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Procedure for Impact Testing of Fused Recycled Glass

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***Abstract*—**Recycled glass material is made from 100% recycled bottle glass and consumes less energy than re-melt technology. It also uses no additives in the manufacturing process allowing the recycled glass material, in principal, to go back to the recycling stream after end-of-use, contributing to the circular economy with a low ecological impact. The aim of this paper is to investigate the procedure for testing the recycled glass material for impact resistance, so it can be applied to pavements and other surfaces which are at risk of impact during service. A review of different impact test procedures for construction materials was undertaken, comparing methodologies and international standards applied to other materials such as natural stone, ceramics and glass. A drop weight impact testing machine was designed and manufactured in-house to perform these tests. As a case study, samples of the recycled glass material were manufactured with two different thicknesses and tested. The impact energy was calculated theoretically, obtaining results with 5 and 10 J. The results on the material were subsequently discussed. Improvements on the procedure can be made using high speed video technology to calculate velocity just before and immediately after the impact to know the absorbed energy. The initial results obtained in this procedure were positive although repeatability needs to be developed to obtain a correlation of results and finally be able to validate the procedure. The experiment with samples showed the practicality of this procedure and application to the recycled glass material impact testing although further research needs to be developed.

***Keywords*—**Construction materials, drop weight impact, impact testing, recycled glass.

I. Introduction

GLASS is virtually 100% recyclable, and the use of waste glass has been developed into many different fields such as aggregates, filter beds, and glass wool [1]. However, these new applications developed from waste glass end up as a down-cycled product of which, after the end of life, the material cannot be recovered or go back to the recycling stream. This is something that the new paradigm shift towards a circular economy is trying to achieve [2]-[4].

Using a combination of design engineering and design thinking methods, the emergent theory is that waste glass can be up-cycled and used for architectural applications. The material provides structural integrity and necessary aesthetic qualities required by both architects and end users. It also demonstrates how households waste can be up-cycled into new architectural and sustainable material with a circular economy approach. The aim of this paper is to investigate the procedure to test for impact resistance of low temperature fused recycled bottle glass for potential applications such as; pavements, wall cladding, or even non-structural furniture. Previous publications by Oseng-Rees et al. [5]-[7] have demonstrated an extensive test methodology for flexural bending, stain and scratch resistance. This paper is using the same low temperature fused recycled glass material as previous publications and aim to develop the test procedures for impact resistance.

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II. Literature Review

A. Fused Recycled Glass Material

Glass is a homogeneous isotropic material, of uniform composition throughout, and cannot be separated into different materials and has identical values of property in all directions [8]. Glass is also considered to be an amorphous solid as it lacks the ordered molecular structure of other solids, yet it has an irregular structure too rigid to be qualified as a liquid [9]. When molten glass cools rapidly, the molecules freeze in random positions and it becomes a transparent material known as glass. However, if the molten glass is allowed to cool slowly, the molecules in the fluid will have time to bond in a crystalline structure, and at this point, crystallisation or devitrification starts to occur [10].

Working with glass in a studio practice can be divided in three categories; hot glass, warm glass, and cold glass. Hot glass has a working temperature above 1000 ºC, and is moulded and shaped while it is at a low viscosity and are often referred to glass blowing processes and using in bottle manufacturing [10]. On the contrary, cold glass refers to working at room temperature, e.g. cutting, leading and polishing. The third term of working with glass is warm glass and the activity takes place at temperatures between 590-930 ºC, where the glass is enclosed inside a kiln. The glass is then shaped with the use of heat and moulds [11]-[13]. Glass fusing is joining two or more pieces of glass together by melting them in a kiln. The heat softens the glass until it becomes fluid, and two or more pieces of glass will flow together. Fusion is sometimes referred to as sintering and defined as the merging of grains of glass into a mass by heating until the surface melts sufficiently to fuse together [14].

The recycled glass material discussed in this paper is made from waste bottles glass which has been fused into a highly crystalline material, through a combination of low temperature fusion and firing schedules that encourages crystallisation. The material has changed visual properties and has no longer transparency qualities and looks more like a stone or a marble material. It is nonetheless hydrophobic and does not absorb water like a ceramic material. It has a working temperature of less than 900 °C.

B. Impact Testing Procedures

The purpose of impact testing is to measure the capacity of a material/shape/product to resist impact. It is tested in terms of two objects striking at high speeds. The results on the tested material after crashing can be studied and they can help to understand the performance of the material under service. There are two main ways of impact testing: pendulum and drop weight.

Drop Weight

BS EN ISO 14545-5 [15] explains a type of ball drop test for ceramic tiles. It consists of a testing apparatus with a 19±0.05 mm steel ball that is dropped vertically. There is guide tube that insures the ball falls on the centre of the test sample which is placed on a rigid support. The rebound height is measured, or alternately, the interval of time between two successive rebounds. Any damage visible from distance of 1 m must be noted. The coefficient of restitution is calculated using different formulas depending on the type of measurement selected.

A similar procedure is described by ASTM D5628-10 [16] to apply to flat, rigid plastic. In this case, a dart with fixed weight is thrown from different heights (or a dart with different heights thrown from the same height) with the objective to obtain 50% of failed samples (called as mean failure energy, mass x height).

Structural elements often need to be evaluated to dynamic loads caused by accidental events. Impact testing is one of the best solutions to test this structural performance. Concrete structural elements are commonly tested to impact resistance with the drop weight method. Rehacek et al. [17] tested fibre reinforced concrete prisms to drop weight impact. Zhu et al. [18] used this procedure for impact testing in U-shaped concrete specimens.

Hobbs et al. [19] described techniques to test flat masonry walls under vehicle impact. A laboratory test rig was designed and built. A vertical drop hammer lifted by a crane was dropped and hit a rotating quadrant transforming vertical energy in horizontal through a load cell that strikes the tested wall. The possibility to control this test in laboratory and repeatability showed that many common masonry walls are capable of the impact loads produced by cars travelling at up to 70 mph.

Kosteski et al. [20] tested a polymer-composite disk shape specimen to impact and analyze the results by the simulation of dynamic crack propagation with the finite element method. The discretization carried out assembled a basic cube module constructed using 20 bar elements and nine nodes and accounted for the theoretical material damage happening. This computational modelling analysis was complemented with experimental tests.

Pendulum

Flat glass for building is referred to be tested with the pendulum method (BS EN 12600) [21]. It is formed by a frame that holds the glass sample vertically. There is an impactor consisting of two pneumatic tyres fitted to the rims of the wheels with two steel weights of equal mass. The steel weights never strike the glass surface as the rubber protects them. The total weight is 50±0.1 kg. The impactor is supported by a cable and kept in suspension with this cable forming an angle of not less than 14° with the horizontal. When it is released, it swings and strikes the glass. The glass is classified in three impact levels according to the drop height.

Tests referred to curtain walls are described in BS EN14019 [22]. The wall surface is vertical and hit by an impactor as specified in BS EN 12600 [21]. When the impactor is released, it swings and strikes the test specimen. The classification establishes different performance levels according to the results of the drop height applied.

Impact tests applied to steel and other metallic materials are based on the Charpy method (ASTM E23) [23]. A V-notched specimen is broken by the impact of a heavy pendulum or hammer, falling at a predetermined velocity through a fixed distance. The specimen is placed on the anvil as a simply supported beam. A variant is the Izod test, where the specimen is placed vertically on the anvil with the notch facing the hammer. The test can measure the absorbed energy by the material.

Maca et al. [24] developed a procedure for testing concrete elements based on the pendulum principles. An impactor of 50 kg was dropped from a height of 4 m which swung and stroke on the specimen surface horizontally. This way, it was easier to avoid double impact moving the specimen a bit further on the impactor trajectory.

Other Types of Impact Testing

The rebound hammer method is used for rock hardness assessment (ASTM D5873) [25]. Also known as Schmidt hammer, it is a portable, cost-effective instrument designed to provide information about surface mass uniformity with enough degree of confidence. It comprises of a spring-loaded hardened steel form that is mechanically discharged against a plunger when the hammer is pressed against the material surface. Part of the stored elastic energy of the spring is absorbed through plastic deformation of the surface and mechanical waves propagating through the material, while the remaining elastic energy causes the actual rebound of the hammer [26]. It can be used for natural rock hardness, as well as for mass concrete.

C. Performance Analysis

A basic way to analyse impact is calculating the proportion of specimens broken in every testing set. It is applied, for example, by ASTM D5628-10 [16].

ASTM D7136 [27] establishes different types of major damage modes according to whether they are externally visible or internal.

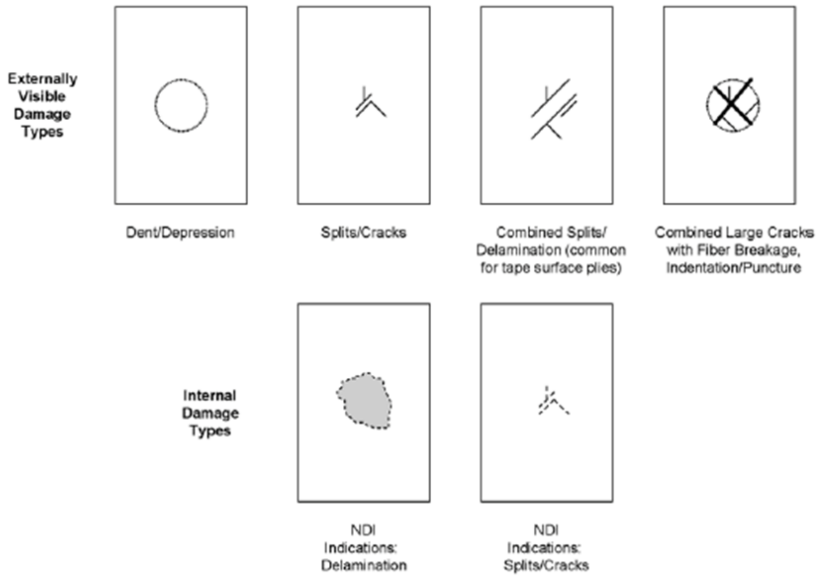

Fig. 1 Major damage modes; ASTM D7136

One common solution is the calculation of energy applied and absorbed. In this case, there is the need to obtain numerical data such as the drop height or time. Accuracy for time calculation is essential for liability in results. Some systems used are slow motion cameras or detectors.

The calculation of the coefficient of restitution is based on the calculation of the height of drop and height of rebound. The equation is:

$$e = \sqrt{h_2/h_1} \quad (1)$$

where e = coefficient of restitution, h_1=height of drop, h_2=height of rebound. It is applied, for example, to ceramic tiles and flooring by BS EN ISO 10545-5 [15].

More accurate techniques are now being implemented for the analysis of impact damage. Kosteski et al. [20] used a Fractovis Gravity Drop CEAST 6789 equipped with a CEAST DAS 4000 data acquisition system, which can provide information about how force and velocity change along time during the impact. Other techniques are, for example, the use of through-transmission ultrasonic C-Scan (TTU C-scan) to detect non-visible damage in the material structure [28].

III. Procedure Developed

It can be understood from the literature review that, even though the tests have different setups, the governing laws still are the same. In fact, for example, a weight dropped from a set height in free fall or pendulum configuration will have a potential energy (PE) at the start and kinetic energy (KE) after the event.

The work-energy principle establishes that the change in kinetic energy is the result of multiplying the average impact force times the distance travelled. Applying the law of conservation of energy, it can be stated that PE before an event must be equal to KE after the event [29].

$$PE = KE \quad (2)$$

For a simple drop test, the equation can be formulated as:

$$mgh = 1/2\, mv^2 \quad (3)$$

where m = mass; h = drop height; g = acceleration of gravity (9.81 ms^{-1}); and v = velocity at impact. Therefore, solving this equation, velocity is calculated from:

$$v = \sqrt{2gh} \quad (4)$$

Friction and drag losses however were minimized setting optical targets at a set distance just before the impact occurred in order to retrieve both velocities just before and straight after the event. Thus, specimens absorbed energy could be calculated:

$$1/2\, mv_1^2 - 1/2\, mv_2^2 = \int F\, dy \quad (5)$$
$$\int F\, dy = Absorbed\ Energy$$

The purpose of all these tests was to estimate the material toughness from a single impact event from both a macroscopic and microscopic perspectives, therefore it was important that the equipment delivered only a single impact to the piece.

Multiple impacts would have caused accumulative damage and defined the test as invalid. Fig. 2 shows the equipment's functionality described by a block diagram.

While the impact itself is induced in similar ways per different materials, for this specific fused recycled glass there were no standards defining what type of impact test (and impactor material) were to be conducted/adopted and ideal energies that the material needed to withstand related directly to damage extent. As an example, for carbon fibre reinforced polymers (CFRP) ASTM D7136 [27] defines the PE as a function of specimen thickness.

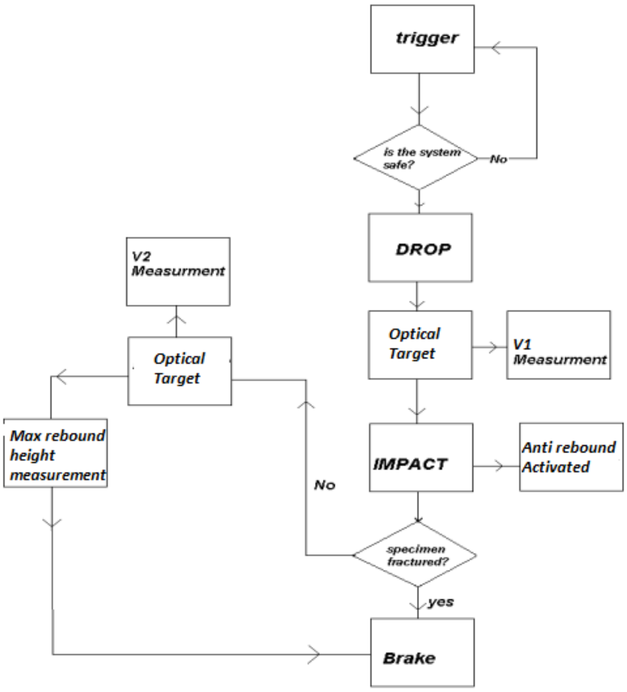

Fig. 2 Block diagram for impact test

For this particular study, the PE was calculated as "worst case scenario for glass specific application" such as:

Application= Reception desk engineering facility
Worst case drop impact=steel (tooling), 2 kg<m<3 kg

The drop height was first designed as a true-life impact event. Given an average height of a reception desk as 0.762 m, and the average height of a human as 1.78 m for males and 1.65 m for females, an estimated worst case scenario of a horizontal arm´s length height difference between the user and the desk top was recorded as 0.588 m. With these figures, it is assumed a maximum PE of 15 J for this purpose.

The drop height *(h)* to achieve a specific PE for a defined mass *m* can be calculated using this relation:

$$PE = mgh \quad (6)$$
$$h = PE/mg$$

The impactor dimensions and material for this study were kept the same as defined by ASTM D7136 [27] as a 900 HB was considered to be sufficient as similar values were used in the tests described by literature review. It has to be mentioned however that the designed piece of equipment is modular, therefore impactor shapes, dimensions and materials could be varied.

The mass of the impactor was manufactured to be adjustable (1.5 kg<*m*<10 kg) such as the drop height (max 1.5 m) to allow users to achieve different energy ranges accordingly. Attention then was paid to how the specimen was held in place. In fact, the supporting fixture needed to represent how the glass would perform in the event of an impact.

Horizontal glass surfaces edges are usually supported by silicone, neoprene or other rubber-based bushes as described by BS ISO 29584 [30]. A polychloroprene (neoprene) with a hardness of (70±5) IRHD was then defined suitable, with a thickness of 0.0015 m.

The tested specimens were square blocks 0.1 m x 0.1 m, cut using a high-powered water jet cutter. However, as mentioned previously, an energy/thickness ratio was nonexistent at this stage therefore two thicknesses, respectively 0.017 m and 0.025 m (±0.001), were chosen according to manufacturing process capability.

The edges of the specimen then needed to be supported, locking vertical movement in the 'z' and slip in both 'x' and 'y' axis ('z' is the axis that corresponds direction of impact, perpendicular to specimen).

Rotation was allowed both around 'x' and 'y' as a specimen subjected to energy absorption will go through bending. It has to be mentioned that this ideally would be a knife edge type support fixture, in this case, as neoprene had to be used, perimetrical 0.005 m wide strips were adopted.

To simplify the process, a square hole was cut in a neoprene sheet 0.01 smaller than the specimen dimension and placed on an alloy base that had a same dimension square undercut. The support fixture is shown in Fig. 3.

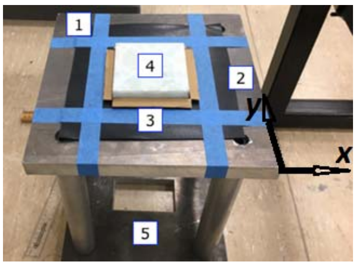

Fig. 3 Support fixture with specimen (from 1 to 5: tape holding neoprene sheet in position, neoprene sheet, malleable adhesive rubber, specimen and support alloy fixture)

IV. Procedure Application

Two different PE were established at 5 and 10 J. Therefore, with an established impactor mass of 2.57 kg, two different drop heights were calculated: 0.19 m and 0.39 m, respectively.

A total of 20 specimens were tested to these drop heights with different thickness (0.017 m and 0.025 m) divided in four sets of five specimens each. The visible damage is shown in Fig. 4 and Fig. **5**.

All 0.017m thickness specimens broke to a 10-J impact, whereas two of 0.025 m thickness (40%) did not. Regarding the 5-J impact event, all 0.017m thickness specimens broke, but none of 0.025 m thickness did.

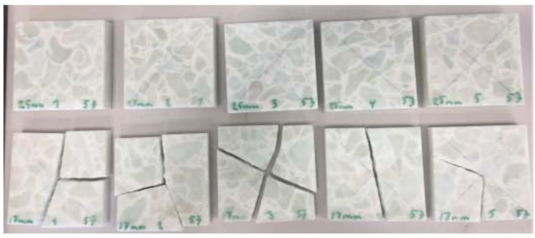

Fig. 4 Results of 5-J impact event (first row: 0.025mm thickness, second row: 0.017 mm thickness)

Fig. 5 Results of 10-J impact event. (first row: 0.017 mm thickness, second row: 0.025mm thickness)

V. DISCUSSION

The initial results obtained could show that this procedure can help study the performance of fused recycled glass to impact. The calculation of PE (in this case using two different drop heights) and application to two different specimen thicknesses (0.017 m and 0.025 m) gave differentiated performance of the material with these variables and allowed compare them easily according to visible damage calculating proportionality of failures (specimens broken).

It was noticed however that, when critical failure occurred, there was a main pattern followed by the main fractures. This showed that the material was performing with quasi-isotropic properties which can be considered as a positive factor considering the non-homogenous nature of the grain structure. This also defined that the procedure was consistent; therefore, it can be repeated and standardized. This procedure was developed as an initial approach to impact testing of fused recycled glass material. Further research needs to be developed to consider this procedure as validated. Reliability and repeatability are the factors to consider for correlation analysis. Additionally, other improvements need to be developed so that the material energy absorption and internal performance can be studied. More data are being collected at present to understand the energy absorption capabilities of this material; however, more in depth inspection techniques will need to be utilised to define also damage occurring at a microscopic level.

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