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Artificial ageing of glass with sand abrasion

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HIGHLIGHTS

- Naturally aged glass was found to be significantly weaker than as-received glass.
- Falling abrasive was investigated as an artificial ageing method for glass.
- The naturally aged glass was used as a reference for the falling abrasive method.
- Existing falling abrasive standards proved unsafe due to overestimation of design strength.
- Alternative ageing parameters offer good correlation to naturally aged glass strength.

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ABSTRACT

The strength of glass is governed by the condition of its surface which deteriorates progressively as surface flaws accumulate on exposure to weathering action during its service life. Therefore, knowledge of the strength of naturally aged glass is crucial in order to ensure its safe use in load-bearing applications. Artificial ageing tests can be very useful in this regard, but they have traditionally focused on degradation in light transmittance properties rather than the strength of glass. Experimental testing has been undertaken in this study to investigate the effectiveness of a falling abrasive method for the artificial ageing of glass. Abrasive medium is allowed to fall freely on monolithic glass and induce a random surface flaw population. 390 annealed glass specimens grouped in 26 series were artificially aged using different combinations of ageing parameters. The specimens were subsequently subjected to destructive and non-destructive testing to determine the influence of each ageing parameter and to establish a combination that produces strength characteristics similar to those of naturally aged glass. Existing artificial ageing recommendations were found to significantly overestimate design strengths by up to 253% at low probabilities of failure, $P_f = 0.008$ and are therefore, deemed unsafe. However, it was found that the falling abrasive method using a different combination of ageing parameters provides good correlation to the strength of naturally aged glass.

1. Introduction

The strength of glass is highly dependent on the condition of its surface. The intrinsic strength of glass is very high and can reach 32 GPa based on the intermolecular bonds that are developed in the glass molecular network [1]. Stress-raising flaws (known as Griffith flaws) accumulate on the glass surface as a result of manufacturing, transportation and surface damage during its service life. This leads to a significant reduction in tensile strength to a value commonly referred to as the extrinsic strength (Eq. (1)).

$$\sigma_f = \frac{K_{IC}}{Y \cdot \sqrt{\pi \cdot a}} \quad (1)$$

where Y: geometry factor (depending on the shape of the crack), α: crack depth and K_{IC}: fracture toughness.

For example, for a typical half penny shaped crack with $a = 50$ μm on the surface of the glass and $K_{IC} = 0.75$ MPa m$^{0.5}$ and $Y = 0.713$, the extrinsic strength of glass is reduced to $\sigma_f = 76.7$ MPa (Eq. (1)). Therefore, a 99.8% reduction is noticed between intrinsic and extrinsic strength.

Damage that accumulates during the service life of glass is a result of natural ageing caused by contact, abrasion or impact and typically depends on the level of exposure. Previous research found a reduction of 35–85% in extrinsic strength with respect to the extrinsic strength of as-received annealed glass [2–5]. Therefore, knowledge of the long term mechanical performance of glass is essential when designing with glass. However, only a few studies are available on the strength of weathered annealed glass [2–7] and even fewer on the strength of weathered toughened glass

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[8]. Frequently, research on the durability of glass components focuses on the response of the interlayer in laminated glass and its viscoelastic response to load duration and environmental conditions in order to investigate the monolithic/layered response of the laminated glass component [9–12]. However, the mechanical durability of the glass itself can be divided into erosive resistance and scratch resistance.

The erosion of glass occurs when glass is exposed to flying projectiles that repeatedly impact its surface (e.g. a glass panel in a façade) and lead to material removal. The risk increases in cases of extreme wind and locations where windstorms are common. The most common types of flying projectiles in urban areas are roof gravel, roof tiles and timber [13]. Sand abrasion is used for the evaluation of the erosive resistance of glass. This can either be achieved by: (a) a sand trickling set-up ([5,14–18]) where sand is allowed to fall freely from a controlled height onto the surface of the glass or; (b) sandblasting ([19–22]) i.e. propelling of sand by compressed air towards the surface of the glass. The erosive resistance of the glass is a function of the particle size, impact velocity, duration of abrasion and mass of abrasive medium [22]. Damage increases with higher quantities of abrasive, impact angles and speed of impact. However, the erosive resistance in these studies is mainly evaluated by means of non-destructive tests (roughness characterisation, optical transmission and mass loss), thereby disregarding glass strength. Basic strength data are shown in [15], [16], however, a comprehensive statistical analysis of glass strength is only available in [5] reporting a 59% reduction in as-received characteristic strength ($P_f = 0.05$) after sand-abrasion with 6 kg of sand dropped from a height of 1 m. However, further experimental testing and a subsequent detailed statistical analysis on glass strength due to erosive ageing mechanisms is needed to determine the influence of the artificial ageing parameters during the sand abrasion and their correlation to naturally induced damage.

Glass elements are also vulnerable to scratches when objects of higher hardness are forced into the glass and dragged along its surface. Scratches can be induced due to mishandling of the glass during transportation/installation processes, cleaning and in-service conditions. Scratch resistance is typically evaluated with indenters and commercially available scratching devices that can accommodate geometrically different indenter tips [23–25]. Depending on the level of damage and their configuration, scratches can be described with one of the following regimes [26]: (a) *micro-ductile*: permanent deformation and potential lateral cracks (Fig. 1) are induced in the glass.; (b) *micro-cracking*: radial/median cracks (Fig. 1) are formed while lateral cracks extend and intersect with the surface; (c) *micro-abrasive*: radial and median cracks are also formed in this regime while the intersection of the lateral cracks with the surface is continuous along the length of the scratch and accompanied by material removal, known as chips (debris, Fig. 1).

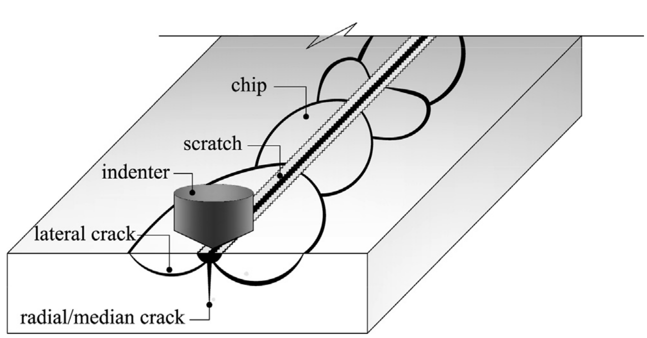

Fig. 1. Morphology and types of cracks.

The scratch resistance of glass and the associated regimes depend on the geometry of the indenter, the chemical composition of the glass, the environmental conditions and the curing time of the scratch, and the scratching speed ([23–27]). Scratches in the micro-ductile regime are more likely to form in glasses with higher silica content. Sharp indenters (e.g. 60°) also result in scratches in the micro-ductile regime while realistic scratches approximating those induced during cleaning (micro-cracking regime) are induced with 90° or 120° conical indenters. Strength recovery after scratching, known as crack healing, was found to occur particularly during the first 24 h of curing time after inducing flaws on the glass surface. The crack healing led to an increase in mean strength of 32% and 42% for curing at ambient conditions (RH = 50%) and curing under water, respectively [27].

Despite the existing research on erosive and scratch mechanisms of glass, a comprehensive and reliable method for the artificial ageing of glass has yet to be established. The selection of a suitable artificial ageing method should depend on the level of exposure/type of application where the glass is to be installed and correspondingly on the expected type of critical flaw (i.e. caused by scratching or erosion). In fact, it was shown that different ageing methods were preferred for two different sources of naturally aged glass, exposed mainly to linear scratching and erosive action, respectively [18,27]. In particular, the induction of scratches is preferred in [27] over other abrasion methods; scratches were found to be a better optical match, based on dye penetrant inspection used to reveal flaws in the naturally aged glass of that study and additionally, artificial ageing with sand abrasion was difficult to reproduce [27]. Whereas glass artificially aged by sand trickling was found to be more representative of the surface roughness and strength of a different source of naturally aged glass exposed to erosive action, than scratched glass [18].

DIN 52348 [28] (similar to ASTM D968-05 for organic coatings [29]) is the only available standard for glass ageing investigations. This standard proposes a sand trickling test for the artificial ageing of glass and the evaluation of its durability. However, DIN 52348 and similarly ASTM D968-05 have some important limitations, namely: (a) there is no published research on the basis of the sand trickling parameters proposed in the standard; (b) there is no published research on the correlation between damage induced artificially and the damage generated by natural phenomena; and; (c) the durability of glass is evaluated in terms of light transmission and the magnitude and scatter of the resulting strength data is disregarded.

This study focuses on applications where erosive ageing on annealed glass is more likely to occur than scratching. In particular, it investigates whether the falling abrasive (also known as sand trickling or dropped grit) method can be used to replicate the strength characteristics of naturally aged glass. The main objective is to identify an optimal combination of artificial ageing parameters that if applied on annealed glass would induce similar levels of damage to those of naturally aged glass. This combination of artificial ageing parameters would therefore, provide a quick and reliable means of assessing the long term performance of novel glass compositions and treatments. Details on the specimens, the falling abrasive method and the non-destructive and destructive evaluation tests (optical microscopy and coaxial double ring tests) used in this study are provided in Section 2. The salient results for the naturally and artificially aged glass are presented in Section 3 including the influence of each artificial ageing parameter on the strength of glass and its correlation to the strength of naturally aged glass. Finally, salient conclusions are found in Section 4.