Fracture characteristics of heat treated glass - Safety glass classification

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Keywords

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2=Toughened safety glass
3=Surface compressive stress
4=AS 2208
5=Safe breakage behaviour
6=Pendulum impact test
7=Fragmentation test

Abstract

A recent experimental study on heat treated glass was carried out by a working group of Standards Australia. The purpose of this study was to improve the test protocol for toughened glass in Australian Standard AS 2208-1996 'Safety glazing materials in buildings'. In this study a relationship was established between surface compression measurements and the observed breakage performance of toughened (tempered) safety glasses of various thicknesses.

This paper reviews the methodologies and interpretations used in three national standards (AS 2208, ANSI Z97.1 and EN 12150-1) for the evaluation of the fracture characteristics of toughened safety glass. Based on the results of the Australian study there is a need for the performance criteria in these test protocols to be revised to so that they reflect the requirements implied by their definitions of what makes toughened glass safe.

Introduction

The three national standards reviewed have the following performance criteria.

AS 2208

The Preface of the 1978 version of AS 2208 [1] stated:

"The performance of safety glazing materials is evaluated by an impact test to simulate human impact of such energy that it could result in cutting and piercing injuries. Toughened safety glass has intrinsic properties which enable its impact performance to be determined by a simplified test procedure" (fragmentation test at edge of glass using a centre-punch)."

The 1996 Version does not make the same statement implying that the simplified test is the norm and not the 'deemed to comply' test as originally prescribed. Consequently, only the edge fragmentation of toughened glass with no specified test sample size has been used in Australia. The limitations of this test were very clearly evident from the results of the test program.

ANSI Z97.1

The ANSI Z97.1 2004 test for compliance is the 100 lb. (45.4 kg) lead shot impact test on a door sized panel of dimensions 863mm x 1930mm. The pass requirement for this test is the identification of the 10 largest 'crack-free' particles which shall in total weigh no more than the equivalent weight of 10 square inches (6,450 mm2) of the original test specimen.

EN 12150-1:2000

This test method standard requires that a 360mmx1100mm sample be broken by impact with a pointed steel tool at a position 13 mm in from the longest edge at the mid-point of that edge, and that if the toughened glass is to be used to offer protection under accidental human impact, it should also be classified according to EN 12600 (pendulum impact test employing a 50 kg twin tyre impactor).

The edge fragmentation requirement was first introduced [2] in Europe in the UK in BS 6206 Amendment No.5 as an additional safety glass test to complement the 'swinging bag' test and was "the fruit of painstaking deliberations within BSI following a fatal accident involving glass in a conservatory door which was allegedly toughened".

The test specimen size used in the EN 12150-1 fragmentation test is considerably smaller than the BS 6206 size test specimen (865 mm x 1930 mm) or the EN 12600 size test specimen (876 mm x 1938 mm). No published reference has been found to justify the selection of this smaller sized test specimen.

EN 12150-1 also specifies a maximum length of 100 mm for the longest particle, presumably because this length of particle would be capable of causing the fatality which prompted BS 6206 Amendment No.5. However it has been demonstrated in previous test programs on toughened glass that toughened glass which readily passes the edge fragmentation test may produce particles exceeding 100 mm in length when broken in the pendulum impact test and when broken at the panel centre by a pointed steel tool. While it may be possible that human impact may occur at edge of a toughened glass panel (for example a partially open unframed door) it is certainly the case, such as in the fatality cited in the Weir paper [2,3] that human impact may occur in the body of a glass panel. In the pendulum impact test the impact is by design at the panel centre. In the AS 2208 WG test program it was found as in previously documented studies [4,5] that occasionally 4 mm to 6 mm thick glass panels resist breakage at drop heights up to 1200 mm. These panels were broke at a drop height of only 200 mm when a fine scratch or Vickers indent was applied to the glass at the impact point.

Definitions

An essential part of a safety glass standard is the definition of what makes the glass safe. In the case of toughened safety glass following are definitions from the three national standards.

ANSI Z97.1 - 1966

Tempered glass, when broken at any point, the entire piece immediately breaks into innumerable small granular pieces.

ANSI Z 97.1 – 2004

"Tempered glass. (also known as a toughened glass). Glass of any shape that has been subjected to a thermal treatment process characterized by uniform heating followed by rapid uniform cooling to produce compressively stressed surface layers. See ASTM C- 1048 (1997) for additional requirement information."

AS 2208 – 1978

A glass which has been converted to a safety glass by subjection to a process of prestressing so that, if fractured, the entire disintegrates into small, relatively harmless particles. The residual surface compression is a minimum of 69 MPa.

EN 12150-1:2000

"Introduction: Thermally toughened soda lime silicate safety glass has a safer breakage behaviour when compared with annealed glass. When it should be used to offer protection under accidental human impact, thermally toughened soda lime silicate glass also should be classified according prEN 12600."

"Clause 3.1 Glass within which a permanent surface compressive stress has been induced by a controlled heating and cooling process In order to give it greatly increased resistance to mechanical and thermal stress and prescribed fragmentation characteristics.

(Fracture Characteristics (EN 12150-1 Clause 5) In the event of breakage, thermally toughened safety glass fractures into numerous small pieces, the edges of which are generally blunt.)"

It is clear that when evaluating the fracture behaviour of toughened safety glass none of these definitions which variously describe small, harmless, granular or generally blunt pieces would permit long pointed pieces.

AS 2208 Working Group Test Programs

Toughened safety glass of various thicknesses and from two recognised toughened glass suppliers was investigated in a series of test programs which incorporated the AS 2208 test protocol consisting of the 46 kg lead shot impactor and the alternate edge fragmentation test carried out on swing bag test size (860 mm x 1900 mm) panels. In addition fragmentation tests were carried out at the panel centre. The toughening process conditions were adjusted by the two manufacturers to obtain a range of surface compressions for each glass thickness. The surface compressions of all panels tested were measured using a laser GASP in accordance with ASTM C 1279 – 94.

Edge fragmentation

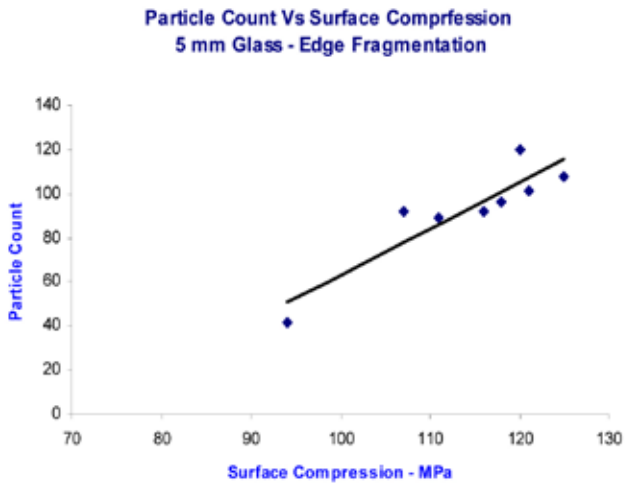
Australia has been using the edge fragmentation test on undefined panel sizes since 1978 when the first version of the AS 2208 safety glass test standard was published. As previously mentioned the justification for the use of edge fragmentation appears to have been lost in history.

Most toughening facilities in Australia manufacture glass to a minimum surface compression of around 90 MPa despite the fact that AS 2208-1996 and AS 1288-2006 require toughened glass to have a minimum level of surface compression of only 69 MPa.

All the samples with surface compression of 90 MPa or greater tested using edge fragmentation generated small particles well in excess of the particle count prescribed in the standard.

Figure 1.

Particle count versus surface compression – 5 mm toughened glass



Photograph 1.

Particle count – 4 mm toughened glass with surface compression of 72 MPa

Figure 2.

Surface compression versus length of particle for 5 mm toughened glass

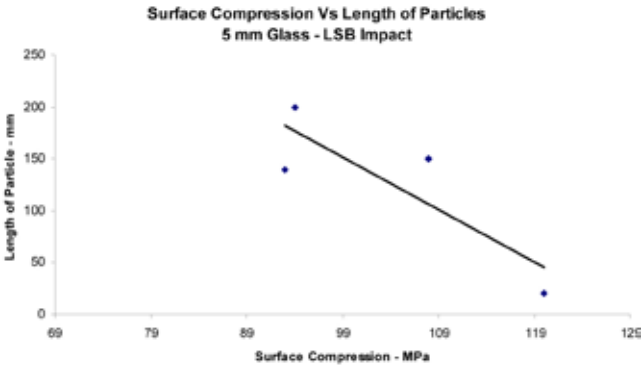


Figure 1 illustrates the relationship between particle count and surface compression using 5 mm thick toughened glass. A similar relationship exists for all glass thicknesses.

Panels deliberately manufactured at low levels of surface compression and tested using edge fragmentation developed large particles. Photograph 1 illustrates such a failure. For this panel of 4 mm glass the surface compression was measured at 72 MPa.

Lead shot bag impact

As mentioned, previous GPD papers [4,5] have reported the occurrence of long particles on breakage of 4 mm to 6 mm toughened glass in the pendulum impact test. In the AS 2208 WG study long particles were found on breakage by the lead shot bag (LSB) of 4 mm and 5 mm toughened glass with surface compression levels in the region of 90 MPa to 100 MPa. Photograph 2 shows long fragments of glass after a LSB impact on a panel of 4 mm thick toughened glass surface compression of 102 MPa. It produced particles up to 103 mm in length. Photograph 3 also illustrates long particles (held in the frame) from the LSB impact.

Centre fragmentation

EN 12150-1 imposes a maximum long particle length of 100 mm for toughened glass. However, as previously mentioned, the only break point specified in EN 12150-1 is at the edge.

Photograph 2.

Long particles resulting from lead shot bag impact of 4 mm toughened glass with surface compression 100MPa.

Photograph 3.

Long particles remaining in the LSB impact frame after 4 mm toughened glass with surface compression 100 MPa was broken by a lead shot bag impact.

The ECE R 43 automotive test protocol [6] for toughened glass includes a fragmentation test at the panel centre break point position and it is well recognized that the centre break point is the most stringent. Most organizations involved in making toughened glass for the automotive industry are very familiar with the fracture characteristics of glass when fragmented at the panel centre.

To comprehensively investigate the breakage characteristics of toughened safety glass panels in the AS 2208 WG test program a number of panels of glass with various thicknesses and varied levels of surface compression were fragmented at the panel centre.

The results of these tests for 5 mm toughened glass are provided in Figure 3. It is clear that there is an inverse correlation between particle length and surface compression. This was also observed for 4 mm and 6 mm thick toughened glass.

Photograph 4 illustrates some long particles generated from the centre fragmentation test with a 860mmx1900mm panel of 5 mm toughened glass having a surface compression of 94 MPa at the centre of the panel. Photograph 5 illustrates the fragmentation in a 860mmx1900mm panel with a surface compression of 135 MPa. There were no long particles generated.

Photograph 4.

Long fragments from centre fragmentation test – surface compression 94 MPa.

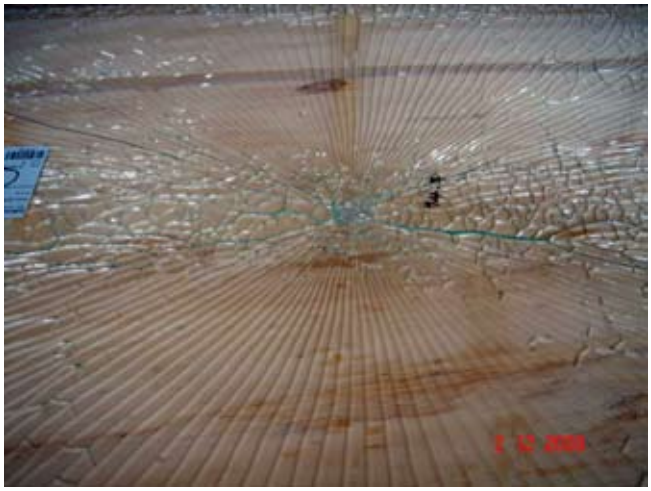
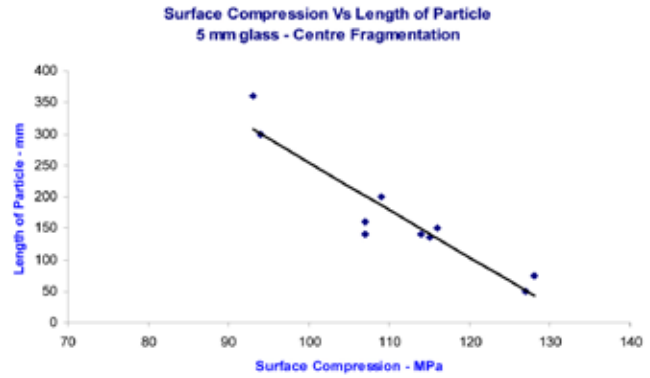


Figure 3.

Particle length vs surface compression – 5 mm thick toughened glass



10 mm thick toughened glass

It had been suggested that for 10 mm toughened glass a reduction of the particle count in the AS 2208 edge fragmentation test to a level of around 25 would reduce the clumping behaviour of the glass responsible for injuries in incidents of 'exploding' shower screens [8]. Some special 863mmx1930mm panels of 10 mm toughened glass were manufactured at a surface compression of 74 – 76 MPa. The samples were then fragmented at both the centre and the edge. A panel with surface compression of 76 MPa

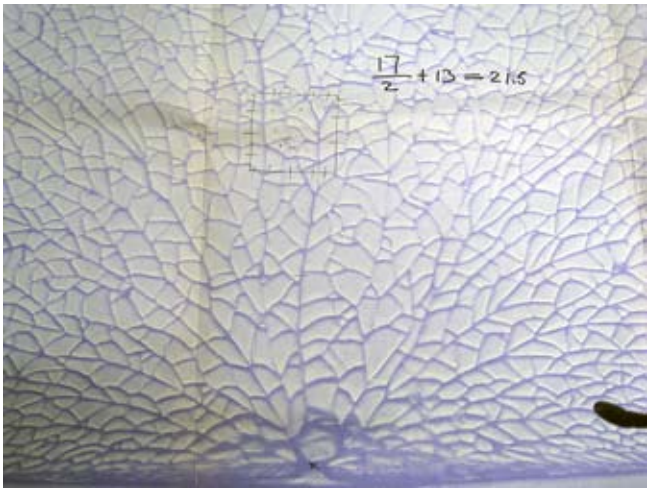
Photograph 5.

This panel of 5 mm toughened glass with a surface compression of 135 MPa exhibited no long particles when fragmented at the centre break point.-

was found to have a minimum particle count of 21.5 (see photograph 6) with a longest particle of 42 mm while a panel with surface compression of 74 MPa manifested long particles up to 200 mm (see Photograph 7). The degree of clumping in the broken panels with low surface compression levels was no different than those with normal surface compression levels.

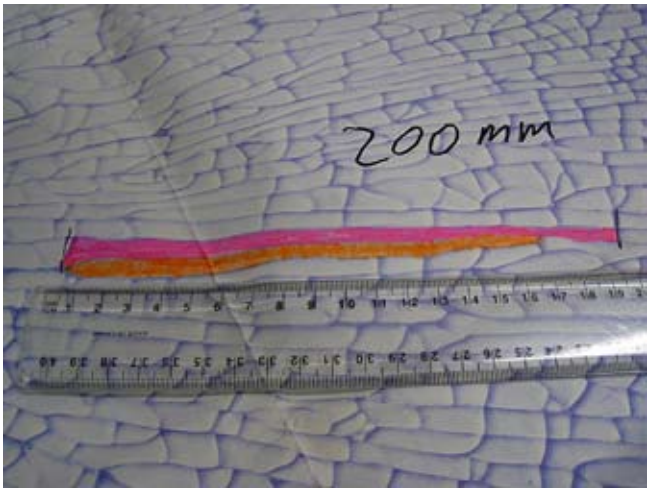
Photograph 6.

Particle count for 10 mm toughened glass with surface compressive stress of 76 MPa fragmented at the edge. Minimum particle count: 21.5



Photograph 7.

Long particles up to 200 mm in length resulting from impact with a metal punch at the panel centre of 10 mm toughened glass with surface compression of 74 MPa



Fragmentation test: Panel size and break point

With the AS 2208 alternative for classification of toughened safety glass of fragmentation at the edge of an unspecified sample size Australian toughening plants have in the past generally used sample sizes ranging from 300mmx300mm to 500mmx500mm. Recently some Australian manufacturers have adopted the EN 12150-1 sample size of 360mmx1100mm.

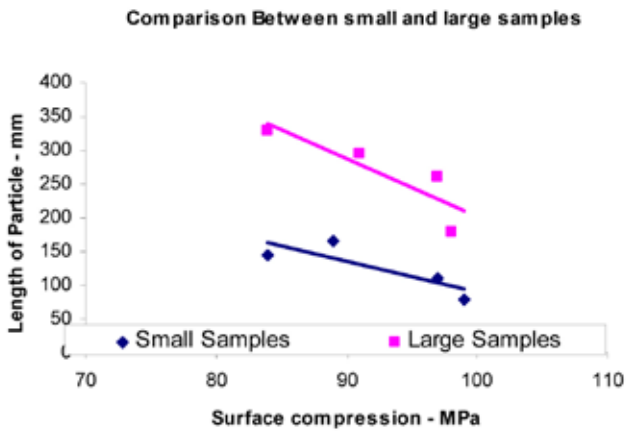
In studies conducted at the China Building Materials Academy [5] a number of 360mmx1100mm samples and 867mmx1936mm samples with different levels of surface compression were fragmented at the panel centre. The results are shown in Figure 4.

It is clear that the length of particle is a function of the panel size. The data clearly demonstrates the inadequacy of the EN 12150-1 sample size as well as the inappropriateness of the edge fragmentation point for the determination of long particles that could cause serious injuries or death in the event of human impact.

360mm x 1100mm is the sample size prescribed in ISO 1288-3 Glass in building — Determination of the bending strength of glass — Part 3: Test with specimen supported at two points (four point bending) EN 12150-1 specifies a mechanical strength value for toughened float safety glass (determined by ISO 1288-3) of 120 N/mm2. This value can readily be met with 6 mm toughened glass and should ensure that long particles are not formed. This value may not be adequate to prevent long particles with toughened glasses thinner than 6mm.

Figure 4.

Length of long particles versus surface compression - comparison between large and small samples.



Discussion

For toughened glass to satisfy its definition of breaking into small relatively harmless particles it requires higher levels of surface compression than implied by existing standards. Both ANSI Z97.1 and AS 2208 state that the minimum level of surface compression required for glass to classified as a toughened glass is 69 MPa. At this level of surface compression toughened glass of thicknesses 10 mm and below will not satisfy the requirements of the definition.

The primary test for the classification of toughened glass as a safety glass is the impact test using either the LSB or the twin tyre impactors. The criteria used to evaluate the broken glass sample have been found to be irrelevant and incorrect. The testing detailed in this paper showed that the EN 12600 requirement for the weight of the 10 largest fragments to less than the weight equivalent to 6500 mm2 of the original test does not address the potential formation of dangerous long particles in fractured toughened glass

The relationship between surface compression and the fracture characteristics of toughened glass has been clearly demonstrated and may be summarized as follows:

- The particle count (edge fragmentation) increases with increased levels of surface compression
- The maximum length of particle generated is reduced with increase in surface compression
- For the same level of surface compression the length of particles increases with decreasing glass thickness (see Figure 5).
- The particle count for a given level of surface compression increases with increasing glass thickness

The relationship between surface compression in toughened glass and the development of long particles is clearly established.

Conclusions & Recommendations

The primary test used in most countries for the evaluation of toughened glass as a safety glass, the pendulum impact test, ignores the length of particles and only requires that particles be weighed. This test allows long pointed particles (or 'splines') that can be well in excess of 100 mm in length. Such particles are not consistent with the definitions for toughened safety glass which prescribe small, granular and relatively harmless particles with blunt edges.

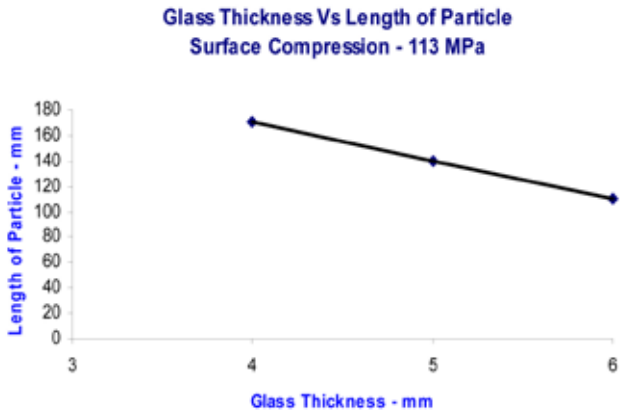
Panels of toughened safety glass that manifested long particles when broken in the pendulum impact test and by a metal punch as the panel centre did not manifest any long particles when fragmented by a metal punch at the edge as specified in AS 2208 and EN 12150-1. While well intended the maximum particle length requirement of 100 mm in EN 12150-1 is meaningless as the edge fragmentation test does not reveal that dangerous particles may result if the panel is broken by an impact at the centre of the panel.

In the test programs described in this paper the length of long particles has been found inversely proportional to the surface compression in the toughened glass. The higher the surface compression the smaller the length of the particles developed at fracture.

The measurement of the surface compression in toughened glass is a strong indicator of its fracture characteristics provided the instrument used is properly calibrated and it is recommended that surface compression measurement be considered as an alternative to the destructive test protocol currently being specified and used. Table 1 below provides minimum surface compression levels for a number of glass thicknesses that will ensure that no long fragments will be developed in toughened glass when broken.

Figure 5.

Glass thickness versus length of longest particle.



	Nominal glass thickness (mm)			
	4	5	6	≥8
Minimum surface compression (MPa)	130	120	115	110

Table 1.

Minimum surface compression for various glass thicknesses to ensure no long particles

References

[1] Australian Standard Specification, AS 2208-1978, "Safety Glazing Materials for Use in Buildings (Human Impact Considerations), Standards Association of Australia

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