The Effect of Short-Term Exposure to Natural Outdoor Environment on the Strength of Tempered Glass Panel

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Abstract Glass that used for architectural and structural purpose will undergo long term exposure to the natural outdoor environment. Exposure to outdoor weather such as temperature, humidity, UV-radiation, pH, etc. may cause deterioration of glass strength. This paper aims to study the effect of short-term exposures to natural outdoor environment on the strength of glass panel. Four sets of tempered glass samples were prepared for direct exposure to the outdoor environment. The samples were exposed to the outdoor environment for 40-, 80- and 120-days. A total of two tests namely microscopic observation on glass surface and four-point bending test on glass panel were conducted. Based on microscopic observation, the intensity of surface defects such as surface scratches, bubbles, and dust were increased for longer period of outdoor exposure. The bending and residual strengths of the glass panel reduced as the duration of the outdoor exposure was increased. The tempered glass material tends to undergo deterioration in strength by weathering process.

Keywords Tempered glass · Four-point bending test · Natural outdoor exposure · Bending strength · Residual stress · Surface defects

1 Introduction

Glass is a non-crystalline solid that is often transparent and widely used as practical, technological and decorative purpose. Due to its superior aesthetic qualities and strength properties, glass is widely used in architectural and structural element [7]. However, glass that used for architectural and structural purpose will undergo long

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term outdoor exposure such as temperature, humidity, UV-radiation, pH, etc. which will cause deterioration of strength on the glass [8, 12]. It is found that the glass will suffer a loss in strength after natural weathering or artificial aging [5]. Although, Afolabi et al. [1] concluded that weathered fully tempered glass had a greater mean strength than ASTM 2012b predictions. However, the initial data of the glass strength 20 years ago was not reported. Temperature is one of the factor that influence the strength of the glass. Like other material, glass also will undergo expansion when heated and compression when cooled. The tensile stress produced during the thermal expansion and contraction due to the surrounding temperature might contribute to the strength loss of the glass material [14]. Besides, when the surface of glass is in moisture condition, the hydrated, leached layer will tend to absorb water. When the surrounding humidity is low, these layer will undergo dewatering and associated with volume shrinkage. Since this layer is bonded to un-leached bulk substrate which does not shrink. The stresses between this two layers will leave craters in the glass surface and decrease the strength of the glass [11]. Under the exposure to the environment, its optical properties, structure, and chemistry will be modified by the different weathering process [4, 9]. The glass surface may be damaged through mechanical exposure in the production, direct exposure to the environment and in practical use such as due to cleaning process or man-made damage. The scratch resistance to visible scratches of tempered glass is found to be lower compared to annealed glass [10]. The mechanical strength is determined by the micro-flaws on the glass surface. These flaw will act as stress concentrators and the glass critical breaking stress will be depends on the size and depth of these flaw [13]. Macrelli [6] stated that glass strength is strongly influenced by the state of its surface due to the presence of flaws in the form of micro-fissures. In order to determine the relationship between the weathering processes to the strength of tempered glass, four-point bending test of tempered glass panel and compression test of tempered glass fragments have been carried out in this study.

2 Experimental Procedure

Twelve samples of tempered glass panel were used to carry out the test. The size of each sample is 1100 mm $\times$ 360 mm $\times$ 5 mm of thickness. The samples were divided into four sets. Three samples were set as control samples and nine samples were exposed to the direct outdoor exposure as shown in Fig. 1 for 40-, 80- and 120-days. The glass was mounted on the wooden rack at 45° angle, and the surface of glass panel is facing the south (Qlab, Outdoor Weathering: Basic Exposure Procedures, 2011). It is believed that facing the specimen toward the equator direction and with a 45° of exposure angle could able to receive the maximum intensity of sunlight. At the designated period of exposure, the samples were collected for laboratory testing. Microscope was used to observe the surface defect of the glass panel. The approximate amount of surface defect was determined.

Fig. 1 Setup of glass samples for direct exposure

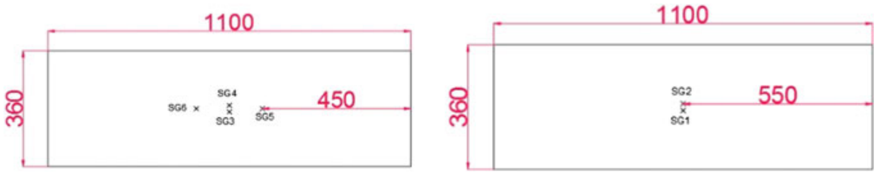

Fig. 2 Location of strain gauges on the bottom (left) and top (right) surface of the glass sample

Six strain gauges were installed on the glass panel at the specific location as shown in Fig. 2. Four strain gauges were stuck on the bottom surface of the glass panel and another two on the top surface. Then, four-point bending test was carry out in accordance with BS EN 1288-3:2000 [3] to determine the bending strength of the glass sample. Figure 3 shows a schematic representation of the four-point bending test. The adopted load application rate was 1 kN/min. The bending stress imposed by the self-weight of glass specimens is calculated based on Eq. (1):

$$\sigma_{bG} = \frac{3\rho g L s^2}{4h} \tag{1}$$

Whereas, the bending strength of the glass specimens are calculated based on Eq. (2).

$$\sigma_{bB} = k\left[F_{max}\frac{3(L_s - L_b)}{2Bh^2} + \sigma_{bG}\right] \tag{2}$$

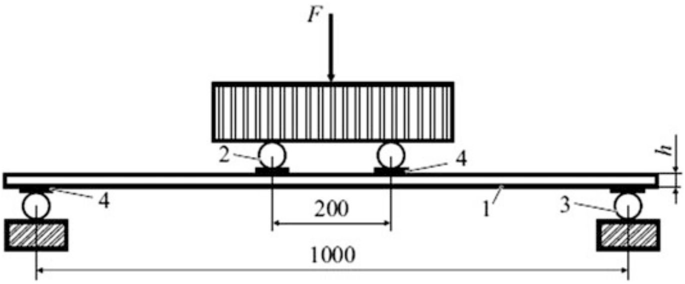

Fig. 3 A schematic sketch of four-point bending tests: 1—glass specimen, 2—bending roller, 3—supporting roller, and 4—rubber strips. Dimensions are given in mm (BS EN 1288-3:2000 [3])

where F_{max} is maximum applied load, L_s is distance between the center lines of the supporting rollers, L_b is distance between the center lines of the bending rollers, B is specimen width, h, is specimen thickness, ρ is density of the specimen and g is acceleration due to gravity.

Residual stress is defined as stress fields that exist in the absence of any external loads. Sometimes, residual stresses are labeled as internal stresses. It can be calculated based on Eq. (3) defines residual strength of glass specimens.

$$\sigma_{res} = \varepsilon E \tag{3}$$

where E is Young's modulus of tempered glass and ε is strain values at the maximum applied load. The Young's Modulus was determined based on Eq. (4).

$$\frac{y}{h} = \frac{3F_{max}}{4EBh^4}\left[\frac{L_s^3}{3} + \frac{L_b^3}{6} + \frac{L_s^3 L_b^2}{2}\right] \tag{4}$$

where F_{max} is maximum applied load, L_s is distance between the center lines of the supporting rollers, L_b is distance between the center lines of the bending rollers, B is specimen width, h is specimen thickness.

3 Results and Discussion

Two tests namely, microscopic observation and four-point bending test were performed to study the effect of direct outdoor exposures on the strength of tempered glass panel. The later test has produced the results for bending strength and residual stress of glass panel at maximum applied load.

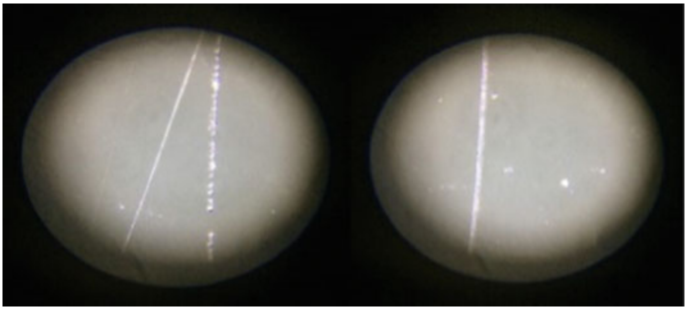

Fig. 4 Image of surface defect captured using phone microscope

3.1 Microscopic Observation

Figure 4 shows the image of surface defect captured using phone microscope. Based on Ye et al. [15], the surface defect is classified as surface scratches, bubbles, and dust. The surrounding of the inclusions particles such as bubble may develop stress that lead to cracking and even breakage during the cooling of the glass. The presence of dust on the glass surface might cause microscopic craters or scratches on the glass if undergo wind bombardment. These microscopic craters or scratches may retain moisture, cause corrosion and impair the strength of the glass material [8]. Based on Fig. 5, the amount of surface defect on the tempered glass increased as the duration of exposure to the environment was increased. It shows that the environmental parameter such as temperature, humidity, and UV radiation have significant impact to the surface characteristic of the glass specimens. Table 1 shows several weather parameters data of Nibong Tebal which is the location that the tempered glass specimens are exposed. The data shows that the climate is hot, humid and rainy during the exposure duration. The climate which has hot

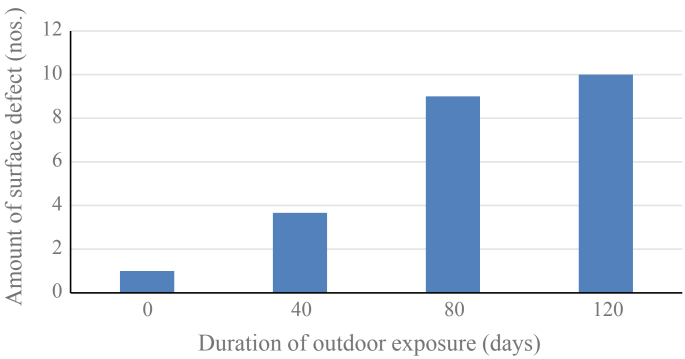

Fig. 5 Average number of surface defect on the glass specimens

Table 1 Summary of environment climate data in 120 days

Environment parameter	Average value
Maximum temperature	32.6 °C
Humidity	76.1%
UV index	10.42

temperature, high humidity and high UV index had cause negative impact towards the surface characteristic of the glass specimens. The longer the exposure to the environment, the larger the amount of surface defect on the glass specimen which will impair the strength of the glass panel.

Based on the results from the surface defect microscopic observation, the number of surface defect increased as the duration of exposure to the environment was increased. Glass is a material which sensitive toward its surface characteristic, the larger the amount of surface defect, the larger the strength degradation [10].

3.2 Bending Strength

Twelve tempered glass specimens with different exposure duration were tested using four-point bending test to determine the bending strength. Figure 6 shows the bending strength of tempered glass panels at different duration of exposure. The average bending strength of the tempered glass samples for outdoor exposure duration 0, 40, 80 and 120 days are 206, 198, 195 and 193 N/mm^2, respectively.

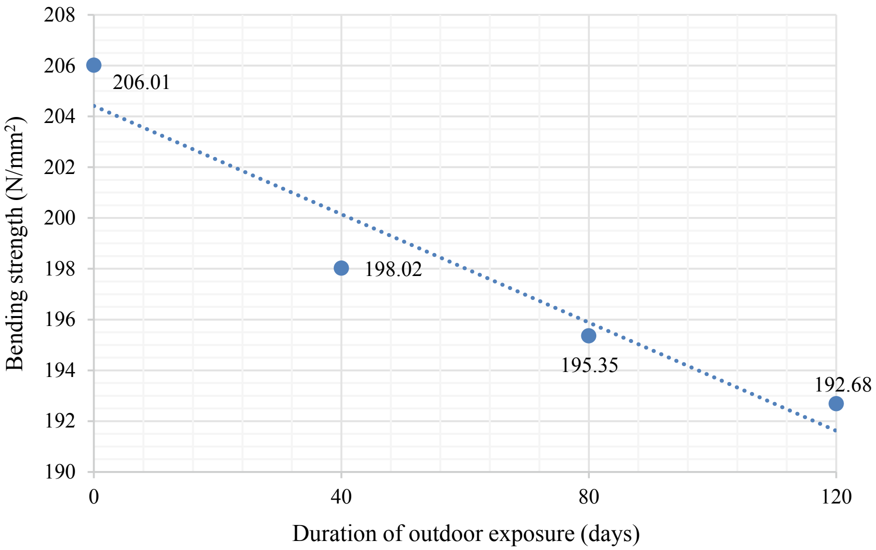

Fig. 6 Average bending strength of glass samples for a duration of outdoor exposure

It shows that the bending strength of the glass panels decreased as the duration of outdoor exposure to the environment was increased.

3.3 Residual Strength

Figure 7 shows the residual strength of tempered glass specimen at different duration of exposure. The residual strength of the tempered glass panel for exposure duration of 0, 40, 80 and 120 days are 88.38, 87.08, 85.96, and 83.75 N/mm^2, respectively. The residual strength of the tempered glass panels decreased as the duration of exposure was increased. Although the difference in the residual strength between the control specimen (0-day exposure outdoor) and test specimen (40-, 80- and 120-days exposure outdoor) are small (1.47, 2.73 and 5.23%), but it shows a trend where the sample undergo deterioration in material strength after weathering process even in a short period of time. This is in line with the finding of Datsiou and Overend [5].

The bending strength and residual strength of the glass samples decreased as the duration of exposure to the environment was increased. The deterioration of glass material may due to the accumulation of moisture on the glass surface from the air humidity or precipitation. Based on the research of Baker and Preston [2], it shows that strength of glass in wet condition is 20% weaker compared to dry condition. Besides, there will be accumulation of dirt and dust from the air on the glass surface when it is exposed outdoor. Wind bombardment of dirt and dust will create

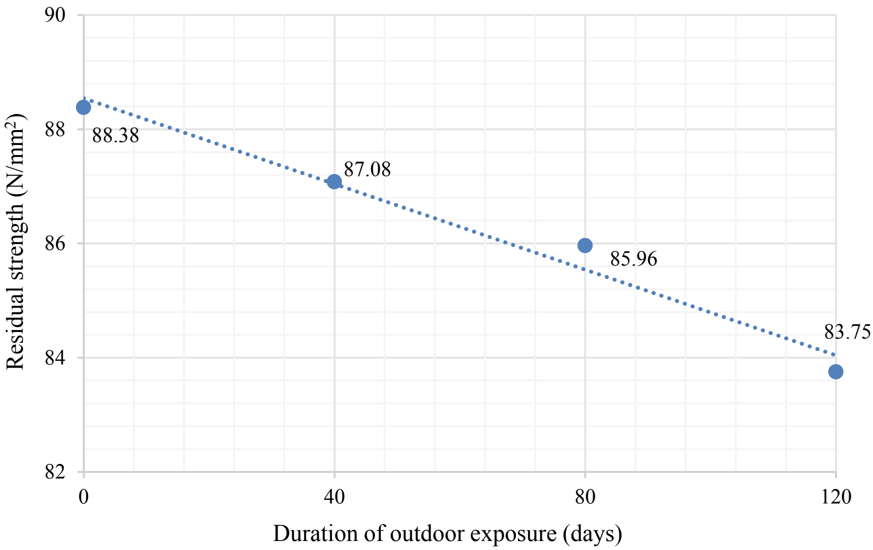

Fig. 7 Average residual strength of glass samples for a duration of outdoor exposures

microscopic craters, which retain moisture, causing corrosion and further weakening the strength of the glass material [8]. Furthermore, the glass panels may undergo expansion when expose to hot outdoor temperature and contraction during cold weather or raining [14]. The expansion-contraction phenomena of glass could cause microscopic craters on the glass surface and further impair the strength of glass material. From this research, it shows that the environmental parameter such as temperature, humidity, and UV radiation could cause negative impact to the strength of tempered glass panel through weathering process.

4 Conclusion

This research studies the influence of direct outdoor exposure on the strength of tempered glass panel. The results from each test are compared and linked to explain the outcome. From the results and discussion, the following conclusion can be drawn from this research:

i. The amount of surface defect obtained from microscopic observation increase gradually as the duration of outdoor exposure to the environment increase. It shows that the environmental parameter such as temperature, humidity, rainfall, and UV radiation are able to cause negative impact to the surface characteristic of the glass panel and further impair the strength of glass panel.
ii. From the four-point bending test, the bending strength of tempered glass panels decreased as the duration of the exposure was increased. The percentage of decrement in the strength between the test specimens (40-, 80- and 120-days of outdoor exposure) and control specimens (no outdoor exposure) are 3.88, 5.17, and 6.47%, respectively. The results obtained from the test shows that the tempered glass panels suffer a loss in material performance as it was exposed to the environment.
iii. The residual strength of tempered glass panels decreased when the duration of exposure was increased. The residual strength value obtained for the tempered glass panel with 0-, 40-, 80- and 120-days of outdoor exposure to the environment are 88.38, 87.08, 85.96, and 83.75 N/mm^2, respectively.
iv. Based on the results obtained, the weathering process could decrease the strength of tempered glass panel.

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References

1. Afolabi B, Norville HS, Morse SM (2016) Experimental study of weathered tempered glass plates from the Northeastern United States. J Arch Eng 22(3):04016010
2. Baker TC, Preston FW (1946) The effect of water on the strength of glass. J Appl Phys 17 (3):179–188
3. BS EN 1288-3 (2000) Glass in building—determination of the bending strength of glass. Part 3: test with the specimen supported at two points
4. Carmona N, Kowal A, Rincon JM, Villegas MA (2010) AFM assessment of the surface nano/microstructure on chemically damaged historical and model glasses. Mater Chem Phys 119 (1–2):254–260
5. Datsiou KC, Overend M (2017) The strength of aged glass. Glass Struct Eng 2(2):105–120
6. Macrelli G (2017) Chemical strengthening of glass by ion-exchange
7. Maloney FJ (1968) Glass in the modern world, a study in materials development
8. Min'ko NI, Nartsev VM (2013) Factors affecting the strength of the glass. Middle East J Sci Res 18(11):1616–1624
9. Papadopoulos N, Drosou CA (2012) Influence of weather conditions on glass. J Univ Chem Technol Metall 47(4)
10. Schneider J, Schula S, Weinhold WP (2012) Characterisation of the scratch resistance of annealed and tempered architectural glass. Thin Solid Films 520(12):4190–4198
11. Shelby JE (2007) Introduction to glass science and technology. Royal Society of Chemistry
12. Shokrieh MM, Bayat A (2007) Effects of ultraviolet radiation on mechanical properties of glass/polyester composites. J Compos Mater 41(20):2443–2455
13. Weissmann R (1997) Fundamental properties of float glass surfaces. In: Glass processing days, 13–15 Sept 1997
14. White RL (2007) Glass as a structural material
15. Ye R, Chang M, Pan CS, Chiang CA, Gabayno JL (2018) High-resolution optical inspection system for fast detection and classification of surface defects. Int J Optomechatronics 12(1):1–10