Comparative study of glass products used in facades and their behaviour in fire

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ABSTRACT

Glass products very often make part of facades as well as compartments inside buildings. Their behaviour in fire is complex and still not well understood. The aim of the following study was to compare the behaviour of float glass, laminated glass with and without a low-E coating, and fire-resistant glass when exposed to high temperatures. In total 27 samples 20x20cm^2, initially around 8mm thick, were tested using a radiant panel consisting of electrical heating pads and the heat fluxes imposed were 15, 30 and 50 kW/m^2. Temperature evolutions on the unexposed side were recorded and compared with those of other glass products exposed to the same regimes. The behaviour of laminated glass, fire-resistant glass and the effects of coating were analysed considering the reactions of interlayers at high temperatures. All three glass products: uncoated and coated laminated glass and fire-resistant glass performed better than standard float glass. The maximum temperature reached on the unexposed side of coated laminated glass was comparable to that of fire-resistant glass for lower heat fluxes. For higher heat fluxes, the fire-resistant glass was the most insulating. However, the behaviour of laminated glass strongly depended on the presence of coating, glass breakage and oxygen penetration in the interlayer.

KEYWORDS: laminated glass, fire-resistant glass, radiant panel, coating, fire, heating pads, heat flux

INTRODUCTION

Glass is a very common material used in facades of most buildings. There are various glass products which can be assembled within framed and frameless systems. Among others: laminated glass (with low-E coating or without), float glass and fire-resistant glass. The fire resistance of glass, embedded in window frames or not, is crucial to assess the possibility of fire spread from one compartment to another or from the inside to the outside of a building.
Many research projects focus on understanding glass breakage phenomenon, both through experimental and theoretical approach. The outcomes of these projects are very often used to assess the creation of openings in windows and other glass elements, which would lead to supply of oxygen in an area subjected to fire. However, the behaviour of processed glass products, such as laminated glass, fire-resistant glass or coated glass, is still not well-explored. Several experimental bench-scale studies are documented in literature describing the behaviour of float and tempered glass, and more specifically focusing on its fracture and fallout [1-5], but there are limited studies concerning the behaviour of laminated glass [5-7] and coated glass [8] in the same scale. The methods used in the above mentioned studies vary in heating conditions from exposure to fuel pans or pool fires [3, 4, 6, 8], propane burners [2] to radiant panels [5, 7] and cone calorimeter [9]. Each of these conditions, as well as the size of the samples, their thickness and the heat flux applied on their exposed surface have a high influence on the interpretation of the results. Additionally, no study was found which would compare the performance of fire-resistant glass, coated glass and laminated glass at high temperatures.
The aim of the research study described in this article was to compare fire resistance and reaction of different glass products exposed to different heat fluxes in otherwise similar configurations.

MATERIALS AND METHODS

Materials

In total 27 samples 20x20cm^2 of laminated glass, laminated glass with a low-E coating (emissivity 0.14), standard float glass and fire-resistant glass were tested, as specified in Table 1. Each type of sample had similar thickness (around 8mm) which allowed to compare the temperature evolutions on the unexposed surface of samples subjected to the same heat flux.
Due to an unavailability of float glass with 8mm thickness, two 4mm thick float glass pieces were assembled without any adhesive between them. They were pressed to each other to eliminate an air gap between them, and an aluminium tape was applied on the edge of the assembly.

Table 1 Glass samples tested in bench-scale.

Type of glass	Material details	Number of samples	Nominal sample thickness [mm]	Heating regime
Uncoated laminated glass	Float glass (~4mm), a layer of PVB (0.76mm), float glass (~4mm)	2	8.76 (±0.43)	15 kW/m^2
		2		30 kW/m^2
		2		50 kW/m^2
Coated laminated glass	Float glass (~4mm), one layer of PVB (0.76mm), float glass with low-E coating (~4mm)	2	8.76 (±0.43)	15 kW/m^2
		2		30 kW/m^2
		2		50 kW/m^2
Float glass	Float glass (2x4 mm ~ 8mm)	2	8.00 (±0.4)	15 kW/m^2
		2		30 kW/m^2
		2		50 kW/m^2
Fire-resistant glass (laminated)	Float glass (~3mm), silica gel, float glass (~3mm)	3	7.9 (±0.9)	15 kW/m^2
		3		30 kW/m^2
		3		50 kW/m^2

Three thermocouples (type K) with twisted endings to ensure a few points of contact, and without copper disks, were glued to the unexposed surface of each sample to measure the temperature evolution, as shown in Figure 1a. The glue consisted of a mixture of Kaolin (58,6%) and sodium silicate solution (41,4%) and it was left at least one day to dry.

Testing method

The bench-scale tests were performed using an apparatus with electrical heating pads as a source of heat [10] (see Figure 1b and 1c). Three different heat fluxes were applied: 15, 30 and 50 kW/m^2 to observe the behaviour of various types of glass products. Indeed, fire-resistant glass is used to withstand significant heat fluxes, while float glass and laminated glass are expected to withstand only small or moderated heat fluxes.
The procedure was similar for all tests and heating regimes. Two parameters were changed to obtain different heat fluxes on the exposed surface of the samples: the target temperature of the heating pads and the distance between the heating pads and the exposed surface of the glass sample. The following parameters were chosen according to the previous calibration of the apparatus [10]:

- The heat flux 15 kW/m^2 was obtained with temperature 850°C in the heating pads and a distance of 40 cm,
- The heat flux 30 kW/m^2 was obtained with temperature 925°C in the heating pads and a distance of 25 cm,
- The heat flux 50 kW/m^2 was obtained with temperature in the heating pads around 1000°C and a distance of 15 cm.

The test samples were placed in a steel sample holder without restrain, with insulation between holder and on the top and the bottom edge of the specimen, to limit the conductive heat transfer from the

steel holder to the samples. The testing procedure foresees that, at the beginning of a test, a protecting plate be placed between the heating pads and the sample, at about 40 cm distance from the heating pads in order to limit its influence on the temperature of the heating pads and to protect the sample (Figure 1b). The protecting plate is then removed when the temperature of the heating pads has reached the target temperature and steady-state conditions are established and the distance between the sample and the heating pads was adjusted (Figure 1c). This procedure with a stepwise variation of the applied flux is to mimic the rapid increase of the level of exposure encountered in a standard fire test. The stabilisation time was around 20 minutes, 24 minutes and 55 minutes for the three levels of heat flux. Each sample was exposed to the heating for 30 minutes.
The coated laminated glass samples were positioned in a way that the coated surface was the exposed surface. For the fire-resistant glass samples, if the expansion of the intumescent layer pushed the exposed glass and, therefore, decreased the distance between the heating pads and the exposed surface, this distance was measured manually and adjusted during the test to keep the targeted value of the incident heat flux.

Figure 1 a) Sample with attached thermocouples, b) experimental setup with protecting plate before the start of the test, c) experimental setup with sample exposed to the heating.

RESULTS

The summary of observations made during the bench-scale tests are presented in Table 2.

Table 2 Summary of the observations made during the bench-scale tests.

Type of glass	Heating regime	Observations
Uncoated laminated glass	15 kW/m^2	Bubbles in PVB appeared when thermocouples reached around 140°C. Glass breakage appeared after around 15 minutes, but no glass fell owing to adhesive behaviour of PVB. Brownish colour observed in the bubbles on top of the samples due to the presence of oxygen.
	30 kW/m^2	In both cases glass broke around 3-4 minutes. In one test a piece of glass fell (9 minutes) and the PVB was directly exposed to heating which resulted in local flames. The rest of the sample did not burn; the PVB trapped between two glass plates started flowing above 250°C.
	50 kW/m^2	In both cases glass broke in the first minute. The PVB started burning first in the cracks and edges. The PVB from inside the glass was flowing out of the sample and burning. The glass stayed intact in the sample holder but fell apart while removing it from the holder after the test.
Coated laminated glass	15 kW/m^2	No glass breakage appeared. No reaction of the PVB observed.
	30 kW/m^2	No glass breakage observed. Bubbles started to appear in the PVB only after 8-9 minutes. Slow reaction and some brownish colour on

		the top of the samples was visible, probably due to the presence of oxygen.
	50 kW/m^2	No glass breakage was observed. Slow reaction of the PVB was observed. No burning appeared.
Float glass	15 kW/m^2	No glass breakage appeared.
	30 kW/m^2	In one sample glass breakage appeared in the third minute. No glass fell down. The second sample did not break.
	50 kW/m^2	Glass breakage appeared in the first minute. In one test a small piece of glass fell, the rest of the sample stayed intact.
Fire-resistant glass	15 kW/m^2	Glass breakage appeared in each of the tests due to fixation and pressure of the reaction. The foamy interlayer kept the broken glass pieces together, so no risk of glass fallout appeared. All samples stayed intact also after removal from the sample holder.
	30 kW/m^2	
	50 kW/m^2	

The temperature evolutions measured on the unexposed surface of the samples are shown in Figures 2a, b and c. The thick lines represent the average of all measurements recorded for two or three samples of the same type, subjected to the same heating regime, while the thin lines and the shading areas represent the range of these measurements. This means that each thick line is a summary of six to nine thermocouple readings, excluding any abnormal results such as thermocouple detachment from the sample.

The temperature evolution of float glass, uncoated laminated glass and the fire-resistant glass are very similar at the beginning of the test despite the fact that float glass is partially transparent to the infrared wavelengths, compared to the laminated and fire-resistant glass which have an interlayer with different absorption spectra. This could be due to the glue used for the thermocouples attachment - the glue does not offer the same transparency as float glass and may absorb wavelengths transmitted by the glass.

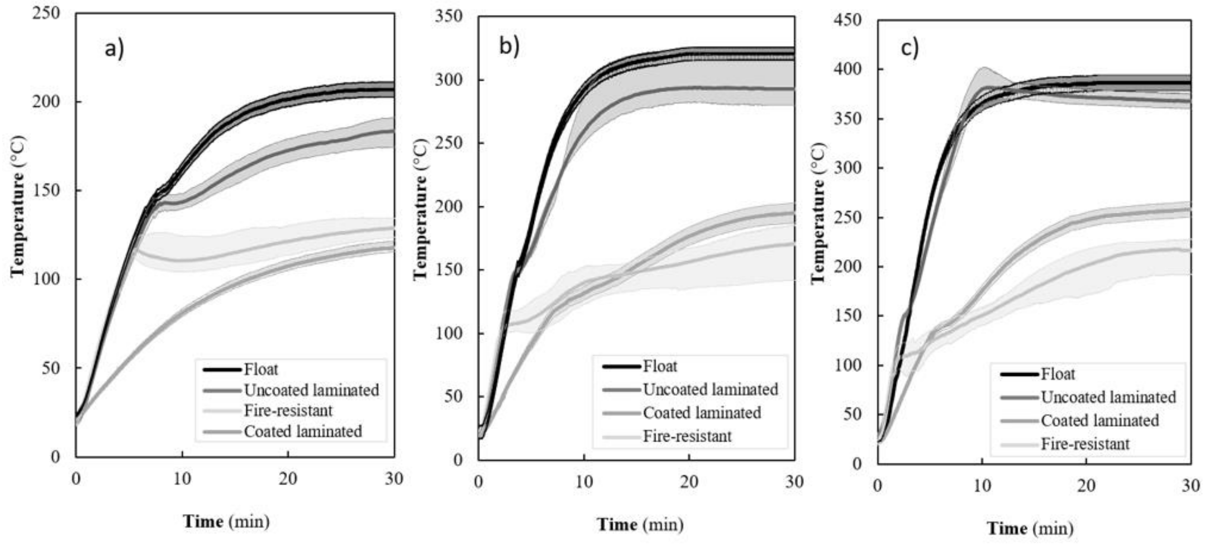

Figure 2 Temperature evolution on unexposed surface of the glass samples subjected to different incident heat fluxes: a) 15 kW/m^2, b) 30 kW/m^2, and c) 50 kW/m^2.

Figure 2a shows the positive effect of coating on the temperature evolution in the glass. For lower heat fluxes, such as 15 kW/m^2 or 30 kW/m^2, the coated samples showed temperatures at the end of the test comparable to those of fire-resistant glass samples. In case of heat flux 50 kW/m^2, this temperature was slightly higher.

DISCUSSION

The results are discussed with a division to uncoated laminated glass and fire-resistant glass due to the significant differences in their behaviour. The effect of coating is explained as a separate subsection.

Reactions in laminated glass

Imposing a heat flux of 15 kW/m^2 on the surface of uncoated laminated glass did not have a significant impact on the integrity of the sample. The highest temperature reached in this case was 183°C - slightly above the first reaction temperature of the PVB layer. Bubbles in the PVB layer started appearing above 140°C and the pressure inside these bubbles caused an expansion of the interlayer to around 3mm. The expanded layer worked as an insulator and contributed to a decrease of temperature visible in Figure 2a between minutes 7 and 10 of the test. This effect is even more visible when compared to float glass (around 25°C of difference at the end of the test).
On the other hand, behaviour of samples exposed to 30 kW/m^2 strongly depended on the glass breakage and glass fall. The first sample, shown in Figure 3, reached around 310°C at the end of the tests and underwent the following reactions: big bubbles appearing in the PVB and causing expansion (Figures 3a and 3b), small bubbles appearing inside the walls of the big bubbles (Figure 3c and 3d) and slow flowing of the PVB (from Figure 3e). In this case, a part of float glass fell during the test, after around 8 minutes, exposing the PVB directly to heating and air, which resulted in flames appearing locally on the surface due to the presence of oxygen. This exothermic reaction was visible in the increase of temperature recording of the two thermocouples close to the fall of glass (refer to Figure 2b – maximum thermocouple recording for uncoated laminated glass).
It is important to mention that the second sample exposed to the heat flux of 30 kW/m^2 did not experience glass fall and reached temperature 285°C at the end of the test. Therefore, PVB did not burn and the PVB flow was visible within the whole surface of the interlayer.

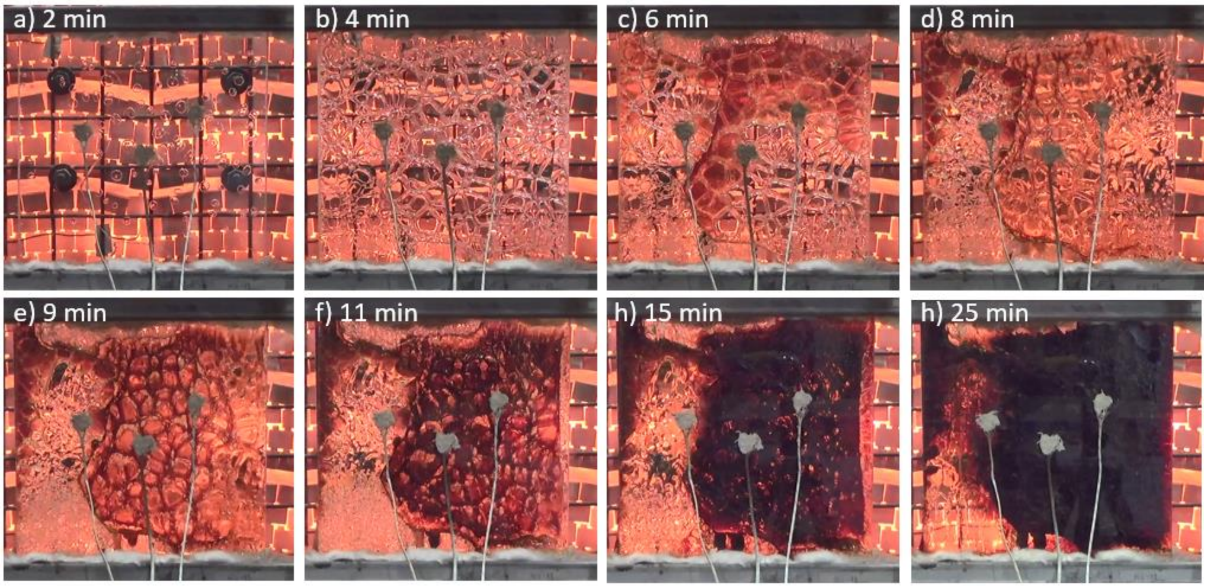

Figure 3 Reactions of uncoated laminated glass exposed to heat flux of 30 kW/m^2 after different timing. Note that the steel square grid and the orange ceramic elements are parts of the heating surface.

The reactions of uncoated laminated glass exposed to 50 kW/m^2 are shown in Figure 4. The first steps of the reaction are similar to those of the samples subjected to lower heat fluxes (Figures 4a and 4b). The flames started appearing along the crack in the middle of the sample (Figure 4d) and on the edges of the sample (Figures 4e and 4f). Similarly to the sample exposed to heat flux of 30 kW/m^2, the PVB combustion resulted in black char residue (Figures 4g and 4h).

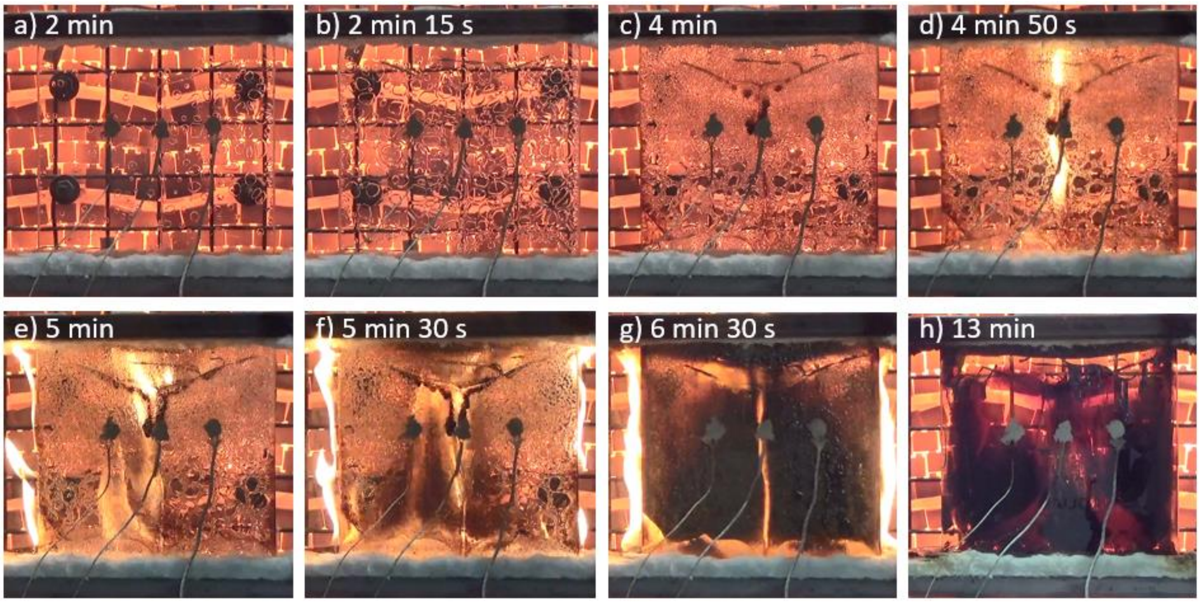

Figure 4 Reactions of uncoated laminated glass exposed to heat flux of 50 kW/m² after different timing

Appearance of bubbles in the PVB in all cases created an expansion of the interlayer thickness of 2 to 4 mm, as shown in Figure 5a, which is significantly lower than the expansion of fire-resistant glass interlayer (refer to subsection *Reactions in fire-resistant glass*).

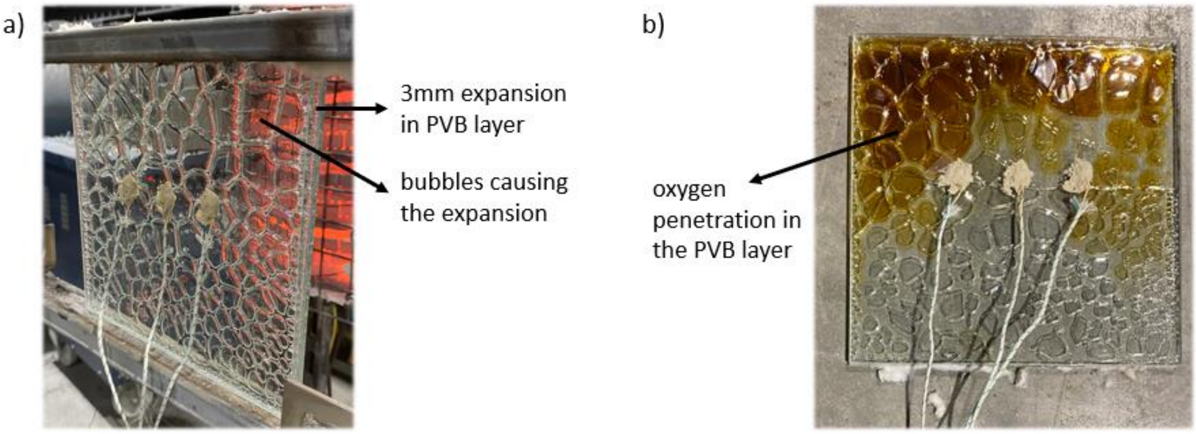

Figure 5 Reaction of laminated glass: a) expansion of the PVB layer, b) sample cooled down after the test.

As the samples were left for a few minutes after the test to cool down, the softened non-burnt PVB solidified, and the bubbles decreased in size (Figure 5b).

Reactions in coated laminated glass

Presence of a low-E coating significantly changes the behaviour of laminated glass when the convective heating is limited, as was the case here. This is the case when the source of radiation (i.e. fire) is far from the heated product. Otherwise, the convective heat transfer may decrease the positive effect of the coating.

The temperature reached after 30 minutes on ambient surface of the glass subjected to heat flux of 15 kW/m² was only 117°C, which was not enough to start a reaction in the PVB layer. Additionally, no glass breakage was observed. On the other hand, the heat flux of 30 kW/m² caused higher temperatures and the bubbles in PVB started to appear slowly after 8-9 minutes of the test (6 minutes delay compared to uncoated sample). Their growth was slower which in some samples resulted in

lower expansion of the PVB layer (around 2 to 3mm) compared to the uncoated laminated glass (approximately 3 to 4mm).
Finally, samples exposed to the highest heat flux of 50 kW/m^2 showed the biggest impact of the coating. None of the samples experienced breakage, which prevented combustion of PVB. In this case, the flowing PVB worked as an adhesive preventing the glass to fall. The integrity of glass was not compromised despite exposure to a high, fire-like heat flux.

Behaviour of fire-resistant glass

Samples of fire-resistant glass subjected to heat fluxes similar to the ones used in standard fire testing underwent various reactions. No glass breakage due to thermal shock was observed, owing to the limited size of the sample. When the silica gel inside the fire-resistant glass reached around 100°C, a visible white foggy layer appeared due to the vaporisation of free water on the interface between the exposed glass and gel layer, as shown in Figure 6a. The fog quickly intensified with the increase of temperature (Figure 6b). In the meantime, more free water included in the gel started vaporising creating small bubbles on the interlayer between exposed glass and the gel (Figure 6c). The more water vaporised across the thickness of the gel layer, the bigger the bubbles grew, until they reached enough pressure to push the glass and cause the fast expansion (Figure 6d, 6e). This pressure led to additional glass breakage. In the foaming process, the thickness of the intumescent layer increased a few times, in average around 4 to 5 times in one sample. However, the foam thickness reached locally up to 15 mm due to non-uniform expansion over the sample.
Afterward, the bond water started vaporizing creating very small bubbles inside the walls of the foam and causing its additional, but limited expansion (Figure 6f). When the foam was fully expanded, with the continuous increase of temperature, various chemical reactions happened, which resulted in the change of colour (Figure 6h). For example, the presence of polyol in the composition resulted in a yellow to brown colour of the foam owing to its organic nature.

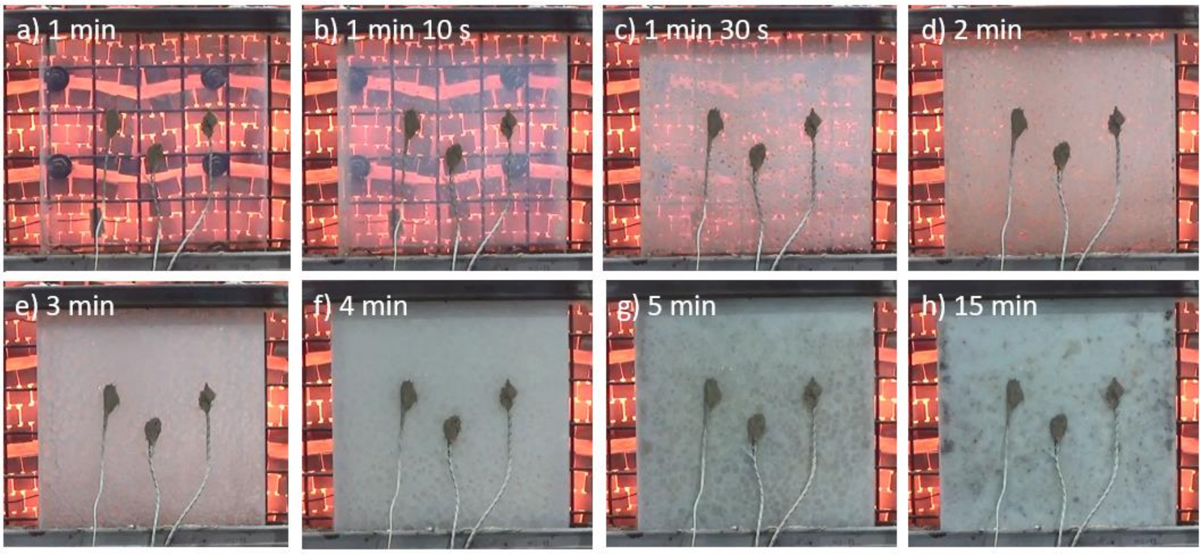

Figure 6 Reactions of fire-resistant glass exposed to heat flux of 50 kW/m^2 after different timing

Small differences in reaction were noted depending on the heating conditions. Samples exposed to a heat flux of 15 kW/m^2 reacted more slowly than samples exposed to 50 kW/m^2 which made the expansion slightly less dynamic and more uniform over the surface of the sample.
The expansion, creation of a low thermal conductivity foam and the latent heat of water vaporisation are the three factors which positively influenced the temperature evolution on unexposed surfaces of the fire-resistant glass samples. Additionally, the softening and melting point of the foam are significantly higher than those of PVB and, therefore, the fire-resistant glass samples did not experience any issue of integrity or stability.

CONCLUSIONS

Glass behaviour in fire conditions is a complex problem which has been analysed here experimentally in conditions similar to those that pertain in a standard fire resistance test. The occurrence of glass breakage and its pattern define how the PVB reacts to the heating, as they influence the supply of oxygen in the PVB interlayer. It is indeed possible to have locally different behaviours in one glass product, combustion along the cracks with a local fast rise in temperature and, away from the cracks, an adhesive behaviour with a low expansion causing a slight decrease in temperature. However, at high temperatures, the PVB layer flows down leaving an empty gap between the float glass layers, which might, but not systematically, cause a glass fallout in a non-load bearing element.

The effect of the low-E coating proved to be significant in the present study. It decreased the risk of glass breakage, slowed down the heating of the sample and, therefore, the reactions in PVB. In the low heat flux (15 kW/m^2) condition, the temperature increase on unexposed side of the coated samples was even lower than in case of fire-resistant glass. This behaviour might be very significant in the early, pre flash-over phase of a real fire and could, in some cases, make the difference between glass breakage leading to flash-over and glass stability leading to a fire that dies down from lack of oxygen in the compartment. However, with the increase of heat flux, the importance of the intumescent layer significantly increased.

None of the samples experienced fallout, owing to their small size. More studies should be performed to examine the influence of glass size on the behaviour and fallout of real scale glass products. Additionally, all samples were tested in controlled conditions opposed to a real fire situation. Therefore, a more complex study should be performed to compare the performance of analysed products in different conditions.

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