# D8.5: Report on the methodology of accelerated erosion testing for reflectors and absorbers

## *WP 8.3: Performance of CSP components in desert environment*

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# Contents

# 1 Introduction

In order to perform a reasonable yield analysis for concentrating solar power (CSP) plants, it is of crucial importance to determine all the relevant parameters that are affecting the electrical energy output. Energy conversion processes are limited in their efficiency due to several constraints and losses can be of optical nature, because of heat losses, or further effects like operation strategy or parasitic energy. For example, the peak optical efficiency of a parabolic trough collector can be written as:

$$\eta_{opt,0} = \rho \cdot \tau \cdot \alpha \cdot \gamma_{IC} \cdot \eta_{mech} \tag{1}$$

Where $\rho$, $\tau$ and $\alpha$ are the mirror reflectance, the glass envelope tube transmittance and the receiver absorptance, respectively. $\gamma_{IC}$ is the geometric intercept factor and $\eta_{mech}$ stands for mechanical imperfections like tracking or structural torsion [1]. It is important to note, that all those variables can change over time and thereby have a significant impact on the annual electricity yield of a CSP plant. Performance forecasts over the complete component lifetime are necessary in order to assess the economic benefit of the system as a whole. Typically the components, that are going to be used for CSP installations are subjected to accelerated aging tests which are especially tailored to meet the conditions to be expected during their lifetime. Many of those testing procedures are already formulated as standards; however a testing methodology to simulate the effects during sand and duststorms (SDS) is not available yet.

# 2 Scope

This guideline is dedicated to present the methodology to be applied if components are to be tested with respect to their resistance towards SDS erosion. It is important to note, that SDS can be very different around the world and meteorological measurements to determine all their physical properties in a temporal resolution are almost impossible to conduct. However various field campaigns from literature and the participating institutes provided enough knowledge to formulate this guideline. For example a two year outdoor exposure testing campaign in various sites in Morocco. Some of the exposed reflector samples have been found to be almost completely unaffected from erosion effects while at specific sites, especially in Zagora (Morocco), the specular reflectance has been significantly reduced after exposure.

This document depicts how tests should be designed and gives the most important parameter ranges in which representative tests should be conducted to simulate severe sandstorm conditions. Still it is highly recommended to confirm and optimize the testing conditions by the outdoor exposure of sample specimen at the respective site. Samples to be tested can be all possible optical components of CSP plants.

# 3 Specimen handling

The samples shall be handled with care. The cleaning is a very important issue for the comparability of the results. The samples must be carefully cleaned before optical characterization. Due to the nature of this aging experiment there will be a substantial amount of dust adhering to the sample surface. The removal of this dust should be carried out as reproducible as possible. The dust needs to be removed completely before performing optical measurements. However it should be avoided to cause more damage by the cleaning.

Samples should be cleaned under extensive demineralized water flow directly after testing to remove loose adhering dust. Still under water flow, the back side should be cleaned first with a soft tissue. When the backside is clean, the sample is turned and with only very little pressure and a new tissue the front side is cleaned under water flow. After some strokes, the tissue should be changed for a new one and slightly more force should be applied to the cleaning action. After the cleaning process the use of oil-free pressurized air is recommended to blow the sample dry.

# 4 Optical characterization

The severeness of erosion testing with different parameters should be evaluated and compared by the use of optical measurement techniques as specified in the SolarPACES Reflectance Guideline Version 2.5 [2]. A full characterization shall be performed before the first and after each accelerated erosion test run.

## 4.1. Measurement of the hemispherical reflectance, the transmittance and the absorptance

The hemispherical reflectance $\rho_{s,h}(\lambda,\theta,h)$ will be measured using a commercial laboratory instrument with an integrating sphere of minimum 150 mm diameter over the relevant solar spectrum from 300 nm to 2500 nm. The $\rho_{s,h}(\lambda,\theta,h)$ is measured at near normal angles of incidence, typically $\theta \leq 15°$ and preferably at 8°. The sample shall be measured three times and be rotated after each measurement by 90° (to obtain measurements at 0°, 90° and 180°, see Fig.1). The solar weighed hemispherical reflectance $\rho_{s,h}([300\text{-}2500\text{nm}],\theta,h)$ is calculated by integration of the reflectance spectrum with the solar spectrum ASTM G173 [3] as below

$$\rho_{s,h}(SW,\theta,h) = \frac{\sum_{i=300}^{2500} \rho(\lambda_i) E_\lambda(\lambda_i) \Delta\lambda_i}{\sum_{i=300}^{2500} E_\lambda(\lambda_i) \Delta\lambda_i} \qquad (2)$$

The solar weighted transmittance is measured analogously. For the determination of solar weighted absorptance, $\rho_{s,h}(SW,\theta,h)$ is measured and subtracted from 1, to convert reflectance in absorptance.

## 4.2. Measurement of the specular reflectance

The specular reflectance $\rho_\varphi(\lambda,\theta,\varphi)$ will be ideally measured at three narrow wavelengths with an acceptance half angle $\varphi \leq 20$ mrad and an incidence angle $\theta \leq 20°$. If the instrumentation available does not permit to measure at 3 $\lambda$, the measurement will be done at only one $\lambda$. If available, the specular reflectance will be measured with the portable reflectometer D&S with $\varphi$ = 12.5 mrad and $\theta$ = 15°.

At least three measurements on different local spots should be performed per sample (see Fig.1). The average should be given as a result together with its standard deviation. This is particularly important since erosion simulation can present considerable inhomogeneity over the eroded surface area. To perform this task, larger samples eroded in an area of e.g. 6 x 6 cm² or 10 x 10 cm² are advantageous since they offer more area to measure on. For specimens that are eroded on the minimum circular area of 2.5 cm diameter, measurement spots might probably overlap partially but great care needs to be taken not to measure outside of the eroded area (make use of a suitable mask).

***Fig. 1: illustration of the positioning of the measurement spots on a reflector sample. The grey circle represents the minimum area of the erosion experiment (2.5 cm diameter), the red circles stand for the D&S measurement spots (1 cm diameter with allowed overlap) and the green rectangle for the measurement spot of a Lambda 1050 spectrophotometer from Perkin Elmer (17 x 9 mm²) in the 0° measurement position. This spot shall be rotated two times by 90°.***

## 4.3. Further evaluation

Microscope pictures of the samples should be taken in the initial state and after every conducted erosion test run (samples have to be cleaned first). This not only helps to understand the development of erosion effects, but it also facilitates the detection of remaining dust on the sample. Therefore it is recommended to first perform microscope analysis and then reflectance measurements. In case there is any dust left, the sample can be cleaned again before determination of reflectance values. It is suggested to observe the development of three different spots on the sample. To perform this monitoring, a microscope with an internal coordinate system is useful so that the same spots on the sample surface can be easily found again.

SEM analysis can be done for all tested samples additionally, to detect the average defect density and maximal depth of the defects with a higher magnification .

# 5 Erosion testing

The testing method presented in the following paragraph can principally be used for any kind of component that should be tested for sandblasting. The parameters are given in order to meet actual field conditions of optical CSP parts, though. Those values have been obtained during meteorological and geological field campaigns which took place in cooperation with the enerMENA meteorological network [4, 5] in Zagora (30°19´50´´ N, 5°50´17´´ W), Missour (32°53´46´´ N, 4°06´37´´ W), both in Morocco and Tabernas (37°01´16´´ N, 2°27´59´´ W), Spain.

It should be emphasized, that in order to achieve realistic results representative for a distinct outdoor site, a field campaign and the following adjustment of testing parameters is indispensable. The testing procedure is based on observations, which were made close to the ground (between one and two meters) and is therefore specifically designed for reflectors. In order to design a testing procedure for absorber tubes or ceramic receiver, field measurements need to be conducted at higher altitudes above ground, were less particles but eventually higher wind velocities can be expected. The area on the specimen to be eroded needs to be at least a **circle of 2.5 cm in diameter**.

## 5.1. Test setup

Possible setups to perform SDS simulation experiments can be based on pressurized air tanks or wind tunnels driven by ventilators. An erosion rig operated with pressurized air in which a stream of particles (the erodent) becomes injected can be seen in Fig.2a. Typically the nozzle diameter is in the range of some centimetres. The wind tunnel solution can be either facilitated by open- or closed loop channels (for open loop example see Fig.2b). Here the tube diameters can be larger and still sufficiently high air flow velocities can be achieved at the sample. Independent of the setup, various parameters have to be controlled. It needs to be mentioned that the necessity of a homogeneous particle flux over the test area is inevitable for comparable and repeatable results.

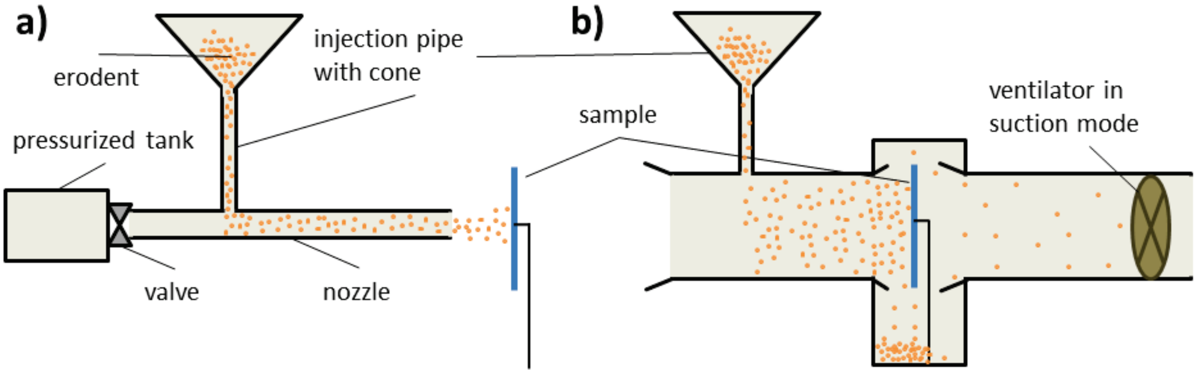



***Fig. 2 : proposed setups for erosion experiments; a) pressurized sand blasting and b) open wind tunnel in suction mode.***

## 5.2. Test parameters

- Impact velocity *v*: Since it is hard to directly determine the velocity of the particles impacting on the specimen, it is proposed to measure the wind speed at the point of the test specimen. For some setups this means that the sample holder needs to be removed and exchanged with an anemometer. The wind speed to be applied during the accelerated testing should be chosen in accordance with field measurements conducted at the sites, the samples should be tested for.. The particles should be injected into the flow at a sufficient distance to the specimen, so that they have reached their final velocity within the flow before impacting on the specimen.

- Impact angle *β*: The impact angle *β* spans between the particle trajectory and the sample surface plane. Therefore a particle impact with *β*=90° stands for a perpendicular impact on the sample. In order to achieve the most realistic testing conditions, *β* should be chosen in accordance with typical outdoor impact angles.

- Physical properties of the erodent: The mechanical properties of sand and dust can be completely different from one site to another. The variation can be present over a great number of parameters. The particle size distribution (PSD), the hardness, the toughness and the shape are the most important ones to be mentioned. Therefore it is recommended to use natural dust from the site to be tested for, for the most representative results. If no such sand samples are available or it is only aimed for a comparative performance study, artificial sand can be taken as erodent material.

- Cumulated erodent mass *γ*: This parameter represents the natural frequency and typical duration and intensity of SDS. It should be chosen in accordance with site specific data. However very often there is a lack of such data.

## 5.3. State of the art field measurements

The following paragraph is dedicated to present a possible way to achieve useful field parameters in order to classify outdoor sites regarding the SDS intensity. From literature like Zhao et al.[6], it became clear that a total suspended particle (TSP) concentration in the range of 0.1 g/m³ is possible during SDS events. Typical wind speed values of 10 m/s give mass flux values of 0.0001 g/(cm² s). Assuming durations of SDS of around 4 hours leads to a total impact mass of 1.44 gram per square centimetre reflector area and sand storm event (see Sansom et al. [7]). However, to end up with a value for this parameter for a CSP specific erosion guideline the reliance on naked literature values with no given uncertainties and some unknown parameters, like the mechanical properties is regarded to be inaccurate.

Within the STAGE-STE project, reflector sample exposure, dust collection (via BSNE sand sampler) and wind velocity measurements were undertaken at three different outdoor sites. From the reflector exposure it could be concluded, that only the site in Zagora exhibits a noteworthy SDS erosion threat since the measured annual specular reflectance losses were 4.4%, 0.4% and 0.1% for Zagora, Missour and Tabernas, respectively. The reflectors were exposed facing south under a horizontal inclination angle of 45° at an approximate height of 1.2 m above ground. The wind velocity and direction was measured at 10 m above ground and the passive BSNE sand trap was mounted at 1.8 m above ground on a rotating wind vane. It collected aeolian material during

December 15, 2016 and April, 4 2017. The BSNE was only installed in Zagora. The respective results of the outdoor campaign are summarized in Tab. 1. It depicts the frequency of the respective wind velocity ranges, the main wind directions, and the mean relative humidity and soil characteristics are given, since they are identified, as critical erosion determining parameters [8]. Furthermore the calculated mass flux from the BSNE sand trap is given, which was calculated by dividing the collected mass through the opening area of the trap and the collection time. The resulting specular reflectance loss is given in the last line for each site. It becomes obvious, that it is difficult to determine all erosion influencing parameters at the same time at a high spatial and temporal resolution. The here presented data e.g. are used to derive the necessary erodent particle diameter and the cumulated erodent mass $\gamma$ only from a single BSNE measurement, which was ongoing for almost 4 months. If natural dust shall be utilized for erosion experiments it is recommended to remove all particles larger than the largest particles captured by the BSNE trap at the respective height above ground by mechanical sieving.

***Tab. 1: summary of field data; $PSD_{gr}$ stands for the gravimetrical particle size distribution, meaning that most of the mass is present in the given diameter range.***

| | **Zagora** | **Missour** | **Tabernas** |
|---|---|---|---|
| frequency in wind velocity interval (in [m $s^{-1}$]) in [%] | | | |
| 8<v<12 | 9.8 | 7.2 | 8.4 |
| 12<v<16 | 2.0 | 1.6 | 0.4 |
| v>16 | 0.7 | 0.6 | 0.0 |
| main wind direction | South-West | West | East |
| mean relative humidity [%] | 25.3 | 47.7 | 51.0 |
| maximum of $PSD_{gr}$ [µm] of soil samples | 150-160 | 32-53 | <32 |
| mineralogical composition sorted after quantity | Quartz(73%), Calcite (8%) | Calcite (67%), Gypsum(14%) | Quartz(66%) |
| BSNE flux [g $m^{-2}$ $min^{-1}$] | 1.4 x $10^{-2}$ | - | - |
| annual loss in $\rho_\varphi$(660 nm,15°,12.5 mrad) | 4.4% | 0.4% | 0.1% |
| Cumulated erodent mass /a derived from DSD (at 20m/s) | 0.65 g $cm^{-2}$ | ? | ? |

We developed another more improved method to derive γ from field measurements by having a look at microscope images of the exposed reflectors and evaluate the defects. This is done using the software ImageJ on a reflector that was exposed in Zagora. The procedure is illustrated in Fig.3. First a background subtraction is applied to the microscope pictures to achieve a homogeneous background brightness, then a threshold for the color value is set to make a clear distinction between defects and background. Afterwards a binary conversion took place, followed by filling up the holes and the separation of adjacent defects. Also defects, that are touching the frames of the microscope pictures are sorted out for the evaluation. The so derived a defect size distribution (DSD) was used as reference for conducting accelerated erosion tests. The cumulated erodent mass of the accelerated erosion experiment was adjusted to reproduce the DSD measured outdoors. The resulting cumulated erodent mass for the sites Zagora, Missour and Tabernas is also shown in Tab.1.

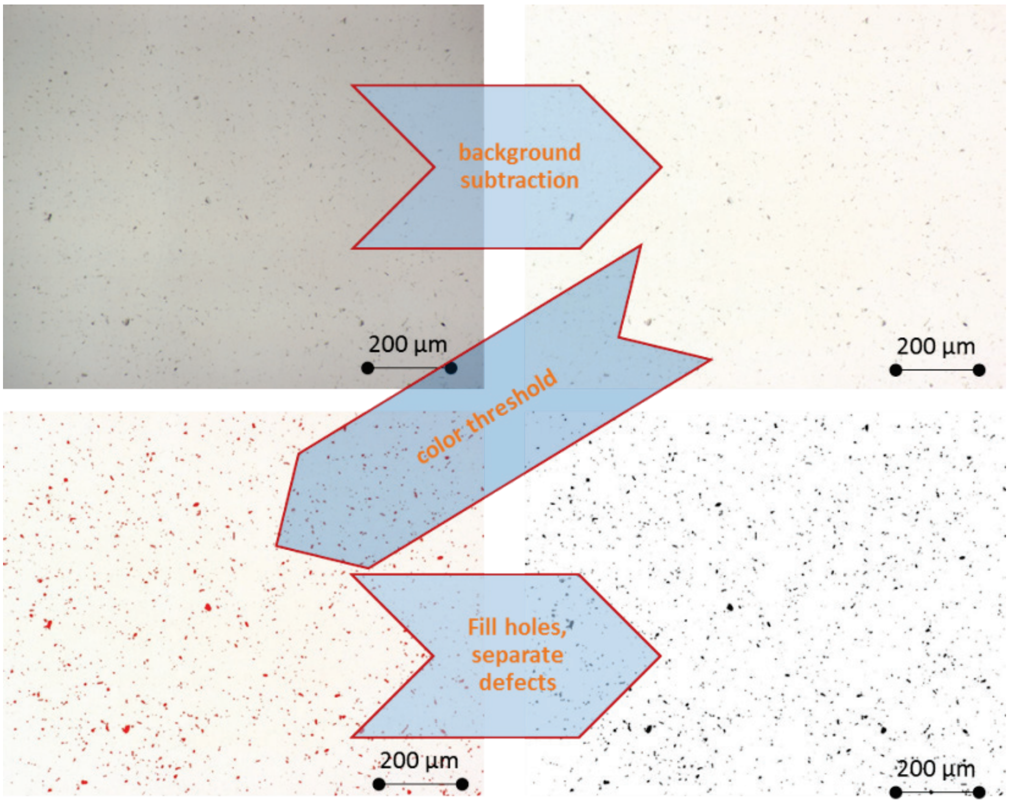



*Fig. 3: illustration of working principle of the developed image analysis method.*

## 5.4. Simplified procedure

Because there is not always the time to perform an extensive field testing that should at least be conducted for 1 year, this guideline presents the testing parameters that should be applied in order to reproduce the erosion condition present in Zagora during 1 year at a height of around 1.2 m. It is a simplified procedure which serves well for comparative material testing, since the input parameters are highly realistic, but it is very probable that the erosion intensity at different heights or at other sites vary from the parameters given in the following:

- The wind velocity *v* for the test shall be fixed at 20 m/s.
- The pure quartz sand **esqua DOR 0.06-0.3** (see Appendix 1) from KSL Staubtechnik GmbH (Lauingen/Germany) is recommended to be taken as a standard sand type. The PSD is in a reasonable range and particles with diameter smaller than 50 µm are almost completely absent. By this, problems with the injection mechanism of the setup can be avoided. Furthermore scholars like Hutchings [9] suggest that a threshold exists for the erosion determining parameters like the particle size and it's reasonable to assume it in this order of magnitude for the diameter.
- The cumulated impact mass $\gamma$ was derived from the conducted experiments and image analysis and was found to be 0.59 g $cm^{-2}$. .
- If no other circumstances justifies testing at a different angle, $\beta$ should be kept fixed at 90° with a deviation smaller than ±5° in order to test for the worst case scenario.

The cumulated impact mass was derived after Fig 4, were three consecutive test runs in the Actube were conducted in order to reach the respective sand mass which results in the same loss of $\rho_\varphi$ as the annual mean in Zagora. The microscope of the reflector treated with 0.66 g $cm^{-2}$ is shown in Fig. 5 and depicts the similar erosion characteristics of the naturally aged, and the artificially aged reflector. The experiments here were conducted at β=45°, in order to have similar conditions as in Zagora, where the reflector was exposed with an horizontal inclination angle of 45°.

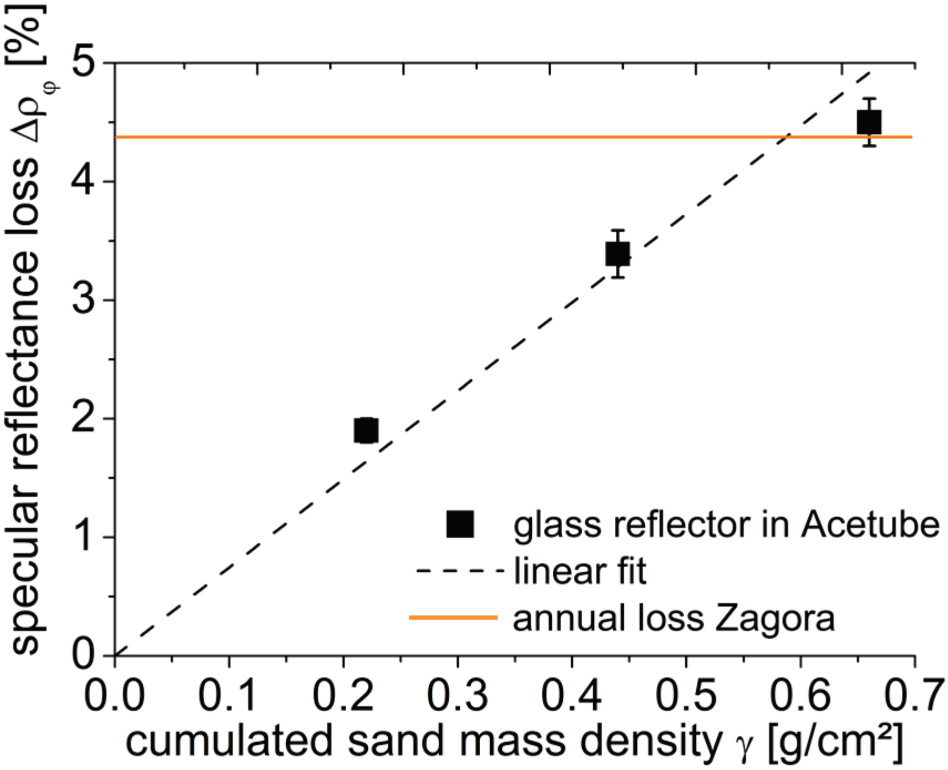



***Fig. 4: reflectance loss of artificially eroded reflector after increasing γ, the orange line depicts the annual reflectance loss in Zagora. Erosion parameters were v=20m/s and β=45° with the DOR sand.***

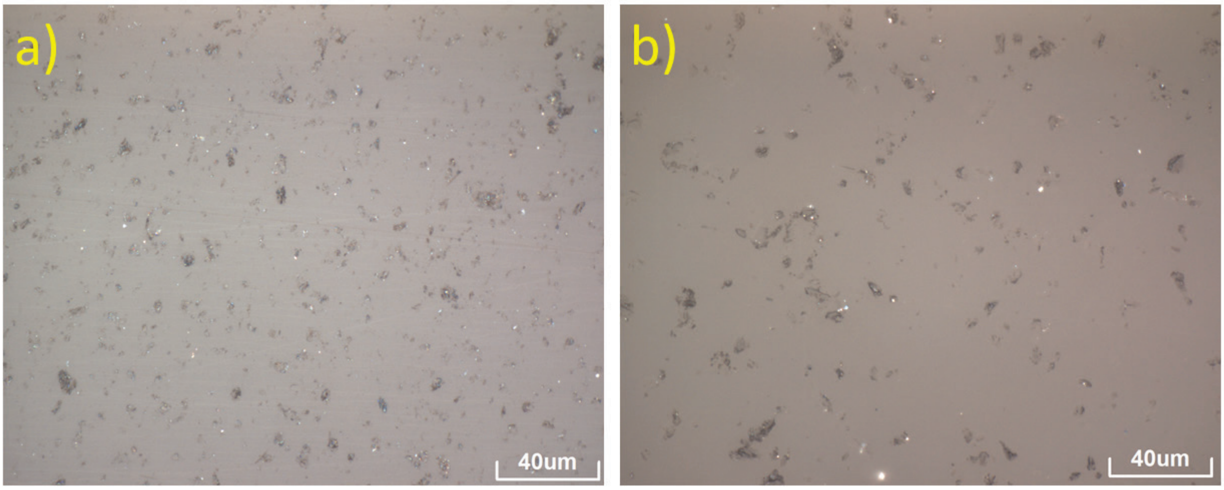


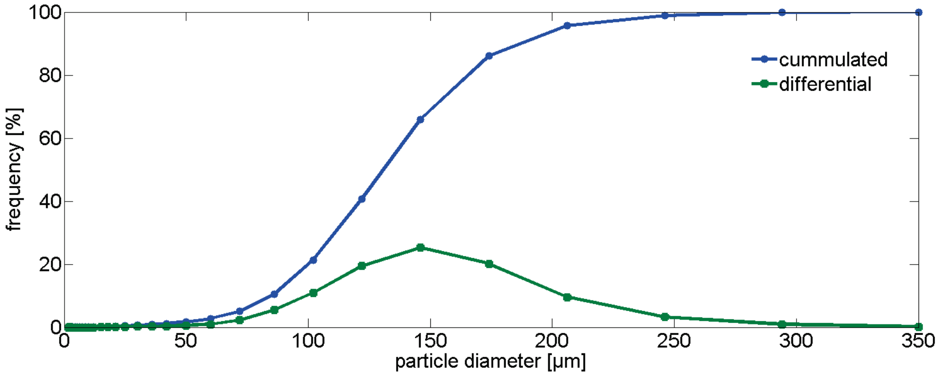

***Fig. 5: microscope pictures of a reflector a) from Zagora with specular reflectance loss of 4.9% , and b) after erosion aging showing a reflectance loss of 4.5%. Erosion parameters were v=20m/s and β=45° with the DOR sand.***

# 6 Report

The test report shall at least contain:

- A reference to this guideline.
- All information on the testing parameters.
- All measured optical characteristics from section 4 (before and after the erosion testing).
- Description of used equipment with related uncertainties.
- Critical assessment of result influencing circumstances.

# 7 Appendix




***Appendix 1: PSD of esqua DOR 0.06-0.3 standard test dust.***

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