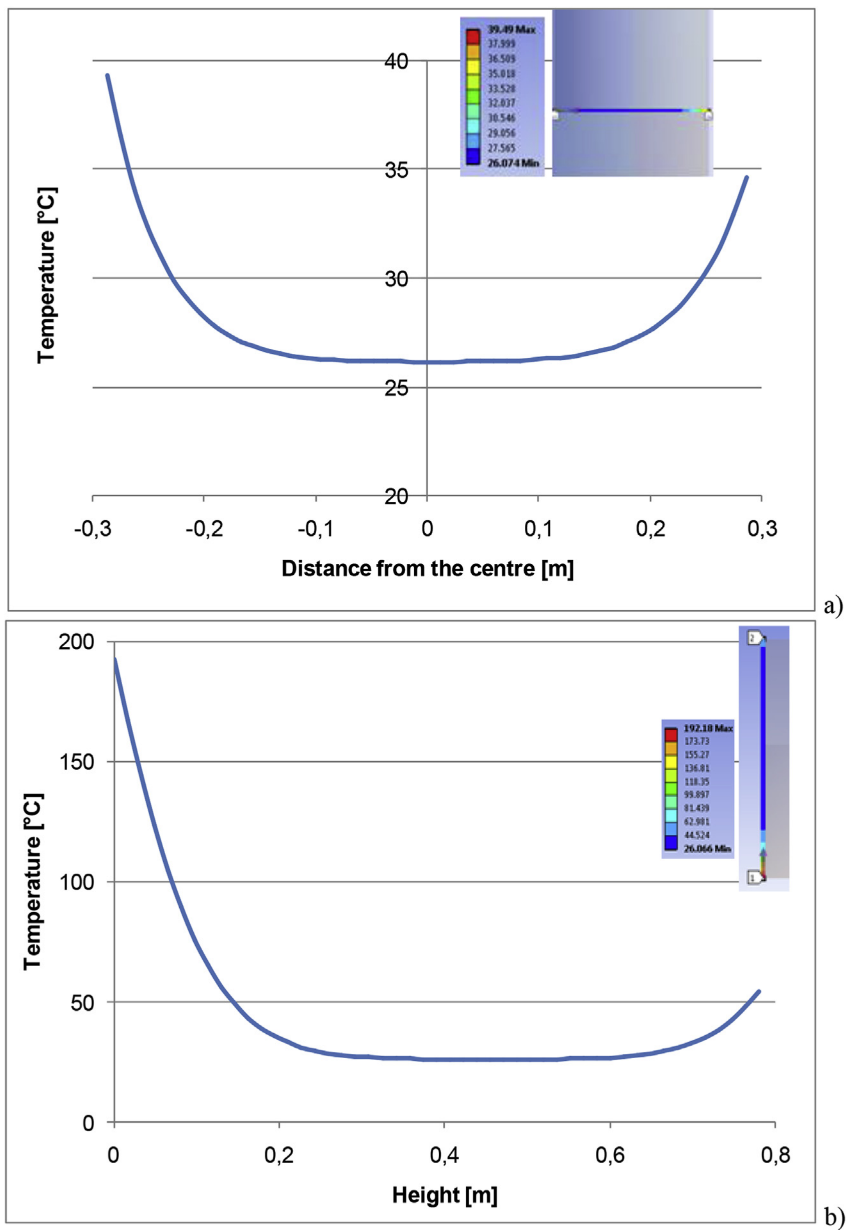


Fig. 14. a, b. Trend of the temperature in bitumen: a) radial distribution and b) axial distribution.

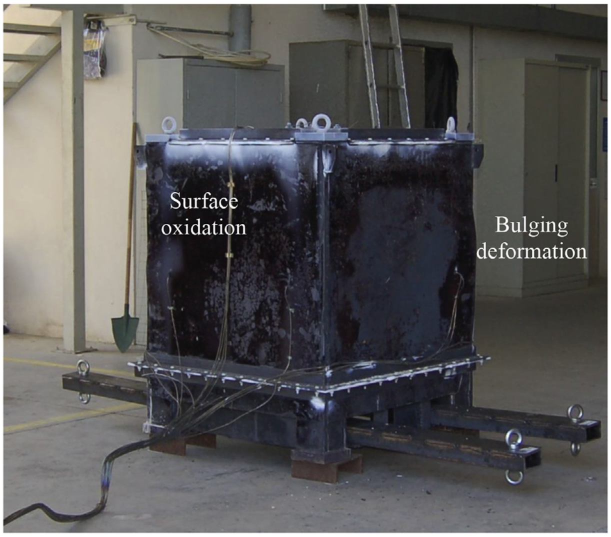


Fig. 15. Overview of the mock-up after the fire test.

the measured and numerically calculated temperatures trend, we find a discrepancy less than 10%: FEM model is so able to simulate well the fire test.

The difference reduces as the accuracy in the modelling increases; as an example for values measured by the TC13 or TC10 discrepancy is less than 10% (Figs. 9 and 10). For the TC8 and the TC10 instead, the numerical and experimental temperatures trends overlap exactly. As for temperature measured by the TC9, the observed discrepancy is caused by edge effects.

Nevertheless a good reliability appears. The overview of the temperature distribution at the section A-A of mock-up is shown in Fig. 11. The thermal gradient leads to a rapid increase of the temperature of the outer surface and of the internal components (gasket, closure lid, etc.) close to them, as observed in the temperature behaviour measured by TC9 (Fig. 10) positioned at the half thickness of the cement mortar far from the adiabatic walls. This implies that the temperature propagates in different ways inside the mock-up and it is also evident how, due to the cement matrix thermal inertia, the temperature increase in the internal components is much more prolonged over the time than the real heating up phase.

At the end of heating phase the maximum temperature reached inside the simulacrum ranges from 300 °C to about 100 °C, whilst it reaches about 665.6 °C at the insulated surfaces.

Fig. 12 shows the temperature distribution inside the cement matrix, in the axial section. By analysing the distribution of the temperature in the drum, we observe that the maximum temperature of 236.58 °C is reached at the lid level, in correspondence of which the thickness of the grouted cement is minimum (see Fig. 13).

Furthermore, the radial and axial temperature distributions in bitumen at 4353 s, which is the instant when the average bitumen temperature is maximum, are plotted respectively in Fig. 14a and b.

The former is calculated along a path located at approximately the mid-height of the bitumen waste package, the latter along the axial direction. Fig. 14 shows that in the radial direction the temperature remains very low. Along the vertical axis the maximum temperature is reached at the bottom of the bituminised package, and at the lid level the temperature is only few degrees beyond the minimum value. This is because of the thermal inertia of the cement layer. Nonetheless, the temperature (maximum value) inside the bitumen, of 192.18 °C resulted lower than the auto-ignition temperature (250 °C).

Finally, although the maximum (measured and calculated) temperatures of 800 °C and 680 °C at the external surface and inner components of simulacrum, and some oxidation and deformation of the outer surfaces (the occurred outward bulging is visible in Fig. 15), the mock-up demonstrated to fulfil the IAEA fire test requirements (nor loss of containment neither safety functions).

Conclusion

The experimental test simulating the fire scenario as specified in the IAEA regulations (i.e. engulfing fire of 800 °C for 30 min) was presented and the results obtained discussed along with the post-test evaluation of its thermal performance (and effects).

The comparison between experimental and numerical results highlights a quite good agreement although the temperatures behaviours do not perfectly overlap each others. The discrepancy seemed mainly due to the modelling assumption: anyhow, the difference reduces as the accuracy in the modelling increases.

The results after half an hour of fire exposure at 800 °C, highlighted that the temperature in the bituminised waste package is about 100 °C, a value well below 250 °C that represents the temperature beyond which auto-ignition of the bitumen occurs.

As for the outer surfaces of the mock-up, the maximum temperature of about 650 °C is not sufficient to determine any loss of containment of the packaging system even if in presence of outward bulging deformation and oxidation of the surface.

Finally, on the basis of the experimental evidences obtained from the mock-up (also supported by the results of the numerical simulations) it can be stated that even the CP5.2 packaging will be able to guarantee the containment and the safety functions.

CP 5.2 packaging will be thus able to withstand the accident conditions of transport, demonstrating that no cliff effect or failure occur.

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