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M. Wu and W.K. Chow, "A review on fire-resistant glass with high rating", Journal of Applied Fire Science, Vol. 23, No. 1, p. 59-76 (2013-2014)

A review on fire-resistant glass with high rating

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September, 2012

Abstract

Architectural features with glass panels are commonly featured in large-scale construction projects. Exterior glass panels have been installed in many new symbolic buildings in cities all over the world, particularly in the Far East including Hong Kong, Singapore, big cities in mainland China, Japan, Korea and Malaysia. Fire hazard of glass façade of such buildings is a great concern. Conventional glass materials are weak spots in building fires, and fire-resistant glass has been developed and installed. Apart from assessing fire resistance of glass panels by standard tests, there are no universal or state standards in fire-resistant glass specifications. It should be noted that a glass façade system is comprised of framework, glass and other accessories. A brief review of fire-resistant glass is presented in this paper. In standard fire resistance tests, the most relevant performance criteria of fire-resistant glass are integrity, insulation and radiation. But in literatures, fire-resistant glass can be divided into two categories: non-insulating and insulating. The chemical compositions of the glass products, which depend on the manufacturing method and the required fire resistance standards, are not listed in architectural specifications. This is common for products manufactured in the Far East. This paper provides an overview of the common types of fire-resistant glass, especially the ones with high ratings, the tests and standards used to assess these products. Two samples of insulating glass available in the local market are selected. Their thermal behaviors while exposed to a heat flux of 70 kWm^{-2} are studied.

1. Introduction

Glass façades are found in many new symbolic buildings [1] all over the world. Many of these constructions are found in the Far East including Hong Kong, Singapore, Mainland China, Japan, Korea and Malaysia. Some are supertall buildings of height over 300 m [2]. A façade glass system is comprised of framework, glass panes and other accessories, such as acoustic insulation and wind pressure relief. Such glass systems are mainly used as vertical walls with special features such as double-skin façades. The trend of using glass systems as floor and ceiling for vision extension has also started [3]. In fire, the spread of flame and smoke from a closed compartment with adequate fire resisting rating to the neighboring areas is often caused by the destruction of glass panes. Openings are then found after breaking the glass. Further, the entire glass system of the panes may not be fixed properly by following the standard. The propagation of fire through glazed opening is a great concern [4]. A wide range of glass materials has been used by the building industry, and these glass materials are classified in standards such as BS 952-1:1995 [5]. Most glass products have very low fire resistance period. Glass panels will crack quickly because of the temperature difference between the surfaces and edges [6-8]. The discharge of cold water of the fire suppression systems, which might break the heated glass panels [9] into pieces, is another concern. Because conventional glass materials are weak spots in a building, fire-resisting glass has been developed.

Fire-resistant glass can be defined [10] as a glass system consisting of one or more transparent or translucent panes with appropriate mounting, e.g. frames, seals and fixing materials. The system can also satisfy appropriate fire resistance criteria. Standard tests in fire resistance assessment of glass products in different countries are reviewed and compared [11]. In these standard tests, the most relevant performance criteria of fire-resistant glass are integrity and insulation. A supplementary criterion of radiation is also specified in some standards such as BS EN 13501-2 [10].

Common glass products which provide some resistance to fire and are given fire ratings are reviewed briefly [4,12-16]. Glass and Glass Federation (GGF) provides a detailed guideline on the specification and use of fire-resistant glass products available in the UK market [17]. The types of glasses and the performances of fire-resistant glass products available in the US are also reviewed [18-19]. Fire-resistant glass can be classified into three types: those satisfy integrity criterion only; those satisfy both integrity and radiation criterion; and those satisfy both integrity and insulation criterion. Some literature refers integrity or radiation as non-insulating [12,17]. Hence, fire-resistant glass can be divided into two categories: non-insulating and insulating. When heat insulation is required, glass systems with protective layers such as toughed glass can be used. The protective layers are made up of materials such as aqueous gel. Another option is annealed glass panes, which consist of intumescent interlayers of metal silicates.

The chemical compositions of the interlayers depend on the manufacturing method and the fire resistance requirement. However, the chemical compositions of the interlayers are not known in the Far East. It has been observed that smoke is emitted when burning the protective layers of these glass products. The smoke emitted from these products can be potentially harmful during fires, causing injuries or even deaths.

This paper provides an overview of the common types of fire-resistant glass, especially the ones with high ratings; it also includes tests and standards used to assess these products. Two samples of insulating glass available in the local market are selected. Their thermal behaviors while exposed to a heat flux of 50 kWm^{-2} are studied.

2. Non-insulating Glass

A wide range of glass products is available for different building and construction purposes [13]. Some of these glass products are regarded as non-insulating fire-resistant, which provide integrity against fire. Integrity can be defined as the ability of a material to withstand fire exposure on one side without the transmission of fire as a result of the passage of flames or hot gases [10].

Wired glass has been the only glass offering some fire resistance for decades, and it has been accepted as a generic product [6,12-13]. Wired glass is made by embedding a wire mesh throughout the glass pane [17-19]. In a fire, the glass usually breaks quickly, but it is still held together by the integral wire mesh at the same spot. The integrity limit is reached when the glass softens and is pulled out of the glazing pocket.

With the development of glass technologies, other non-insulating glass products, such as toughened soda lime-silicate glass, toughened borosilicate glass, glass ceramics etc., have been developed. These products are toughened physically or chemically to increase resistance to thermal stress [12-13]. They can better withstand the impact of thermal shock and block the passage of flame and smoke, but they cannot stop heat transmission by radiation and conduction. When building occupants evacuate, intense radiation is a threat if the glass areas are adjacent to escape routes. Hence, products with the ability to reduce radiant energy are developed.

Reflective coated glass is made by applying thin layer of oxides or other compounds of tin, aluminum, titanium and alloys such as stainless steel on the glass pane surface [20]. The metal coating is visually transparent and can reduce the heat transferred to the glass by reflecting radiant energy in a fire. Most of the energy reduced is in the infrared portion of the spectrum where the glass is opaque and a good absorber. The effect of a metallic coating on fire-resistant glass was reported by Fawcett [21].

Resin laminated glass is the other type that can reduce heat transmission. It is made by bonding layers of glass with polymer layers. During a fire, the polymer interlayer carbonizes to give an opaque layer, which holds the glass panes together and reduces heat radiation [17]. These are also wired, tempered borosilicate and ceramic glasses. It is suggested that several polymers, such as the ones from fluorocarbon family, can be used in the layers of this glass [22-23]. However, polyvinyl butyral (PVB) with fire-resistant addictives is the most commonly used material [18, 24]. As the adhesive polymer layer prevents the dispersal of glass fragments during an impact, resin laminated fire-resistant glass is also used as safety glasses [25].

Both reflective coated and resin laminated glasses have the ability to reduce heat transmission in fires. However, they cannot provide insulation in standard fire resistance test, and they are not usually considered as insulating glass.

Fire-resisting properties of these products are summarized in Table 1.

3. Insulating Glass

Insulation is the ability of a material to withstand fire exposure on one side without the transmission of fire to the unexposed side by limit heat transfer due to conduction, convection and radiation (in addition to integrity) [17]. Insulating glass can block significant amount of heat transfer; it is manufactured by laminating glass pane with fire resistant layers. There are two main types of insulating glasses: intumescent laminated and gel laminated glass.

Gel insulated glass are produced by sealing aqueous gel layers in the inter-space between toughened silicate glass panes [18]. During a fire, the gel releases water and absorbs considerable amount of energy. Water evaporates and the fire side glass breaks. Evaporation of the water results in the formation of an insulating crust, which prevents the penetration of heat. This product is made to the required size as it cannot be cut. Performance range of this type of products is made possible by the varying thickness of the gel [17].

The main components of the aqueous gel interlayer are water, water soluble salt and polymer which act as a gelling agent [26-28]. Derivatives of acrylic acid, such as acrylamide, are commonly used to form polymer. The polymerization is achieved by adding a catalyst and a cross link agent, for example diethylaminopropionitrile (DEAPN) and N,N'-methylenebisacrylamide (MBA). Due to the toxicities of acrylic acids, the use of other non-toxic components, for example polyvinyl alcohol, have also been proposed [27,29]. The water soluble salt is generally a salt of alkali metal or ammonium, for example chlorides of sodium and calcium, and it should be compatible with the rest of the chemical system. The salt often has strongly corrosive effects on the metal fame of the glass system; anticorrosive chemicals, such as an alkali phosphate, can also be added to the aqueous gel [26]. The aqueous gel layers are sealed within layers of toughed glass panes using conventional sealing system, and a primer can also be used to generate adhesion between aqueous gel and silicate glass panes [30].

Intumescent interlayer laminated glass incorporates special inorganic interlayers, which turn opaque and foam to form a thick solid layer upon exposure to heat. This intumescent interlayer inhibits the passage of conductive and radiant heat and becomes resistant to fire. The glass layers adjacent to the fire crack retain integrity owing to adhesion with the interlayers. They are generally made with annealed glass and can be cut. Depending on the thickness of the glass, the number of interlayers and interlayer combination, fire resistance (integrity and insulation) of up to 2 hours can be achieved, if appropriate glass and frame sizes are used [31-32].

The intumescent laminated glass is made by drying hydrated alkali metal silicates mixture on glass panes, and the production process has been described in a number of patents [31, 33-35]. The main component hydrated alkali metal silicates were reported to have a weight ratio SiO_2:M_2O in the range of 2.5:1 to 5.0:1 and a water content of 10 to 40 percent. Sodium silicate is used as intumescent material, and the commercial product with weight ratio SiO_2:Na_2O of 3.4:1 is considered suitable for this use. It is suggested that addictives can improve fire resistance of the intumescent interlayer. The effects of organic compounds on the fire resistance of interlayer were reviewed, and some examples of organic compounds include glucose, glycerol and glycerin [36-38]. When exposed to fire, the fire side glass sheet is likely to shatter into pieces of intumescent layer and fall off. A primer layer is applied between the exposed glass pane and the intumescent layer; the layer contains silanes such as fluorosilanes can be used as protective layer [39]. The adhesion between the primer layer and the intumescent layer decreases at high temperature, and this causes the fire side glass to separate completely from the intumescent material which remains intact.

Fire-resisting properties of these insulating products are summarised in Table 1.

4. Fire Testing

The degrees of fire protection required for different areas of a building vary according to building codes. The glass assemblies in these locations must carry the same or higher fire resistance rating. Fire resistance is the time that the member or assembly withstands a fire test without failure [6].

There are currently a large number of different standard tests in fire resistance testing, and these tests include comparable fire endurance testing procedures and requirements [11]. The glass products must be tested as a part of a complete fire-resistant glass system. The glass system is installed in the open face of a vertical fire test furnace in which the fire severity follows a prescribed time-varying temperature curve, known as the standard temperature-time curve. The standard temperature-time curves used in different countries are identical [40], and Figure 1 shows typical a standard temperature-time curve [10, 41-43]. The common acceptance criteria for the fire test include integrity and insulation. The criterion radiation specified in some standards [10,43] is only required by a limited number of countries. Although the actual time in the standard tests is recorded to the near-integral minute, fire resistance ratings are given at standard intervals, e.g. 15, 20, 30, 60, 90, or 120 minutes [44]. Comparisons of typical standard fire resistance tests [41-43] in different countries are shown in Table 2.

Standard fire resistance test is intended for product classification against pass or fail criteria with controlled fire conditions. It allows the expected performances of test elements to be compared over a common basis [16]. However, there is no direst correlation between the fire test results and the duration of resistance in a real fire [45]. Conditions such as fire exposure in a real fire are much more complicated than the ones specified in standard tests. The ratings and classifications of fire-resistant glass products obtained from these standard fire tests are indications of performance, but they do not represent the behaviour of these products in a real building fire.

In United States and Canada, fire testing is conducted in two parts. The first part is the fire endurance test which includes the essential procedures aforementioned. After the furnace test, the glass assembly is subjected to the hose stream test immediately following standards such as ASTM E 2226 [46]. During the procedure, water is pumped through a fire hose onto the entire exposed area of the glass assembly. At the same time, it has to remain intact with minimum amount of breakage that is allowed by the test standards. The hose steam test was developed in the 1800s, and it concerned the integrity of structural elements [19] and was later adapted to test fire-resistant glass. There are debates about the use of hose stream tests for fire-resistant glass products. Some believe that hose stream tests can demonstrate the ability of fire-resistant glass to withstand thermal shock [15 and 47-48]; others think that hose stream tests are not designed for testing thermal shock, thus they are inadequate for fire-resistant glass testing [19 and 49-50]. Currently, hose stream tests are not used in any other counties except United States and Canada.

Common glass products break into long sharp shards under impact. In order to reduce the possibility of severe cutting and piercing injuries, safety testing is needed for glass products if they are to be placed in locations where accidental impact may occur. The safety glass products are required not to break or break safely during standard safety tests. Impact safety rating are given by standard tests, including standards BS6206 [51], BS EN 12600 [52], ANSI Z97.1 [53] and CPSC 16CFR1201 [54].

5. Cone Calorimeter Tests

Two samples of insulating glass, i.e. one gel laminated and one intumescent laminated, are selected. The gel laminated sample has a length of 10 cm, a width of 10 cm and a thickness of 2.5 cm. It is labeled as sample 1 as shown in Figure 2. The intumescent laminated sample of length 10 cm, width 10 cm and thickness 2.6 cm is labeled as sample 2 in Figure 3. The behaviors of these two samples when exposed to a heat flux of 70 kWm^{-2} are studied in a cone calorimeter, following the standard ISO 5660-1 [55].

Upon heating, the fire side glass broke; the interlayers turned opaque and formed a solid layer to keep the protected side glass intact. Pictures of sample 1 and sample 2 after heating are also shown in Figure 2 and Figure 3 respectively.

Heat release rate and CO_2 levels during the tests were too low, so they were not recorded. The CO levels during the tests are listed in Figure 4. The total mass loss and total production of CO with test conditions are summarized in Table 3.

6. Conclusions

Nearly 30 years ago, it was recognized that most victims of fires die from smoke or toxic gases and not from burns, and smoke is the main threat to life in a building fire [56]. However, smoke toxicity standards have not yet even been established in building codes and regulations of fire safety provisions in Hong Kong and many countries in the Far East [57]. One of the main reasons is that it is difficult to study the toxicity of smoke. The release of toxic gas does not only depend on the burning materials, but also on the manner how the materials are burnt [58]. When the protective layers of fire-resistant glass are heated, smoke is a huge concern. Therefore, both smoke concentration and toxicity should be assessed. Smoke toxicity should also be recommended in assessing the fire responses of glass products.

Fire-resistant glass products have the ability to remain its integrity in fires. They are good replacements of standard glass products used in building. However, the compositions of fire-resistant glass products are not released by manufacturers, especially those from the Far East. It has been observed that smoke is emitted when burning the protective layers of glass products. This raises a safety question concerning smoke emissions, especially for buildings with large glazing area ratios. Efforts should be put in to study the smoke emitted from burning the fire-resistant glass products.

7. Additional Comments

The paper was published as a journal paper [59]. With the practice of publisher, preprint is allowed to upload at a website. There are further studies on this topic [60-73].

Acknowledgement

The work described in this paper was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China for the project "Smoke Emission in Burning Fire Resisting Glass with Higher Rating" (PolyU 514507) with account number B-Q05q.

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ARevFG1fromWM2A

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A472UL22-1b (opened 3 Aug 2023)

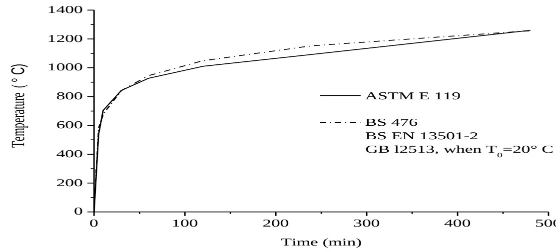
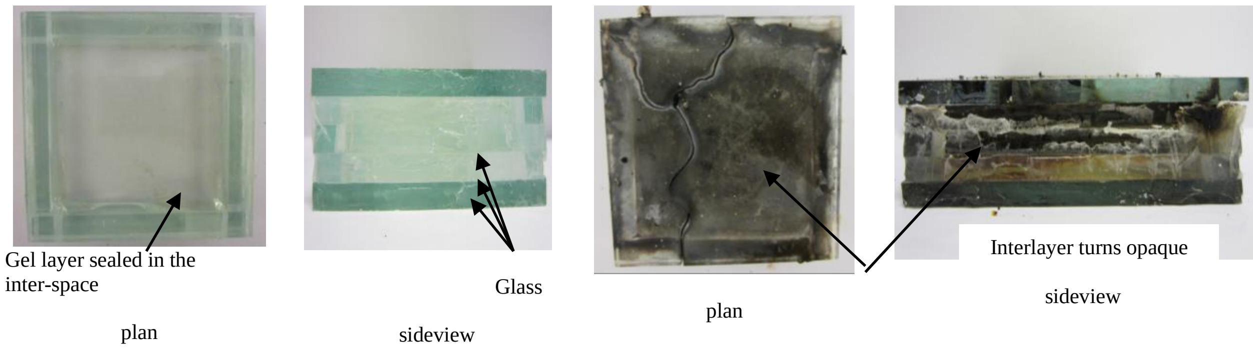


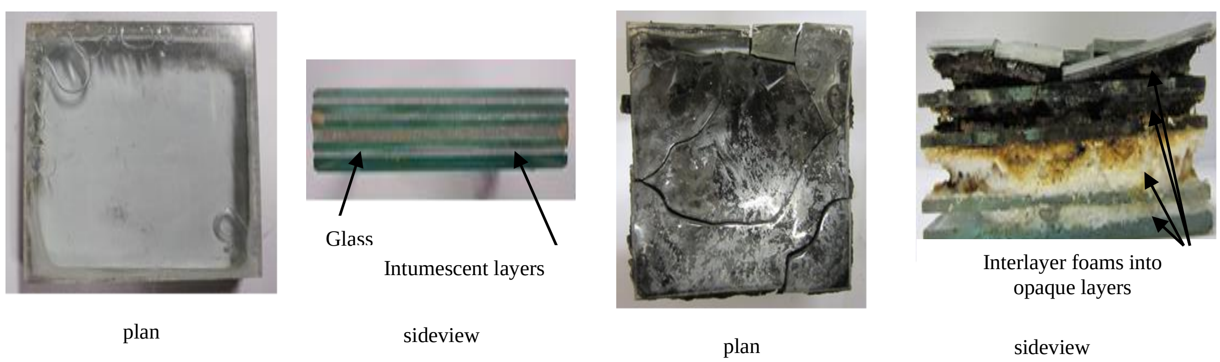
Figure 1: Standard temperature-time curves



(a)Sample 1

(b) Sample 1 30 mins after exposure to heat

Fig. 2: Sample 1 (gel laminated fire-resistant glass) exposed to 70 kWm^{-2} cone calorimeter test



(a) Sample 2 **(**intumescent laminated fire-resistant glass)

(b) Sample 2 after 30 min of exposure to heat

Figure 3: Sample 2 exposed to 70 kWm^{-2}

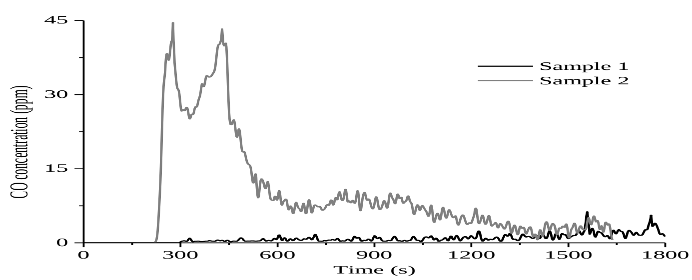


Figure 4: CO concentration recorded in the cone calorimeter

Table 1: Properties of typical fire resistant products

Type of glass	Reference	Method of providing fire-resistance
Wired glass	GGF, 2009	The glass breaks early on in the fire but is held together and in place by the embedded wire mesh.
Toughened soda lime-silicate glass	GGF, 2009	They are toughened physically or chemically to increase resistance to thermal stress. They can better withstand the impact of thermal shock and block the passage of flame and smoke
Borosilicate	Lyon,2007	
Glass ceramics	GGF, 2009; Curkeet, 2003	
Reflective coated glazing	Curkeet, 2003	The metal coating is visually transparent and reduces the heat transferred to the glass by reflecting radiant energy (mostly infrared) from a fire.
Resin laminated glazing	Curkeet, 2003	The resin-based interlay is formulated to have resistance against fire and flaming. When exposed to a fire, the interlayer carbonizes to give an opaque layer, which holds the glass together and reduces heat radiation.
Gel laminated glass	Lyon, 2007; Amstock, 1997	The gel interlayer absorbs heat by the evaporation of water and produces an insulating crust in the event of fire, which prevents the penetration of flame and smoke.
Intumescent laminated glass	Lyon, 2007; Amstock, 1997	Intumescent interlayer turns opaque and foams to form a thick solid layer on exposure to heat inhibiting the passage of conductive and radiant heat.

Table 2: Comparisons of standard fire resistance tests used in different countries

	Temperature / time condition (see Figure 1)	Performance criteria (conditions of failure)			
		Integrity	Insulation	Radiation	Hose stream
BS EN 13501-2	$T = 345 \log_{10}(8t + 1) + 20$	Gaps and cracks on the unexposed face: - allow flames or hot gases through and ignite a cotton fibre pad; or - can be penetrated through by gap gauges.	Temperature on unexposed face reaches: - a mean value of 140˚C (mean temperature) above its initial value; or - 180˚C above its initial value at any position.	Radiant heat value measured from the unexposed face: - at 1m away reaches 15 W/m^2	N/A
ASTM E119	538°C at 5 minutes 704°C at 10 minutes 843°C at 30 minutes 927°C at 1 hour 1010°C at 2 hours 1093°C at 4 hours 1260°C at 8 hours or over	Gaps and cracks on the unexposed face: - allow flames or hot gases through and ignite a cotton fibre pad.	Temperature on unexposed face increases: - 139˚C above its initial value.	N/A	Specified water pressure and duration of application: i.e. 207 kPa and 0.16min/9.3m^2 for 1.5 to 2 hr ratings.
GB l2513	$T = 345 \log_{10}(8t + 1) + T_0$ where, T_0 is the initial furnace temperature and should be in the range of 5-40˚C.	Gaps and cracks on the unexposed face: - allow flame penetrating through them and lasted for 10s or longer; or - allow flames or hot gases through and ignite a cotton fibre pad.	Temperature on unexposed face reaches: - a mean value of 140˚C (mean temperature) above its initial value; or - 180˚C above its initial value at any position.	Radiant heat value measured from the unexposed face: - at 3m away reaches 0.42 W/cm^2; or - at 1.2 times of the length or width away (whichever is the smaller one) reaches 3.35 W/cm^2.	N/A

Table 3: Summaries of fire-resistant glass samples in cone calorimeter test

Properties	Sample 1	Sample 2
Heat flux (kWm^{-2})	70	70
Total weight loss (g)	95.4	25.9
pk[CO] (ppm)	6.3	44.6
CO yield (kgkg^{-1})	0.0005	0.02