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EFFECT OF SAND BLASTING ON SODA LIME GLASS PROPERTIES

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ABSTRACT

The present work is based on a simulation in laboratory of the erosion of a soda lime glass caused by sand blasting during sandstorms. It deals with the effects of sand blasting duration (from 0 to 60 min) and impact angle (from 0 to 90°) on the material and its properties. The principal erosion characteristics and properties of the material studied are the mass loss, the erosion rate, the surface roughness, the optical transmission and the mechanical strength. The influence of the optical transmission degradation on the relative efficiency of solar panels protected by eroded glass was also examined. The sand used has mostly a rounded shape and presents a grain size distribution between 300 and 500 µm and hardness greater than that of the glass tested. The evolution of the roughness and the optical transmission with variable duration present an important variation at the beginning and tends towards a constant level after about 20 minutes. The mass loss is function of the sand blasting duration and the impact angle. It is maximal for an impact angle of 90°. Fracture strength (up to 300 min) indicates that there is an important drop in strength values (about 13%) after 30 minutes with a significant dispersion. The strength values tend then to level out with a reduced dispersion after 60 minutes. Weibull distribution function was used to characterize statistically the variation of the mechanical strength by comparing samples in the as received state and eroded by sand blasting during 30 and 60 minutes. The as received glass Weibull plot shows a large dispersion expressed by a low Weibull modulus (m = 5.41) and a relatively higher average strength value (σ_{moy} = 76 MPa). A lesser dispersion and a lower average strength value were obtained for the glass eroded during 30 minutes (m = 8.2 and σ_{moy} = 66 MPa). The average strength remains almost constant while the dispersion becomes much reduced for the glass sand blasted during 60 minutes (m = 10.4 and σ_{moy} = 64 MPa). The variation of the relative efficiency of glass protected solar panels versus sand blasting duration (seen up to 300 min) shows a slow regular decrease until 0.91 for a 90° impact angle and until 0.95 for 30°. Finally, the microscopic observations of the damaged surfaces showed traces of lateral cracking formation, cracks interaction from different impacts and also craters after material removal.

Key words: Soda lime glass, erosion, sand blasting, physical properties

I. INTRODUCTION

Silicate glasses are characterized by a high hardness and a high shear resistance related to the strong atomic bonding of the silica network and by low fracture toughness. The absence of plasticity makes the glass susceptible to brittle fracture. Indeed, the lack of plastic molecular rearrangement brings about high stress concentration at the glass surface flaws during normal loading. Its mechanical strength is mainly governed by its surface state [1]. As it is directly related to the surface flaws distribution, a statistical analysis is necessary for characterizing the glass strength dispersion. Flawless glass such as untouched glass fibers can have a very high tensile strength approaching the theoretical value while current glass sheets or glazing contaminated with contact and elaboration flaws have very low and dispersed strength values reaching sometimes 1/1000 the theoretical value.

Besides, the environment can also influence the glass mechanical strength. A humid environment enhances the phenomena of stress corrosion that causes sub critical crack growth, phenomena known as "static fatigue". Glass can therefore break inadvertently in the long term even with stresses lower than those generally accepted in the short term.

In Saharan regions, glass articles are frequently exposed to sand blasting damage. The glass surfaces are deteriorated by the impact of fine sand particles of different shapes carried by the wind. The material removal caused by these repetitive impacts can be detrimental to the glass mechanical strength and its optical properties [2]. It has reported by Bousbaa et al. [3] that in Algerian Sahara the vehicles windshields damaging by sandstorms is a common phenomenon that can cause serious problems. When the windshield glass is exposed to severe impact particles for few hours, the surface becomes blurred. The transmission loss and stray light caused by this type of erosion makes difficult and sometimes dangerous the driving of these vehicles. Similarly, it was reported that in a real situation, an aircraft is most likely to encounter dusts and sand during take-off and landing [4]. The erosion by solid particles affects optical transmission and causes strength degradation of glass frequently used for windows covering infrared systems in flying and in the aerospace industry.

In general, the kind and extension of solid-particle erosion of brittle materials are affected by the properties of the target material (hardness H_T, fracture toughness K_{CT}), the properties of the erosive particles (hardness H_P, fracture toughness K_{CP}, shape, size and specific gravity) and by external conditions (impact velocity, incidence angle and temperature)

The different investigations, made by different authors [5, 6, 7, 8] on the erosion of brittle materials for explaining or modeling the phenomena observed, reveal its complexity related to the numerous parameters intervening simultaneously.

Slikkerveer et al. [9, 10] showed theoretically and experimentally, that the influence of impacting particles can be described with one parameter only its kinetic energy. The authors indicated that the kinetic energy dissipated during the erosion process is of particular importance for quantifying the erosion of brittle materials. They showed for the case of glass erosion, that an energy of 100 Joules is necessary for tearing off a quantity of matter with a measuring range of 1 cm^2 of surface area and 1 mm depth. This energy corresponds in reality to the energy induced by the exposure of a glass to 20 grams of eroding particles projected at a speed of 100 m/s.

The glass erosion mechanism is mainly a brittle type of erosion characterized by the formation of lateral cracks that develop into chipping nearly parallel to the surface. The lateral cracks are considered responsible for material removal while the co-existent radial cracks, which are oriented normal to the surface, a source of strength degradation [6, 11]. However, it was also shown that glass tends to be eroded by plastic deformation similarly to ductile materials under particular conditions when eroded by very fine particles at low velocities [5].

The objective from this work is to present some of the results of the influence of sand blasting duration and the incident angle on soda lime glass obtained by simulating in laboratory the effect of sand blasting generally occurring in Saharian regions.

II. EXPERIMENTAL PROCEDURE

1. Sand Characteristics

The eroding particles used in this study were sand that comes from the beginning desert of Algeria (region of Biskra). The particles appear mostly rounded in shape although sometimes angular forms appear as it is shown in Figure 1. It was noticed that the sand is composed from colored particles with variable sizes. The grain colored aspect suggests they have a diversified mineralogical composition. The particle size distribution was determined by sieve analysis. The distribution shows that most sizes lay in the interval (300 - 500) µm. The average particles diameter was about 400 µm.

In order to measure the hardness and the fracture toughness of the sand particles, particles were glued into a thermosetting resin pellet. Before making the indentations for these measurements, we proceeded to successive micro-grinding operations made with different fractions of alumina oxide. A polishing final operation with iron oxide particles of 1 µm mean size was used to obtain a good flatness of the pellet surface with a well-prepared particle surface. The sand particles Vickers hardness was determined using a load of 0.5 N and a dwell time of 15 seconds. The obtained values present a certain dispersion Hv = 7.32 ± 2.94 GPa [12]. These values are higher than the glass hardness values despite their diversified mineralogical composition. Because of the impossibility to measure directly the sand particles Young's modulus, we could not have an estimation of the fracture toughness.

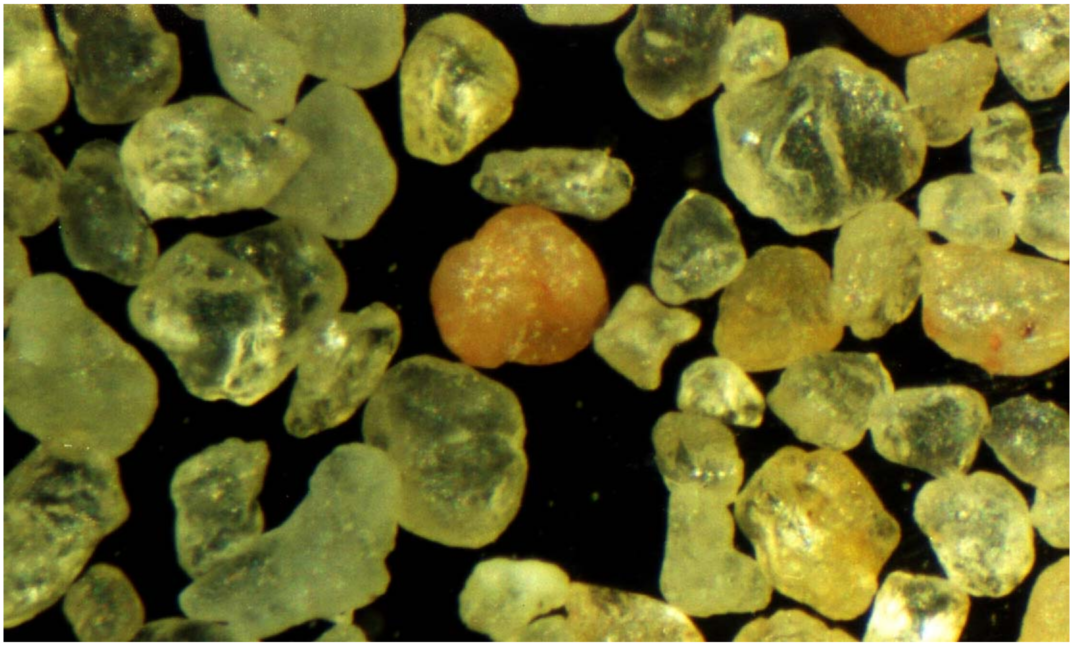

Fig. (1) sand sample showing the particles shape and the average grain size

Table 1 shows some values given by some authors [13-17] of Vickers micro-hardness Hv and toughness K_{IC} of sand used as erodent.

Table 1: Some values of hardness and fracture toughness of silica sand.

Particle material	Composition (wt%)	H_v (GPa)	K_{1c} (MPa.m$^{1/2}$)	Reference
Silica (Quartz)	99 SiO_2	13.1	1.4	Shipway[13]
Ouargla sand	> 74 SiO_2	14.49	2C=20.9	Bousbaa [2]
Silica sand	__	35.3	__	Yabuki [14]
Silica sand	__	11.0	1.2	Feng [15]
Natural Quartz	high purity	≈ 6	≈ 0.7	Gulden [16]
Silica Sand	__	13	1.3	Wheeler [17]
Biskra sand	__	7.32	__	Bousbaa [12]

The eroding particles commonly used in eroding tests are either made of alumina (Hv = 18 GPa, K_{IC} = 3 - 3.5 MPa.m$^{1/2}$) or of silicon carbon (Hv = 25 – 30 GPa, K_{IC} = 7 – 11 MPa.m$^{1/2}$). Diamond particles with a much higher hardness and a relatively high fracture toughness (Hv = 80 – 100 GPa and K_{IC} = 7 – 11 MPa.m$^{1/2}$) are also used in specific tests [15].

2. Glass characteristics

The target material used is a soda-lime silica glass available in Algeria market. The glass sheets were delivered in their as-received state with a thickness of 3 mm. The chemical composition is mainly made of 72.3 % SiO_2, 6.7 % CaO and 14.7 % Na_2O. Some physical characteristics are given in table 2.

Table 2: Some of the physical glass properties.

Properties	Values
Thermal dilatation coefficient α	$8.5\ 10^{-6}\ K^{-1}$
Young modulus E	72 Gpa
Poisson's coefficient ν	0.22
K_{1c}	0.74 MPa $m^{1/2}$
Transition temperature Tg	535 °C

Glass samples with dimensions ($50x20x3\ mm^3$) were prepared. Some of these samples were submitted to a chemical treatment in order to compare them to the as received state. The chemical toughening treatment was made by ion exchange during 5 hours at 460°C. The salt bath used contains a salt of KNO_3. The Vickers micro-hardness obtained is about 6.47 GPa. The micro-hardness and the fracture toughness of the glass used were measured by Vickers indentation using a load of 1 N and a dwell time of 20 seconds. The dimensional measurements of the imprint diagonals and of the radial micro-cracks were made on an optical microscope (Neophot 21). The hardness is measured using a Vickers micro-indenter connected to the microscope. We have used the following formulas [18]:

$$Hv = 1.854\ P/(2a)^2 \quad (1)$$
$$K_{CT} = 0.016(P/c^{3/2})(E/H_T)^{1/2} \quad (2)$$

3. Erosion tests

Different erosion test rigs were proposed in the literature [19, 20,…]. These depend on the impact velocities used. As recommended by the standards for airborne particles erosion testing (DIN 50 332 and ASTM G76-89), we opted for a horizontal jet impingement system (Figure 2). It is composed of an ejector in form of an elongated cylindrical with a conical convergent end allowing regular particles suction. The air speed used for projecting the sand particles out of the convergent was fixed to 20 m/s. The details can be found in reference [12]. The samples can be oriented at different incident angles.

The erosion tests were carried out in the following conditions:

- constant parameters:
* sand size particles (washed and dried) ≈ 100 to 800 µm
* air blower velocity: 20 m/s,
* sand feed: 1.66 g/s
* distance between the pipe convergent nozzle and the samples: 25 cm

- variable parameters
* duration t = 10, 20, 30, 40, 60 min and t up to 300 min for strength tests and photovoltaic efficiency measurements
* impact angles: 30, 45, 60, 90°

4. Measurements

- Roughness, optical transmission and strength measurements: The roughness measurements were made on a profilograph. The mechanical bending strength was measured on a tensile testing machine. The optical transmission was measured using a densitometer (MD 100) using a 550 nm wavelength.

- Solar panels efficiency measurement: For the glass protected solar panels efficiency determination, a solar generator type made of 18 polycrystalline silicon cells was used. The technical characteristics of the panel are as follows: P_{MAX} = 4.8 W, $I_{P(MAX)}$ = 0.6 A, $U_{P(MAX)}$ = 8 V and T_{MAX} = 70°C. The efficiency is determined from the exposure of one single cell having the dimensions (50x20 mm^2).

There are numerous parameters to take into account when evaluating the solar panel efficiency. During the experimental tests, the protecting glass samples were first exposed to sand blasting on one side for different durations and different impact angles. We have continuously measured the evolution of optical transmission and roughness of the sand blasted surfaces. We then placed these samples on the cell surface in order to estimate the relative efficiency variations under ambient temperature (28 °C) at midday (between 12 and 14 hrs GMT).

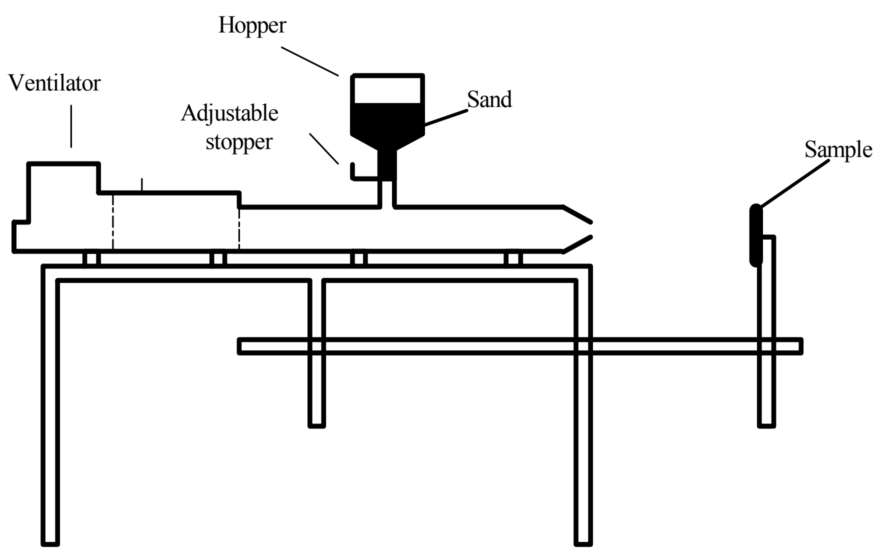

Fig. (2) Illustration of the sand jet impingement apparatus used for erosion tests with orient able sample holder

III. RESULTS AND DISCUSSION

1. Roughness

Figure 3 shows the variation of the surface roughness as a function of the sand blasting time. The roughness Ra increases strongly until about 20 min duration and tends to a constant level beyond. The roughness profiles show the formation of single defects when the sand blasting duration is less than 20 min. It is clear that interaction begins to occur between micro-cracks after 20 min duration.

The ratio of the hardness of the sand particles Hv_P to that of the glass specimens Hv_G is between 0.95 and 2.22. According to Wada's analysis [21], when the ratio $Hv_P / Hv_G >> 1$, the removal of material can be explained by the fact that the target exhibits inelastic deformation which is accompanied by radial and lateral cracks formation. Lateral cracks extend from the impacted regions parallel to the surface and the erosion occurs by the loss from the laterally cracked regions. When the ratio $Hv_P / Hv_G < 1$, the particles are not able to penetrate into the target and thus do not generate lateral cracks in the target. In our case, the Hv_P / Hv_G ratio is found with a prevailing tendency greater than unity (mean value 1.585), and consequently the lateral cracking mechanism can be invoked. Nevertheless, lateral cracks are not clearly observed, probably because the eroded surfaces are too severely damaged for the durations used. The lateral cracks are considered responsible for material removal and the radial cracks a source of strength degradation. The effects of the interaction between impact sites and the effects of the cumulated residual stresses caused by repetitive impacts make it difficult to elucidate in these conditions the erosion mechanism (formation and interaction of lateral cracks).

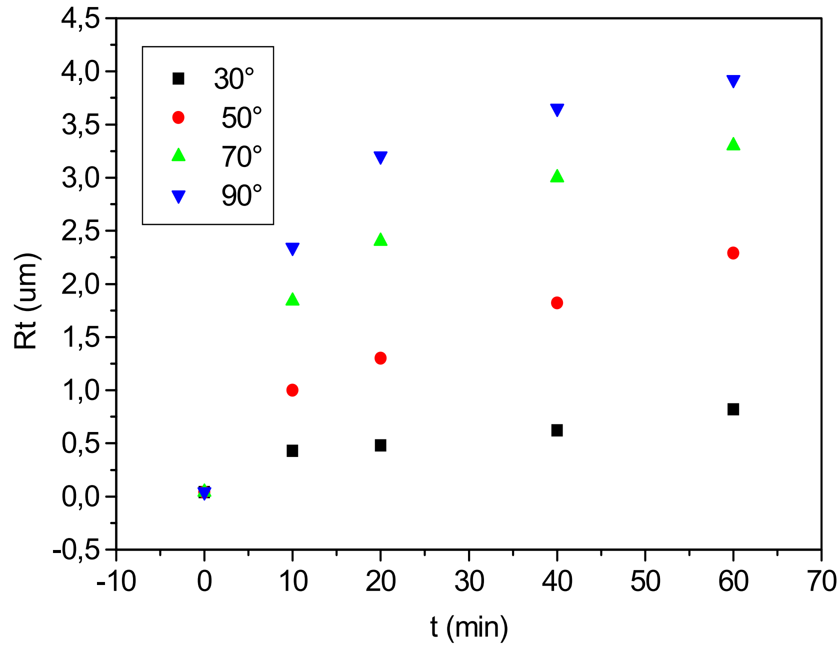

Fig. (3) Evolution of the surface roughness versus sand blasting duration for different impact angles.

2. Optical transmission

Figure 4 shows the variation of the optical transmission as a function of duration for different impact angles. The optical transmission T drops sharply initially, and then tends to a constant level. For 60 min of exposure to sand blasting, it falls from 91.5 to 51% for 90° impact angle and from 91.5 to 86% for 30° impact angle. The erosion pits cause the loss of transmission by diffusion and reflection because of a gradual increase of the micro-cracks density and the effect of the cumulated residual stresses in the eroded surface.

3. Mass loss

Figure 5 shows the mass loss variation versus the sand blasting time for different impact angles. We can observe that the behaviour over 20 min is nearly linear. Extrapolation of the curve indicates that there is an incubation period. This time estimated at about 3 min for the chosen test conditions indicates that for lower duration, there is not mass removal.

The kind and extension of the damage caused by sand blasting is dependent on the kinetic energy of the impacting particles, their shape and on the mechanical properties of the particles and the target. With sand blasting time, an increasing number of superficial micro-cracks and craters develop. Interactions between different impacts could also occur.

Observations of the exposed surfaces revealed the development of small craters that are randomly distributed, as well as the formation of lateral micro-cracks. Under continuous sand impacts, these micro-cracks develop into conical flakes (Figure 6). It is well known for indentation theory [22] that these lateral micro-cracks on brittle materials are mostly caused by sharp particles or by blunt particles with relatively important impact forces. It also appears clear that the damaged zones were of different sizes. The density and the surface extent of these flaws increase with the duration of the exposure to sand blasting. An important increase in the roughness of the exposed surface was noticed before reaching an average constant level of about 5.3 μm.

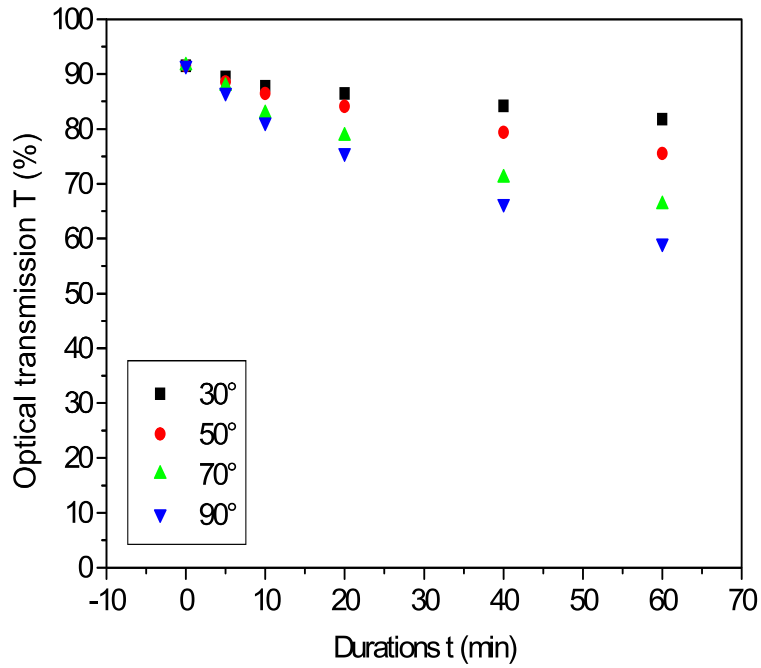

Fig. (4) Variation of the optical transmission versus the erosion duration for different impact angles.

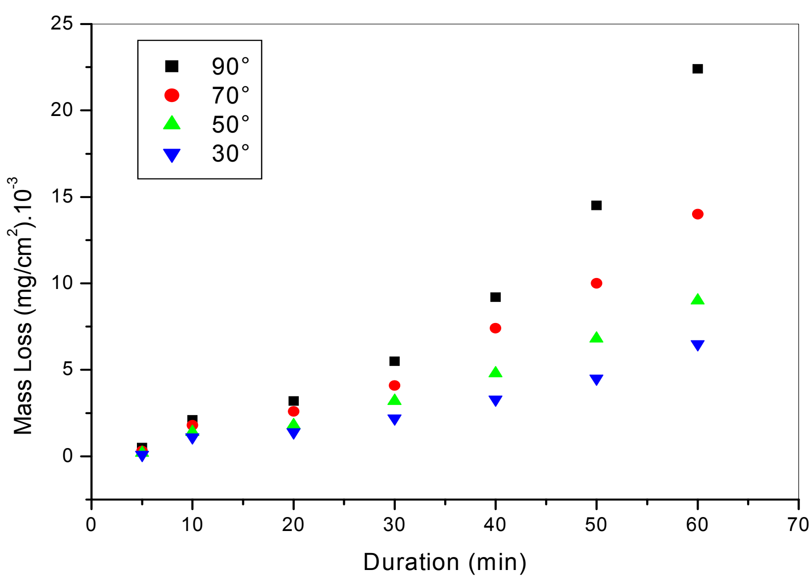

Fig. (5) Variation of the mass loss versus duration for different impact angles.

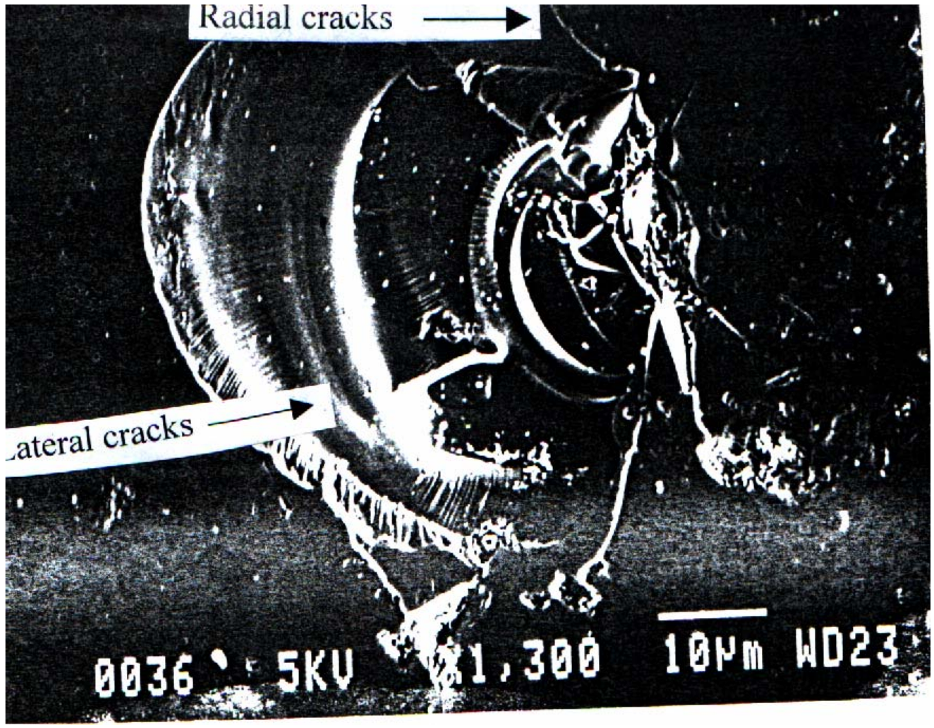

Fig. (6) MEB Micrograph of typical damage induced by sandblasting on soda-lime glass.

4. Erosion rate

Several works were done to study the erosion rate. It was shown that the material loss is evaluated supposing that the erosion rate is proportional to the sum of matter removed by every impact [23]. The matter volume removed is determined using indentation fracture mechanics. Figure 7 illustrates the variation of erosion rate as a function of time for different impact angles. We can observe that the curves increase with time. The extend of the erosion rate increases with impact angle increase. At 90° impact angle, when the sand flux is normal to the sample, the damage is more severe and the material removal is maximum. In this case where the tangential impact forces are negligible and the normal forces of impact are the strongest, the erosion is more effective. The lateral cracks are diffused around the impact site. The cracks morphology is similar to that produced by sharp indenter. The incubation time decreases with the incident angle.

5. Photovoltaic efficiency

The glass protected solar panel relative efficiency variation versus sand blasting duration up to 300 min is shown in Figure 8. There is a slow regular decrease of 0.91 for an impact angle of 90° and of 0.95 for an impact angle of 30°. This drop is mostly related to the presence of the superficial flaws that affect the light transmission. In the natural conditions, the light transmission can also be altered by dust or sand particles that rest in the damaged zones (Figure 9).

6. Mechanical strength

Bending strength tests were first done on glass samples eroded during different times up to 160 minutes [24]. The results of these preliminary tests are shown on Figure 10. The main remark that can be made from this figure is that there is a sharp drop in strength within an hour duration followed by an almost constant level of strength values and a decrease of the standard deviation as the duration increases. In order to obtain a better insight into the strength variability with sand blasting, a Weibull statistical analysis was made on a larger number of samples eroded during two different times (30 and 60 minutes) and on as-received samples.

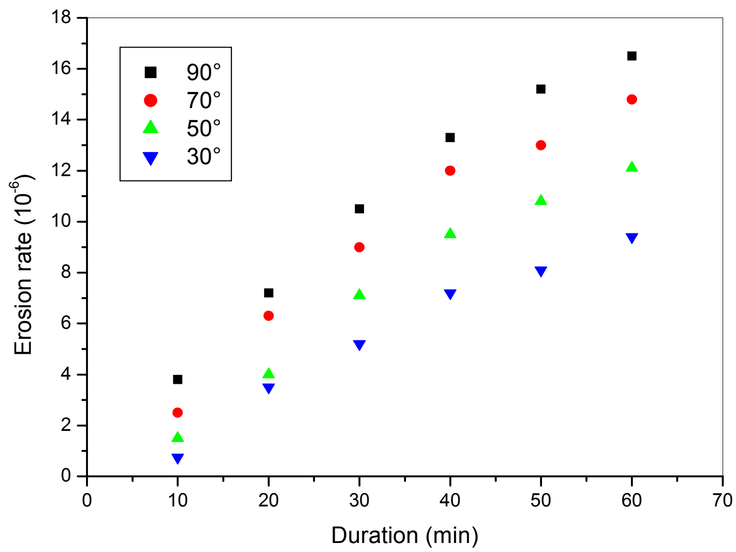

Fig. (7) Evolution of erosion rate as a function of sand blasting duration for different impact angles.

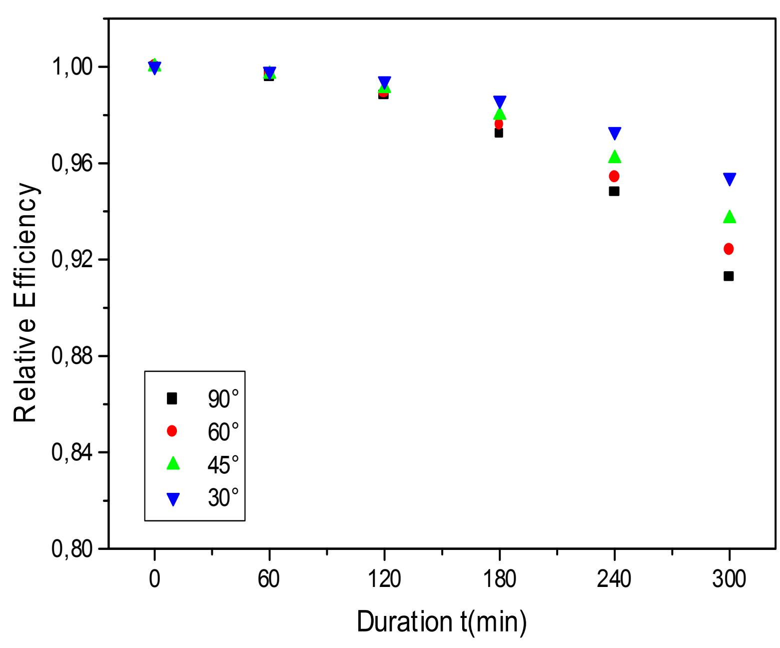

Fig. (8) Variation of the relative efficiency versus sand blasting duration for various impact angles

Weibull model is well suited for characterizing strength and lifetime variability of brittle materials under various loading conditions [25, 26, 27]. It is based on the weakest link concept considering the material structure as a chain whose strength is controlled by its weakest link, the equivalent of the most critical flaw. According to this model, the strength distribution is characterized by the function:

$$P = 1 - Exp [(\sigma/\sigma_o)^m] \quad (3)$$

where m and σ_o are the two parameters defining the Weibull distribution. These parameters are determined experimentally. The parameter m is the Weibull modulus which indicates the spread of the strength variability (a small number implies a high dispersion of values). Typical values encountered in glass strength are between 5 and 15. The second parameter σ_o is a scaling parameter corresponding to the strength for a probability of failure. In order to determine these two parameters, the Weibull function is rewritten in a linearized form as:

$$LnLn[1/(1-P)] = mLn(\sigma) + Ln[(1/\sigma_0)^m] \quad (4)$$

This equation can be plotted as a straight line LnLn[1/(1-P)] versus Ln(σ) whose slope is the Weibull modulus m and whose intercept at the origin is $Ln[(1/\sigma_0)^m]$. A failure probability P_i is assigned to each strength value σ_i after ranking all the measured values in ascending order from 1 to n, n being the number of samples tested. The estimator of the failure probability used is: $Pi = i/(n + 1)$

The Weibull plots corresponding for the three different states (as received and eroded during 30 and 60 minutes) are shown in Figure 11. The as received glass curve shows a higher dispersion of values expressed by a low Weibull modulus (m = 5.41) and an average strength value (76 MPa). The 30 minutes sand blasted glass plot shows a lesser dispersion (m = 8.2) and a lower average strength value (66 MPa) while the 60 minutes sand blasted glass plot presents the lowest dispersion (m = 10.64) with a comparable average strength value (64 MPa). It is also to be noticed that even though the curves for the as received and 30 minutes sand blasted glass states seem to present a change in slope for low values. They were considered as unimodal forms. According to the theory related to bimodal forms corresponding to two different flaw populations that control strength, the Weibull curve present a change in slope and is represented by two straight lines when the concavity is oriented towards higher values. According to Ritter et al. [28], these are characterized by curves which are concave upward with one part approaching asymptotically the flaw distribution with the smaller Weibull modulus m at low strengths and the other with the higher m at high strengths. The curves in our case seem to present a downward concavity instead. They are considered therefore of unimodal forms.

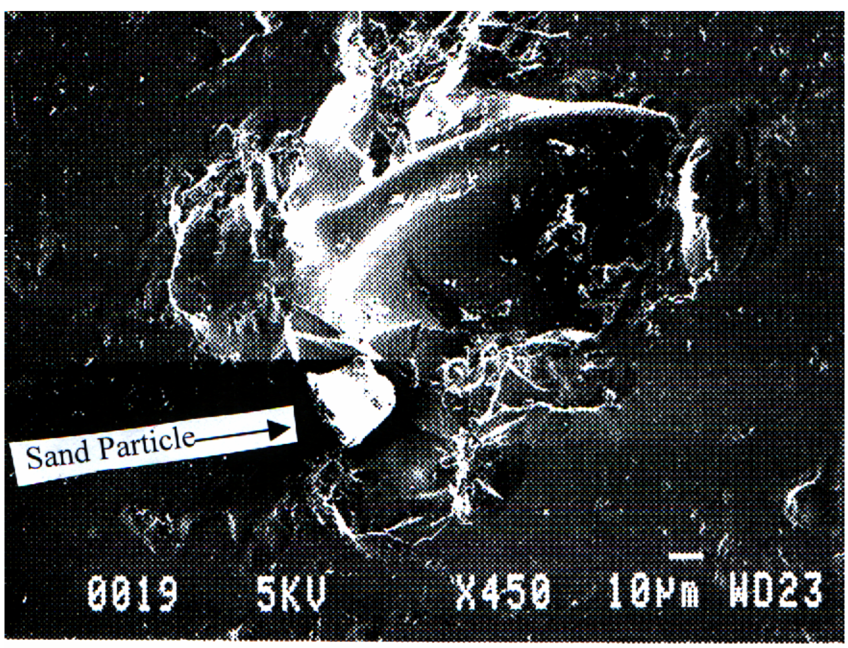

Fig. (9) Micrograph showing a small sand grain lodged in a damaged impact site

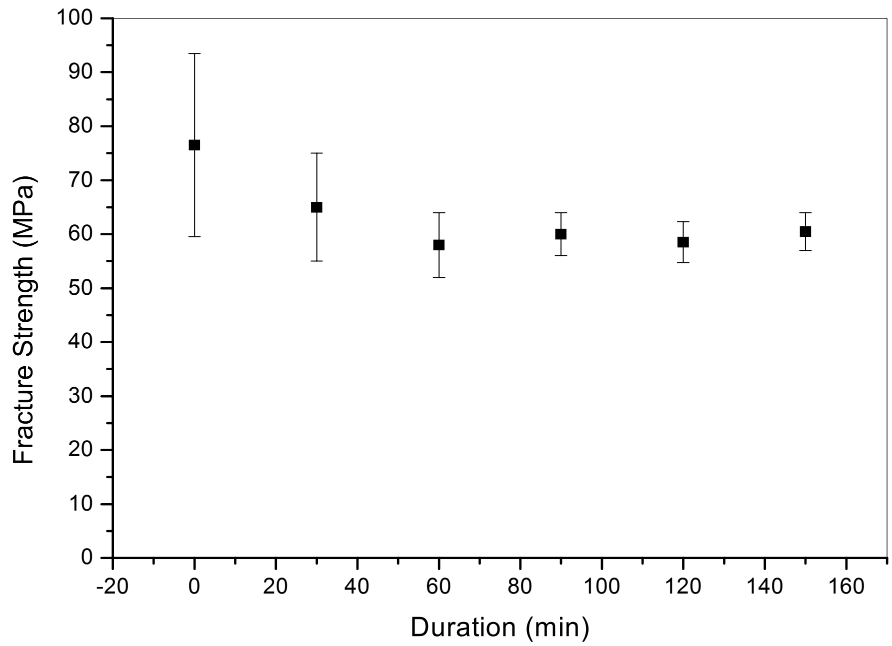

Fig. (10) Fracture strength versus sand blasting duration for non eroded samples and the large scattering values obtained for the short durations.

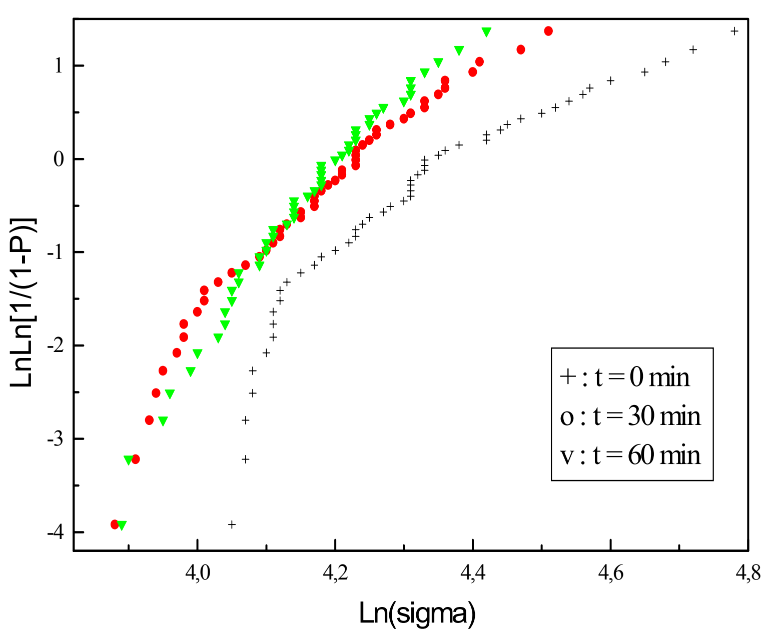

Fig. (11) Weibull plots obtained for three glass states (as received, sandblasted for 30 min and for 60 min).

CONCLUSION

The effects of the sand blasting duration and impact angle on the glass properties show that the roughness increases and tends towards a plateau, while the optical transmission decreases and tends towards a threshold estimated at about 51% of the initial transmission. We noticed that the glass erosion is maximal for an impact angle of 90°. The mechanical strength tends also to stabilize after a sharp drop (13%) during the first 30 minutes sand blasting duration at an angle of 90°. The variation of the relative efficiency of glass protected solar panels versus sand blasting duration (seen up to 300 min) shows a slow regular decrease until 0.91 for a 90° impact angle and 0.95 for 30°. Microscopic observations reveal that the damage is similar to that induced by sharp indentation such Vickers indentation on glass. There is formation of a plastic imprint with radial cracks and some scaling caused by the development of lateral cracks that extend and curve up to the surface.

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