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Evaluating the fire behaviour of cement-based lightweight materials with textile waste incorporation using a cone calorimeter

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ABSTRACT

The conscientious utilization of natural resources and the efficient waste management have become a matter of great concern in recent years due to the harmful impacts on the environment. The construction sector presents itself as one of the sectors that most contributes to raw materials consumption and waste generation, demanding the investigation of more sustainable and eco-friendly building materials, where the valorisation of wastes originated from other industries can be promising. Following the sustainability concept in construction materials, this work investigates the potential use of textile waste in cement-based lightweight construction material, evaluating the fire reaction of the material using the cone calorimeter equipment. The samples were tested at three different radiant heat fluxes (35 kW/m^2, 50 kW/m^2, 75 kW/m^2) to simulate different fire situations. For the highest heat flux, the lightweight construction element with textile waste incorporation showed a Heat Release Rate Average $\leq$ 18 kW/m^2, a peak Heat Release Rate Average $\leq$ 60 kW/m^2, and a Total Heat Release Average $\leq$ 33 MJ/m^2. These results reveal a very satisfactory fire behaviour compared to other materials and show the suitability of using textile waste as lightweight cement-based materials.

1. Introduction

Sustainable development is a concept that has several definitions. The most common one declares that today's generation should not compromise the ability of future generations to meet their needs. The three columns of sustainable development are economic and environmental protection as well as social development [1]. It is known though that the planet capacity to support people needs is determined by natural constraints and human priorities [2], whose response is severely threatened.

In this context, the construction industry has been contributing negatively to the impacts on the environment. The high use of natural resources, the high energy consumption and the consequent emission of greenhouse gases have led to a worrying environmental deterioration. Thus, in recent years, there has been a strong concern with environmental issues, in such a way that more and

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more investments have been made in increasing sustainability. The development of sustainable construction and building materials with a reduced environmental footprint in both manufacturing and operational phases of the material lifecycle is attracting increased interest in the housing and construction industry worldwide [3].

In this respect, there is a need to use industrial by-products and wastes which are available in a large scale and require proper disposal and alternative uses. From a sustainable technical building perspective, different research works aim to investigate the potential of using different by-products and wastes as resources to obtain alternative and more sustainable building materials [4–7].

The textile industry represents an important role on the global economy and, consequently, in the amount of waste generated. In the European context, Italy stands out as the main textile producer followed by Germany, United Kingdom, France and Spain [8]. In Portugal, textile industry also has a prominent position in the economy, being manly located in the North region with over 150 years of large-scale production [9]. Furthermore, textile production has been causing negative impacts on the environment and emerged as one of the major contributors to the generation of various types of environmental impacts [10] during the manufacture of the products, achieving 17 tons of CO_2 emissions for 1 ton of textile produced [11]. In addition, it is also stated that the large amount of waste generated is essentially related to the cut in the textile production processes [12] and the textile waste resulting from this activity can be defined as post-industrial or post-consumer [13]. Post-industrial textile waste results from the manufacturing process and usually involves garment cutting waste, excess fabrics, and rejects due to quality assurance. In Portugal, 230 tons of these unusable textiles are discarded and deposited in landfills every year [14]. Post-consumer textile waste results from the unwanted clothing discarded by the consumer after use [12,15].

The current situation in terms of textile waste production shows the urgent need to introduce this type of wastes in the value chain, following the principles of circular economy. Reusing and recycling can contribute to minimize the negative impact on the environment when comparing with incineration and landfilling [16]. Textile waste recycling rate is approximately 13 %, being relatively low compared to other types of wastes. However, given that some types of textile waste contain many toxic materials and heavy metals, reusing can be more advantageous than recycling [17].

Given these environmental concerns, reusing textile waste as a material source for the generation of added-value products following the circular economy concept may be promising in mitigating those impacts [18]. In the construction industry perspective, the incorporation of textile waste in building materials production can contribute to reduce energy consumption associated to the exploitation of natural resources and perform a significant role in the different perspectives of sustainability [19,20].

Previous studies developed by the research team revealed that the thermal reinforcement of external double walls with textile fabric waste and textile fabric sub-waste in the air layer led to an increase of the wall thermal resistance in 56 % and 30 %, respectively, when compared to a double-wall solution with no insulation material in the air layer [7]. Further investigation was carried out to analyse the addition of textile waste in cement-based blocks, being concluded that this type of waste after being mixed with cement grouts results in a lightweight material, with high integrity and a favourable behaviour to drilling and cutting [21]. The thermal performance of lightweight cement-based blocks incorporating textile waste was also characterised by experimentally monitoring different parameters, such as heat fluxes and inner surface temperatures. The thermal transmission coefficient, thermal resistance and thermal conductivity were estimated, revealing promising behaviour of the material for insulation purposes [22].

This previous investigation justifies the analysis of other properties of the cement-based lightweight blocks incorporating textile waste, namely the reaction to fire behaviour. The European standard fire classification of construction products and building elements, EN13501–1 [23], stablished the known fire reaction euro classes, ranking materials from A to F, based on reaction to fire performance, smoke production and flaming droplets/particles. The Heat Release Rate (*HRR*) and the Total Heat Release Rate (*THRR*) are critical parameters that measure the amount of heat energy released per unit time during the combustion of a material. The achievement of this parameters is crucial in determining the intensity and severity of a fire, as it directly impacts fire growth and flashover potential. Understanding the *HRR* of different materials, including textile fabrics, is essential for fire safety assessments, fire modelling, and developing fire-resistant materials. Based on this knowledge, new fire resistance solutions and flame retardants can be developed to improve fire behaviour of innovative materials [24]. *HRR* can be determined through experimental tests such as cone calorimetry, which was used in this study. Furthermore, it is also intended with this investigation to fill in a gap found in the literature concerning the development of building materials incorporating textile fibres. The characterisation of this textile waste material regarding its reaction to fire was performed using the cone calorimeter equipment, through the test method established by ISO 13927 standard [25], whose experimental procedure was already used by other authors to analyse the fire behaviour of different materials [26–28]. The specimens manufactured from textile waste were tested for three different radiant heat fluxes to simulate different fire situations: the beginning of fire propagation, the beginning of flashover and the fully developed fire [25].

The research work here presented will allow, on the one hand, to contribute to a more detailed characterisation of this type of materials and, on the other hand, to encourage the reuse of textile waste as sustainable material components, following the circular economy principles.

2. Material and methods

2.1. Materials characterisation

2.1.1. Textile waste

The textile waste used in this investigation was provided by a Portuguese textile factory located in the Northern region of Portugal. The textile waste under study was composed by 70 % wool, 25 % viscose and 5 % elastane, and presented low density (217 kg/m^3) and a high-water absorption (892 %) [21], when compared to other types of textiles [29–31].

The textile waste was cut into smaller pieces with a maximum length of 30 mm to facilitate the workability of the mixtures and the moulding of the specimens [21], as presented in Fig. 1.

2.1.2. Physical, mechanical and thermal properties of textile based-material

The composition of the mixture used to manufacture the specimens was cement, water and textile waste (*CT – Cement Textile*) according to previous research work [21], which is presented in Table 1, in weight percentage (*wt%*).

Previous tests [21] show that the specimens manufactured with this composition stabilise the mass loss at 28 curing days and at the end of this time the specimens present a density value equal to 566.26 kg/m^3. According to the specification EN 206–1 [32], a construction material produced with ordinary Portland cement can be considered with low-density when it has density values lower than 2000 kg/m^3, which is the case of the proposed material.

Previous tests performed according to specification E393 of LNEC [33] allowed to conclude that the textile based-material is characterized by a high water absorption by capillarity in comparison with other construction materials [34,35], increasing 53.7 % over its initial weight, likewise, it presented a capillarity coefficient equal to 2.66 g/cm^2/h$^{1/2}$. This value is also considered high when compared to other materials used in construction [36–39]. However, this property may not be considered adverse if the materials are applied in interior environments, as partition walls elements or as a core of multilayer solutions.

Regarding mechanical behaviour, satisfactory results were achieved showing to be a material with resilience properties. Compressive strength tests were performed on specimens with this composition, in accordance with the standard EN 12390–3 [40]. Fig. 2 shows the load displacement behaviour, revealing that there was no rupture by compression, presenting a continuous load absorption until their deformation. At the end of the tests, the material appeared moderately deformed, but after applying the load, it recovered its initial shape [22].

Fig. 1. (a) Original factory textile waste; (b) Textile waste after cutting.

Table 1
Composition of the *CT* mixture, in weight percentage (wt%).

Textile waste (wt%)	Cement (wt%)	Water (wt%)
8.75	32.85	58.40

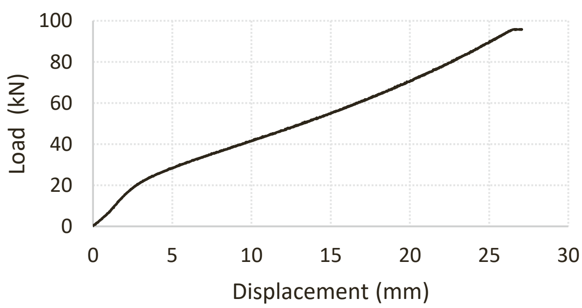

Fig. 2. Compressive load vs displacement.

The thermal behaviour of the specimens incorporating textile waste was also performed [22] through the analysis of heat fluxes, internal surface temperatures and thermal transmission coefficients, according to the specifications of ISO 9869–1 [41], and also through infrared thermal imaging in order to analyse the surface temperatures and complement the test performed, according to the specifications of ISO 9869–2 [42]. The thermal performance tests allowed the characterisation of the thermal material behaviour, reaching the characteristic values of the Thermal Flux (*qi*) of the material, Thermal Transmission Coefficient (*U*), Thermal Resistance (*R*) and the theoretical value of Thermal Conductivity (λ). The obtained values are presented in Table 2 and show the potential utilization of this textile waste as a component of building materials for insulation purposes, compared to commonly used building solutions such as simple masonry walls and lightweight concrete insulating forms [43].

In Table 3, a comparison of the textile waste-based material under study (*CT*) with commercially available insulation materials commonly used in the construction sector is presented concerning density and thermal conductivity. The results obtained by other authors concerning the development of alternative materials for insulation purposes with different types of wastes are also presented.

Additional information is also indicated in Table 4 allowing to compare the thermal resistance of the purposed textile-based material with conventional solutions. It can be seen that a lightweight cement-based block incorporating textile waste can lead to an improvement of the thermal performance resistance comparing with current bricks and blocks traditionally used for walls solutions.

Given the promising properties of the material regarding mechanical and thermal performance, a more detailed characterization of the proposed material is necessary, namely in what concerns to fire behaviour, which is the aim of the investigation here presented. In the following sections, the experimental procedure will be described, and the obtained results will be discussed.

Table 2
Average results of *CT* samples [21,22].

Density (kg/m^3)	Water absorption (%)	Capillarity coefficient (kg/m^2/s$^{1/2}$)	Thermal performance results			
			qi (W/m^2)	*U* (W/m^2 °C)	*R* (m^2 °C/W)	λ (W/m °C)
566.26	53.7	0.385	22.4	1.19	0.67	0.149

Table 3
Density and thermal conductivity of current and innovative building solutions.

	Density (kg/m^3)	Thermal conductivity (λ) (W/mK)
CT (material under study) [21,22]	566.26	0.149
Expanded polystyrene (EPS) [44]	15-20	0.040
Extruded polystyrene (XPS) [44]	25-40	0.037
Polyisocyanurate/Polyurethane foam (PIR/PUR) [44]	20-50	0.040
Wood fibre (rigid) [45]	160	0.0038
Wood fibre (flexible) [45]	50	0.0038
Mineral wool (MW) [44]	100-150	0.042
Glass wool [44]	15-100	0.040
Black cork agglomerate [44]	90-140	0.045
Insulating concrete [44]	1000	0.36
Cavernous concrete [44]	800-1000	0.33
Cavernous concrete [44]	600-800	0.25
Perlite or expanded vermiculite aggregate concrete [44]	400-600	0.20
Pumice aggregate concrete for masonry blocks [44]	500	0.16
Expanded polystyrene aggregate concrete [44]	600	0.22
Hemp [45]	25-28	0.039-0.040
Hempcrete [45]	275	0.060
Mixture of 60 % Nylon/Spandex and 40 % Polyurethane [46]	993	0.095
Nonwoven fabric [47]	25-45	0.035-0.0339

Table 4
Thermal resistance of *CT* and conventional solutions.

	Thermal Resistance (*R*) (m^2 °C/W)
CT (material under study) (10 cm) [21,22]	0.67
Hollow ceramic brick (10 cm) [44]	0.27
Massive ceramic brick (10 cm) [44]	0.13
Concrete blocks (10 cm) [44]	0.16
Lightweight concrete blocks (10 cm) [44]	0.27

2.2. Experimental program

2.2.1. Manufacture of the mixture composition

The textile waste was added to a cement grout resulting from the mixing of water with Portland limestone cement (CEM II/B-L 32.5 N). The composition used in the manufacture of the specimens (*CT – Cement Textile*) can be observed in Table 1. The mixture should be as homogeneous as possible and then placed in the mould. The specimens were demoulded after 3 days with the application of compressed air and, in order to not compromise the integrity of the specimens, acetate paper was added to the bottom of the mould and release oil was applied to reduce the adhesion between the specimen and the mould. Samples were left to dry at ambient temperature for 28 days. The size of the specimens tested in this work is 100 mm × 100 mm × 35 mm, whose dimensions have been established in accordance with the specifications presented in ISO 13927 standard [25]. The manufacture of the specimens can be seen in Fig. 3.

2.2.2. Experimental setup

As mentioned previously, the textile waste used in this study is composed by 70 % wool, 25 % viscose and 5 % elastane. According to the literature, viscose is a highly flammable fibre but wool is not [48,49]. Furthermore, when exposed to fire, textile fibres are divided into two categories: lignocellulosic fibres, like cotton and flax, which are easy to ignite and flammable; and protein fibres, such as wool and silk, in which is more difficult to start the flame [50]. In addition, the textile waste is wrapped in a cement slurry, which gives it greater fire-retardant capacity.

To assess the fire behaviour performance of the specimens manufactured with *CT*, a set of experimental test was performed in cone calorimeter as prescribed by the standard ISO 13927 [25]. The cone calorimeter is an instrument to simulate and evaluate the material combustion properties exposed to high temperatures, representing the that occur in a real fire situation. It is a device that measures the fire reaction properties of a material when subjected to a constant radiant heat flux. This device has a high precision load cell allowing the mass registration of the sample over time of thermal exposure [26]. The cone calorimeter was calibrated for a distance of 25 mm between the lower base of the cone and the upper surface of the sample. During the test, the Heat Release Rate (*HRR*), the Total Heat Released (*THR*) and the Mass Loss (*ML*) of the sample were measured.

The equipment performs small-scale fire reaction testing of materials standardized by ISO 13927 [25], which specifies a method to assess the *HRR* of a sample exposed to controlled levels of radiant heat fluxes ranging from 0 kW/m^2 to 100 kW/m^2. The tests were performed for three radiant heat fluxes, 35 kW/m^2, 50 kW/m^2 and 75 kW/m^2. According to ISO 13927 [25], a heat flux of 35 kW/m^2 simulates the onset of fire propagation, the heat flux of 50 kW/m^2 simulates the onset of flashover and the heat flux of 75 kW/m^2 simulates the fully developed fire. In addition to the *HRR* and *THR*, the equipment software also displays the Mean Heat Release Rate (*MHRR*), the Peak Heat Release Rate (*PHRR*), the Total Mass Loss (*TML*), the Loss Rate of Mass (*MLR*), the Ignition Time (T_{ign}) and the Flameout (T_{out}) [25].

To carry out the experimental tests, 18 specimens were manufactured, being6 specimens tested for each heat flux. Of the 6 specimens, 3 were used to assess the mass loss and the other 3 were used to determine the temperature variation across the thickness of the specimen. The temperature was registered using three type-K thermocouples, *T1*, *T2* and *T3*. The thermocouple *T1* was placed on the lower face of the test piece (3 mm height), thermocouple *T2* was placed in the middle of the specimen thickness (15 mm height), and thermocouple *T3* was placed just before the test piece surface (28 mm height). The cone calorimeter used in the present study and the thermocouples position can be seen in Fig. 4. Table 5 shows the initial mass of the specimens (*CT-01* to *CT-18*), the mass at 28 days and the type of essay in which the specimens were used.

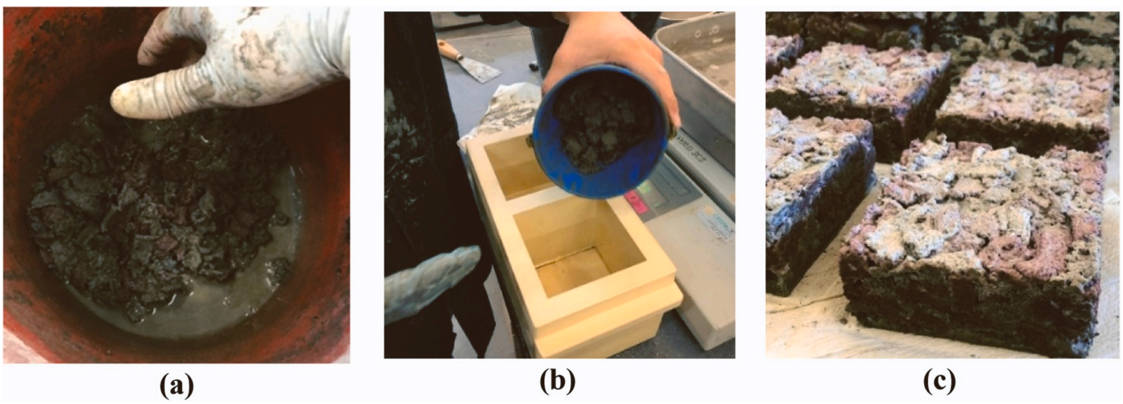

Fig. 3. (a) Cement grout with textile residue; (b) Specimen mould; (c) Final appearance of specimens after drying.

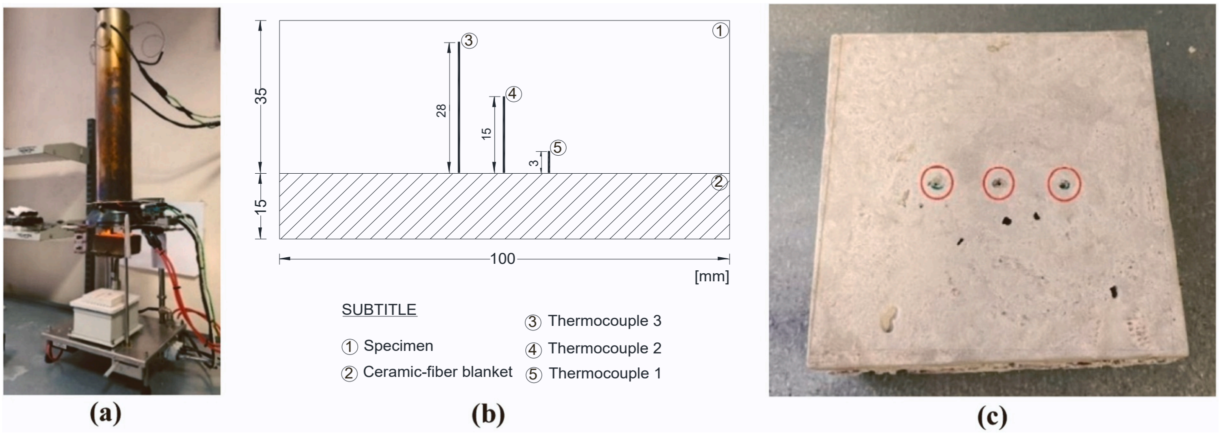

Fig. 4. (a) Cone calorimeter; (b) Scheme of thermocouples location on the specimen; (c) Thermocouples location on the tested specimen (*CT-16)*.

Table 5
Mass of specimens and type of essay.

Specimens	Initial mass (g)	Mass at 28 days (g)	Type of essay
Heat flux of 35 kW/m^2			
CT-01	354.9	187.9	Mass loss
CT-02	355.3	186.9	
CT-03	355.2	188.8	
CT-04	354.7	195.9	Temperature evolution
CT-05	354.7	194.1	
CT-06	355.1	180.6	
Heat flux of 50 kW/m^2			
CT-07	355.3	189.6	Mass loss
CT-08	355.1	188.0	
CT-09	355.3	185.9	
CT-10	354.9	190.6	Temperature evolution
CT-11	354.8	179.8	
CT-12	354.9	177.7	
Heat flux of 75 kW/m^2			
CT-13	355.2	189.7	Mass loss
CT-14	354.9	186.7	
CT-15	355.0	184.6	
CT-16	355.5	176.2	Temperature evolution
CT-17	354.8	177.0	
CT-18	355.3	178.8	
Average	355.1	185.5	-
Standard deviation (SD)	0.24	5.90	-

The specimens were wrapped in aluminium foil surrounding all the sides, except the one where the heat flux was applied, Fig. 5. The test ends after the flameout and the mass loss stabilization. In cases without ignition or mass loss stabilization, the test is completed after 10 min, a time considered enough for the analysis of the temperature's evolution.

3. Results and discussion

As previously referred, the experimental tests allowed to the measure the mass loss, the heat release rate, and the total heat release of the specimens. A comparison between the measured temperatures throughout the height of the specimens when subjected to heat fluxes of 35 kW/m^2, 50 kW/m^2 and 75 kW/m^2 was also performed. These results are summarized in **Table 6** . A detailed analysis of the results obtained for each heat flux value is presented in the following sections.

3.1. Heat flux of 35 kW/m^2

The *HRR* (Fig. 6(a)), *THR* (Fig. 6(b)), mass loss (Fig. 6(c)) and the evolution of the temperatures (Fig. 6(d)) were measured for specimens when subjected to a heat flux of 35 kW/m^2. The obtained results of these fire reaction properties are graphically presented in Fig. 6. The results show that no ignition of the specimens occurred for this heat flux value and a mass loss stabilization was observed, so the test ended after 10 min.

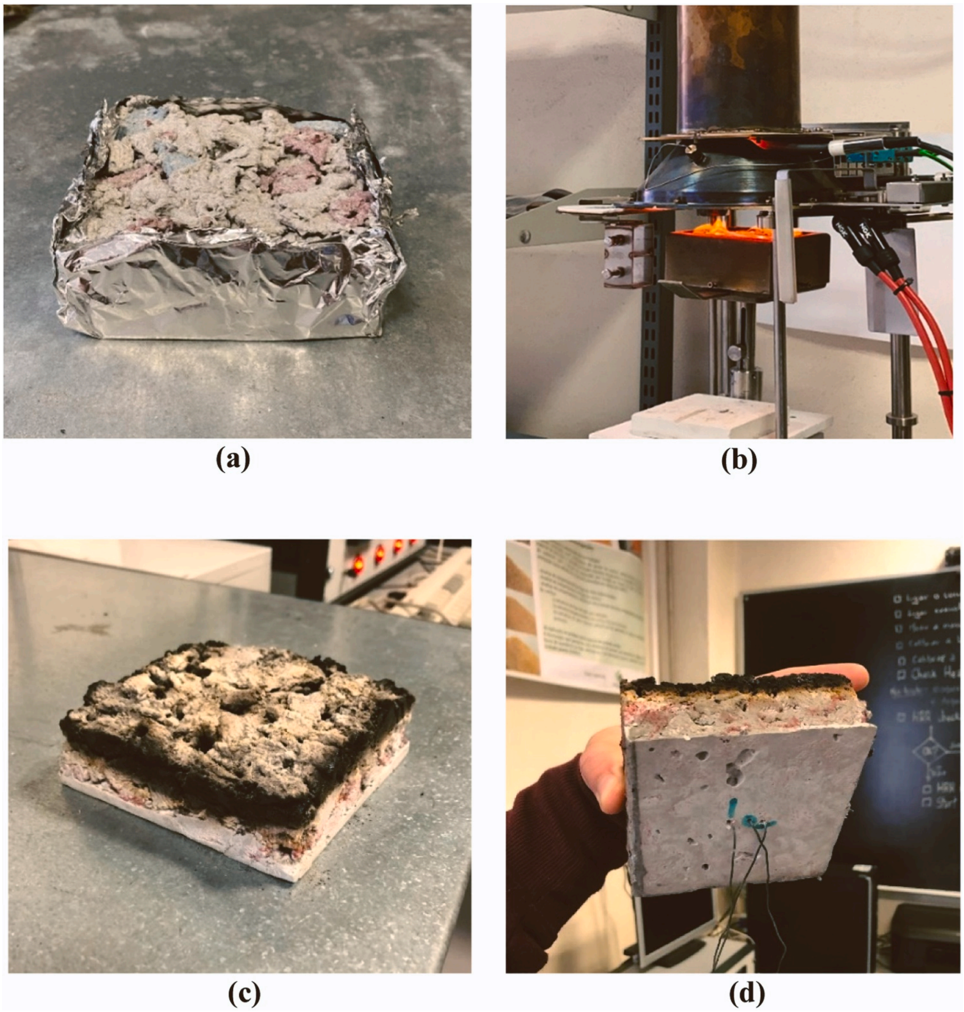

Fig. 5. (a) Specimen *CT-13* wrapped in aluminium foil; (b) Ignition of the specimen *CT-13*; (c) Final appearance of specimen *CT-13* after test; (d) Final appearance of specimen *CT-16* with the thermocouples.

Table 6
Results of heat release, mass loss and temperatures.

	Heat Release					Mass Loss		Temperatures		
	T_{ign} (s)	T_{out} (s)	MHRR (kW/m^2)	PHRR (kW/m^2)	THR (MJ/m^2)	TML (%)	MLR (g/s)	T1 Maximum values (°C)	T2	T3
Heat flux of 35 kW/m^2										
CT-01			6.88	9.20	4.17	8.03	0.026			
CT-02			9.30	11.57	5.60	7.86	0.024			
CT-03			8.27	10.87	4.97	8.32	0.031			
CT-04			9.10	11.45	5.48			97.15	107.35	521.95
CT-05			7.51	11.40	4.52			93.32	112.03	397.00
CT-06			8.40	9.78	5.05			89.73	98.64	522.01
Average			8.24	10.71	4.97	8.07	0.027	93.40	106.01	480.32
SD			0.92	0.99	0.55	0.23	0.004	3.711	6.795	72.157
Heat flux of 50 kW/m^2										
CT-07	69	112	9.36	24.44	5.62	8.69	0.027			
CT-08			4.76	11.83	2.88	9.81	0.031			
CT-09	13	153	10.84	43.72	6.52	9.77	0.033			
CT-10	51	203	13.64	31.07	8.22			97.35	184.25	621.81
CT-11			12.83	15.34	7.72			93.05	120.19	544.19
CT-12	17	252	18.98	48.00	11.45			92.64	137.71	570.98
Average	37.50	180.00	11.74	29.07	7.07	9.42	0.029	94.35	147.38	578.99
SD	27.05	60.73	4.74	14.73	2.86	0.64	0.003	2.609	33.107	39.426
Heat flux of 75 kW/m^2										
CT-13	9	1624	16.57	59.76	28.89	22.95	0.026			
CT-14	12	1641	17.40	56.07	30.79	24.64	0.026			
CT-15	9	1595	17.42	58.04	29.87	22.26	0.024			
CT-16	7	1745	23.03	72.59	43.02			399.2	493.6	845.1
CT-17	15	1683	14.46	51.99	26.19			397.1	463.1	776.9
CT-18	12	1585	21.10	58.73	36.05			366.7	494.5	733.4
Average	10.67	1645.5	18.33	59.53	32.47	23.28	0.025	387.7	483.8	785.1
SD	2.88	60.0	3.15	6.96	6.10	1.22	0.001	18.18	17.83	56.28

For a heat flux of 35 kW/m^2, the specimens show an average value of 8.24 kW/m^2 for the *MHRR* and a maximum value of 11.57 kW/m^{2}for the *PHRR*. After 10 min of testing, the average value of *THR* is 4.97 MJ/m^2. A value of 8.07 % was achieved for the *TML* and 0.027 g/s for the *MLR*.

The utilization of thermocouples allowed a more accurate collection of the temperatures over time in the tested specimens. Data acquired by thermocouple *T1* revealed an average temperature value of 49 °C after 5 min of testing, while at the end of the measurement 93 °C were achieved, with tendency to stabilise. The thermocouple *T2* registered an average temperature value of 75 °C after at 5 min of testing and at the end of the test this value exceeded 106 °C, with a tendency to stabilise. Regarding the temperatures registered by thermocouple *T3*, the average value exceeded 376 °C at the end of 5 min, and 480 °C at the end of the test, showing a tendency to stabilise. The variation of temperatures over time recorded by the thermocouples for this heat flux can be seen in Fig. 6(d).

3.2. Heat flux of 50 kW/m^2

The fire reaction properties for the specimens subjected to a heat flux of 50 kW/m^2 are plotted in Fig. 7.

For a heat flux of 50 kW/m^2, the specimens present an average value of 11.74 kW/m^2 for the *MHRR* and a *PHRR* of 48.00 kW/m^2. After 10 min of testing, the average value of *THR* was equal to 7.07 MJ/m^2. Regarding the *HRR*, Fig. 6(a), there was an initial period during which specimens did not release any heat. The material temperatures were below the pyrolysis temperatures of the specimens. After this period, *HRR* suffered a rapid increase due to specimen's combustion and rapidly reached its peak value. This behaviour occurs for all specimens with exception of CT-08 and CT-11. After10 minutes of testing, the specimens presented an average value of *TML* equal to 9.42 % and a *MLR* equal to 0.029 g/s.

Concerning temperatures measurement, the average temperature recorded by thermocouple *T1* after 5 min of testing exceeded 70 °C, and at the end, it stabilised at 94 °C. The average temperature values registered by thermocouple *T2* for the analysed periods of time exceeded 83 °C and 147 °C, respectively, also revealing tendency of stabilization. The values registered by thermocouple *T3* revealed an average value that exceeded 146 °C after 1 min of experiment and the surface of the specimens were totally on fire: The average temperature on the specimen's surface has exceeded 463 °C after 5 min while at the end of testing it has already exceeded 578 °C, with a tendency to stabilise. The variation of temperatures over time can be seen in Fig. 7(d).

3.3. Heat flux of 75 kW/m^2

Fig. 8 present the variation curves of *HRR* (Fig. 8(a)), *THR* (Fig. 7(b)), remaining mass of specimens (Fig. 8(c)) and the evolution of temperatures recorded by the thermocouples (Fig. 8(d)) for a heat flux of 75 kW/m^2.

The specimens presented an average value of *MHRR* equal to 18.33 kW/m^2 and a *PHRR* equal to 72.59 kW/m^2. After 30 min of

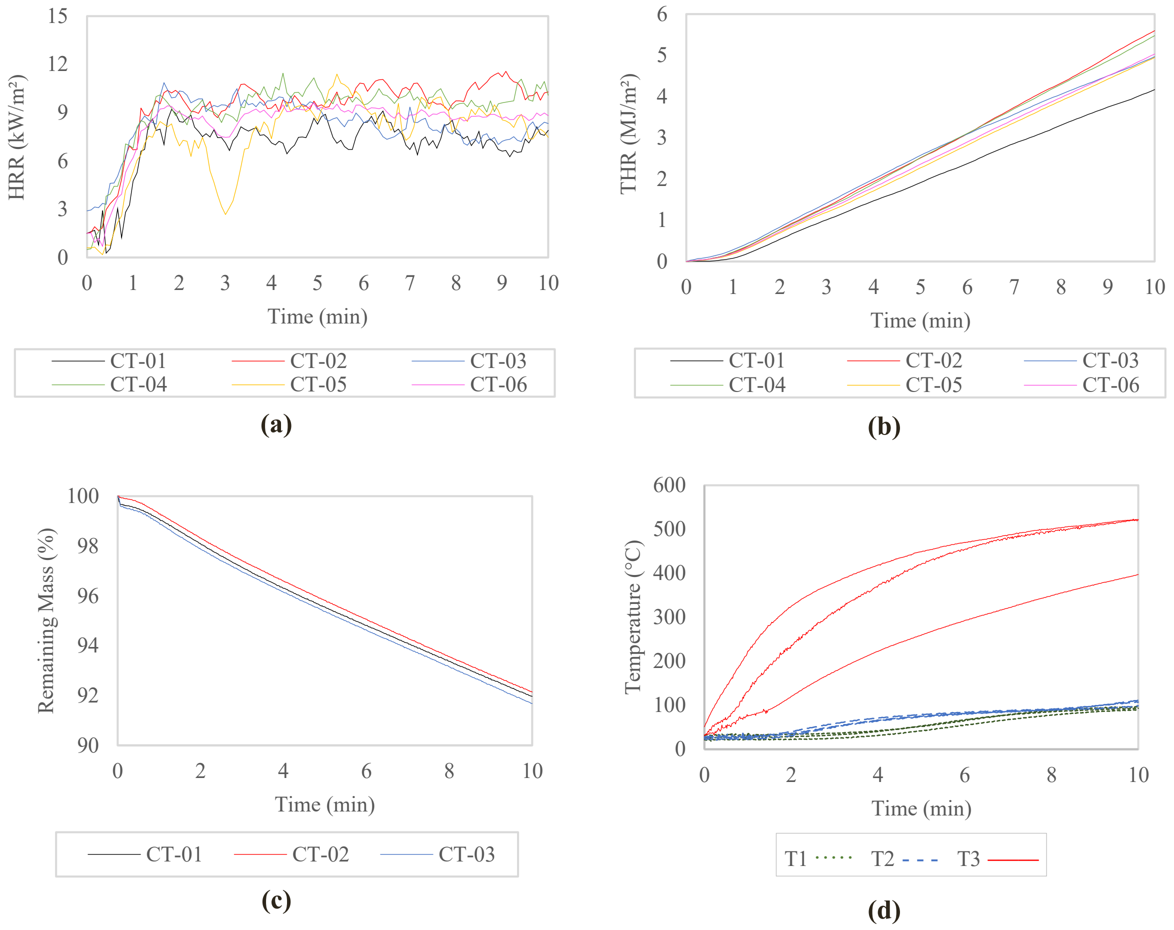

Fig. 6. For 35 kW/m^2: (a) Heat release rate; (b) Total heat release; (c) Remaining mass; (d) Evolution of the temperatures recorded by the thermocouples.

testing, the average value of *THR* was equal to 32.47 MJ/m^2. For this heat flux value, there was combustion in all the specimens during almost the entire test. The average ignition time was 10.67 s (T_{ign}) and an average of 1645.5 s (27.43 min) elapsed until the flameout (T_{out}) was reached. The test ended after 30 min, and the specimens present an average value of *TML* equal to 23.28 % and a *MLR* equal to 0.025 g/s.

Regarding the temperatures, the average temperature recorded by thermocouple *T1* at the end of 5 min has exceeded 66 °C and at the end of the test, after 30 min, exceeded 387 °C, with tendency to rise. The average temperature recorded by thermocouple *T2* showed that at the temperature has already exceeded 79 °C after 5 min of experiments and it exceeded 483 °C, with tendency to rise, at the end of testing. Concerning the values acquired by thermocouple *T3*, it was verified that after 1 min, values exceeded 100 °C and the surface of the specimens were completely on fire. At the end of 5 min, the average temperature has exceeded 347 °C and for the final period of measurement, the temperature recorded was 785 °C, with tendency to stabilise. In Fig. 8(d), it can noticed that there is a plateau around the 100 ºC which is due the moisture content of the specimen.Comparing the results obtained for the different heat fluxes values for a heat flux of 50 kW/m^2 there was ignition of the specimens during the first minutes of testing (142.5 s) and, for a heat flux of 75 kW/m^2, there was ignition of the specimens during almost the entire measurement period (1634.8 s).

Concerning the specimen's behaviour related to the temperature variation, temperatures, it can be concluded that for the first 10 min of testing, and for the different heat fluxes, the thermocouple *T1*, recorded values close to each other, reaching temperatures nearby 100 °C. For a heat flux of 75 kW/m^2, the plateau occurred at a temperature near 100 °C due to water evaporation. In this process, the materials accumulate energy in an endothermic behaviour. Only at the end of this process, after 15 min of testing, the temperature increases significantly reaching temperatures higher than 387 °C. The thermocouple *T2* recorded similar temperatures for both heat flux of 35 kW/m^2 and 50 kW/m^2 during the first half of the test, however, in the remaining 5 min, for a heat flux of 50 kW/m^2, the thermocouple shows higher temperatures compared to the temperatures registered for a heat flux of 35 kW/m^2. For a heat flux of 75 kW/m^2, thermocouple *T2* recorded similar temperatures for both heat flux of 50 kW/m^2 and 75 kW/m^2, during the first 10 min of testing, however, in the remaining 20 min for a heat flux of 75 kW/m^2, the temperatures recorded continue to increase because the samples are still burning, reaching temperatures higher than 483 °C at the end of the test. The thermocouple *T3*, placed just before the test piece surface, was the one that recorded higher temperatures registered for the different heat fluxes. In this thermocouple, slightly

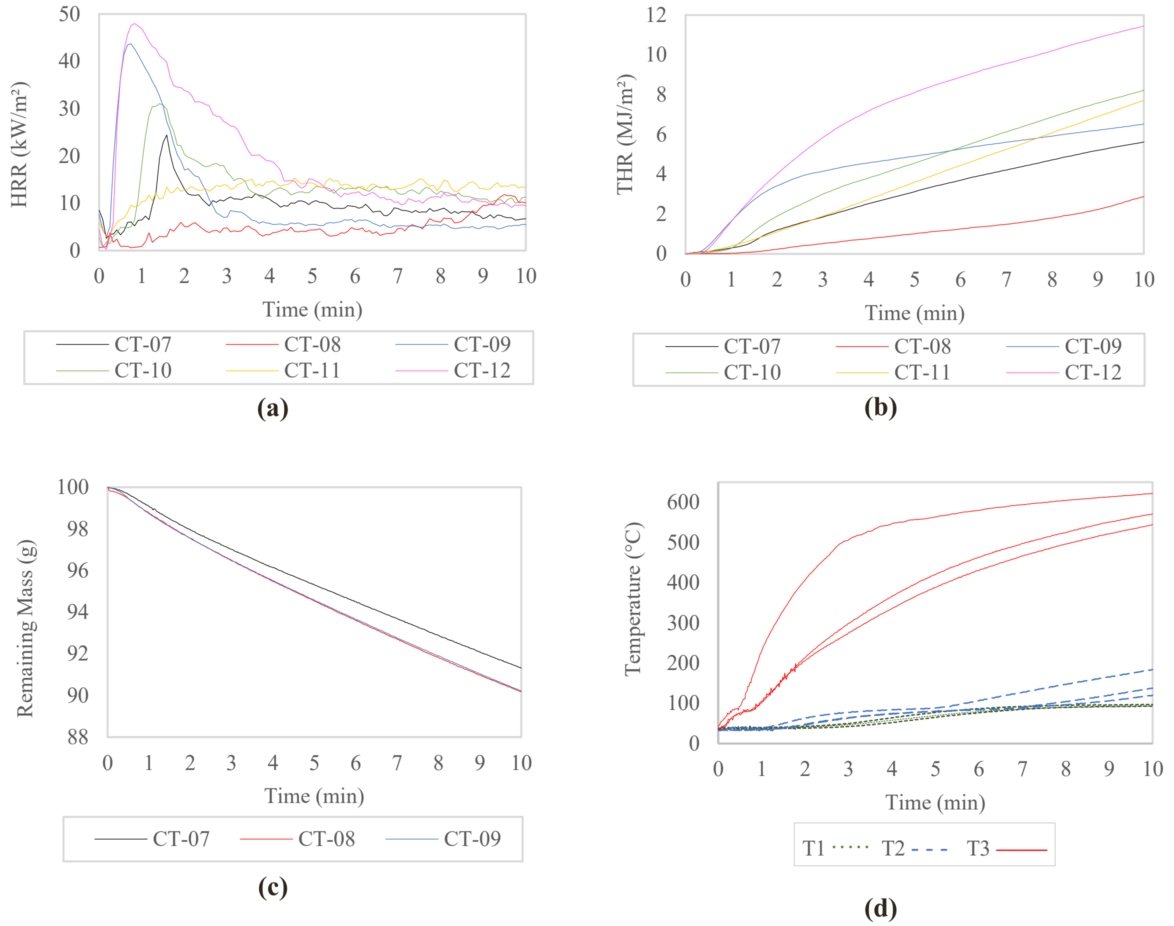

Fig. 7. For 50 kW/m^2: (a) Heat release rate; (b) Total heat release; (c) Remaining mass; (d) Evolution of the temperatures recorded by the thermocouples.

higher temperatures were recorded for a heat flux of 50 kW/m^2 compared to a heat flux of 35 kW/m^2. A heat flux of 35 kW/m^2 at the end of test reached temperatures above 480 °C while a heat flux of 50 kW/m^2 reached temperatures above 578 °C. For the highest heat flux value, 75 kW/m^2, during the first 10 min of testing, similar temperatures were recorded for both heat flux of 50 kW/m^2 and 75 kW/m^2, however, for a heat flux of 75 kW/m^2, during the remaining 20 min of testing, the temperatures continue to increase, the samples are still burning, reaching temperatures higher than 785 °C when the test ended.

Regarding the other parameters under analysis concerning the fire behavior of the textile-based material, *HRR* is an important parameter giving information about the intensity at which the fire releases the heat energy. The values obtained for the *HRR* indicate the potential risk of fire and the flammable material. Therefore, a lower *HRR* value leads to a lower fire risk offered by the material. Compared to the heat flux of 35 kW/m^2, the *HRR* values obtained for the heat flux of 50 kW/m^2 and 75 kW/m^2 showed more variability in the results, resulting in the specimen's combustion. The values of *HRR* and *THR* res obtained for the different heat fluxes showed a behaviour of the tested specimens reliable to the results verified by other authors [51–54]. For the worst situation, with a heat flux of 75 kW/m^2, that simulates the fully developed fire, the peak of *HRR (PHRR)* was less than 72.6 kW/m^2. It is observed that the values obtained for the proposed material are in accordance with the ones of commonly used lightweight construction elements, such as gypsum plasterboard, with a *PHRR* $\leq$ 150 kW/m^2 [52], solid wood panels with a PHRR $\leq$ 200 kW/m^2 [54,55], cross-laminated timber (CLT) panels with *PHRR* $\leq$ 120 kW/m^2 [56] or cork panels with *PHRR* $\leq$ 160 kW/m^2 [57], Table 7. Thus, it can be concluded that panels based on textile wastes present lower combustibility, representing a lower risk of fire. The specimen's behaviour clearly shows that the *HRR* and *THR* values increase as the heat fluxes increase.

The values of Mass Loss for a heat flux of 35 kW/m^2 are similar to the ones obtained for a heat flux of 50 kW/m^2, nearly 9 %. The *TML* values for a heat flux of 75 kW/m^2 was comparatively higher, around 23 %, which is justified by the fact that the specimen ignition occurred at the beginning of the experiment. Regarding the results obtained for the *TML* for different heat fluxes, it can be concluded that the behaviour of the textile based specimens are in accordance with the results verified by other authors [28,58].

According to EN 13501–1 [23], the fire reaction classification is based on the total heat release within 600 [s] of thermal exposure, $THR_{600\ s}$. The threshold to classify a construction product as class B is a *THR* $\leq$ 7.5 MJ and for a class C is a *THR* $\leq$ 15MJ. Considering the obtained results and the sample dimension, all the samples can be classified as class B.

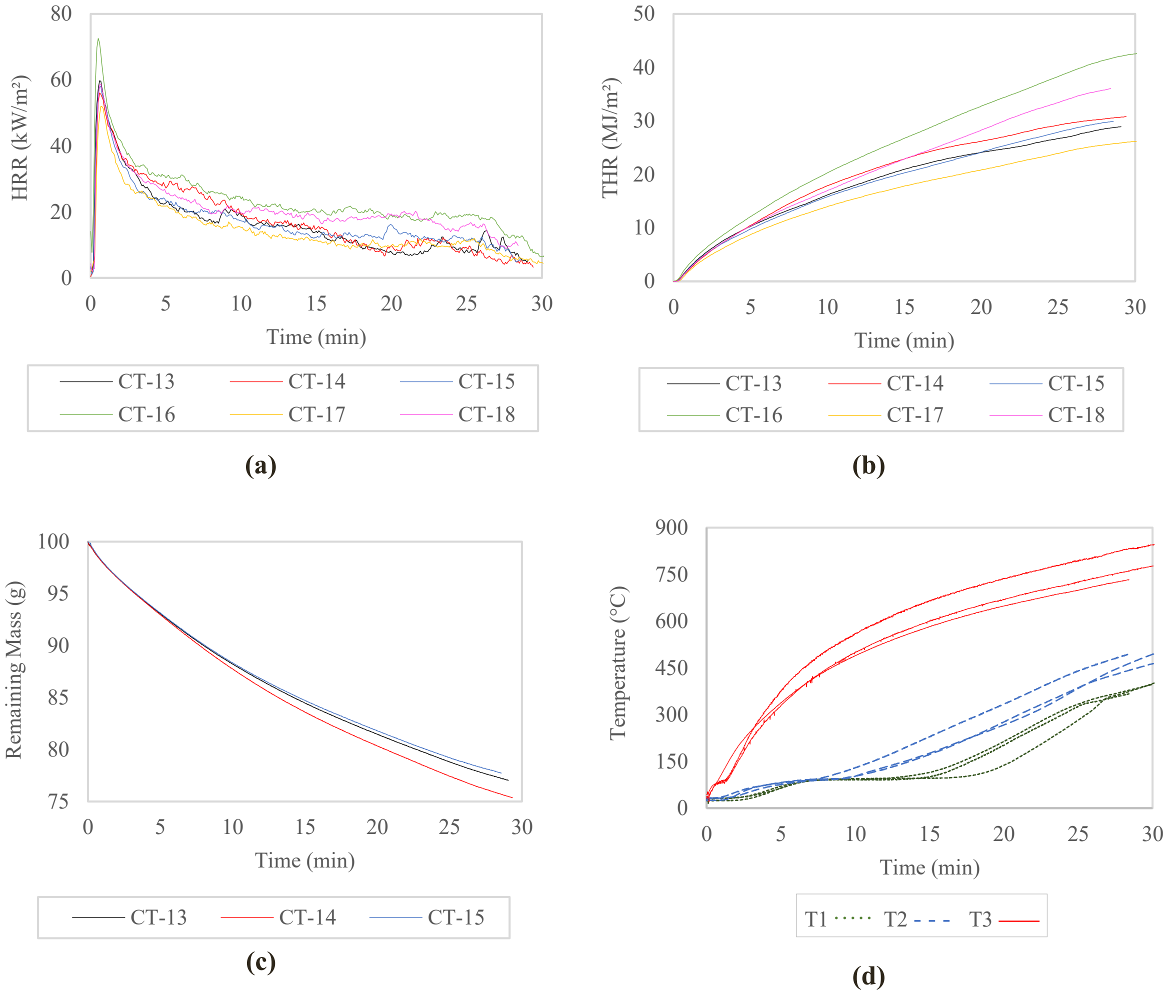

Fig. 8. For 75 kW/m^2: (a) Heat release rate; (b) Total heat release; (c) Remaining mass; (d) Evolution of the temperatures recorded by the thermocouples.

Table 7
Comparison of density and Peak Heat Release Rate (*PHRR*) of commercial construction material vs material under study, for a heat flux of 50 kW/m^2.

Material	Density (kg/m^3)	PHRR kW/m^2
Material under study [21,22]	566.26	29
Gypsum plasterboard [44]	1200	150
Solid wood panels [46,47]	553	200
CLT panels [48]	500	120
Cork panels [49]	153.8	160
Normal concrete [59]	2500	4
Ordinary cement mortar [59]	1900	3

4. Conclusions

The high generation of textile waste and the high consumption of raw materials in the construction sector have been encouraging the development of alternative building solutions following the sustainability and circularity principles. The incorporation of this type of wastes as building materials components has aroused the interest of the scientific community, whose investigation shows promising properties, namely for thermal insulation purposes. However, more research is required concerning the fire reaction textile waste-based materials. In this context, fire behaviour of cement-based lightweight materials with textile waste incorporation was assessed using a cone calorimeter for different heat fluxes values. The experiments revealed that ignition of the specimens only occurred for heat fluxes of 50 kW/m^2 and 75 kW/m^2,while for a heat flux of 35 kW/m^2 no ignition of the samples was observed.

The results obtained allow to conclude that lightweight construction elements incorporating textile waste did not present a flammable behaviour when subject to the cone calorimeter tests, contradicting the initial idea that they would react badly due to the large presence of textile waste, which is considered highly flammable.

The achievements regarding physical and mechanical characterization, with special emphasis on fire reaction, show the suitability of the proposed lightweight cement-based material incorporating textile waste for building solutions purposes, namely to be used as panels or particleboards. Furthermore, this solution can be an alternative to conventional ones, such as plasterboard, plywood or cork panels. In addition, the valorisation of this type waste can contribute to produce more sustainable building materials and, simultaneously, minimize the impacts on the environment that would result from the treatment to which it is usually subjected.

CRediT authorship contribution statement

Luís Mesquita: Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **Ana Briga-Sá:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Formal analysis. **Otávio Conde:** Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Leandro Magalhães:** Writing – review & editing, Writing – original draft, Visualization, Resources, Investigation, Data curation. **Débora Macanjo Ferreira:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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