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EXPERIMENTAL EVALUATION AND MAPPING OF THE DEFORMATIONS INDUCED BY THERMAL STRESS ON PHOTOVOLTAIC PANELS

Buratti C. and Goretti M.
Department of Industrial Engineering,
University of Perugia,
Via G. Duranti 67 - 06125 Perugia,
Italy,
E-mail: cburatti@unipg.it

ABSTRACT

The aim of the present paper is to evaluate deformation state due to temperature on photovoltaic modules surface. Laboratory measurements were carried out employing single grid strain gauges, in order to determine stress in significant points of four different samples subjected to temperature variations. Experimental data were used to draw thermal expansion maps, to predict the highest stress values, according to materials and assembling. Finally results were analysed and compared, in order to characterize the performances expected from photovoltaic panels and to prevent cell breaking.

INTRODUCTION

Decay of photovoltaic panels depends not only on chemical action of pollution and atmospheric agents, but also on thermal stress caused by solar radiation. Evaluation of photovoltaic modules deformations on different points, from the centre to the edges, over the cells or the gaps, by the frame or along the electrical connections, allows to identify the most critical zones, which must be improved in order to avoid structural damages. A careful selection and a correct assembling of materials are very important for applications of photovoltaic systems, such as their integration in building components and noise barriers [1].

In the present paper an experimental evaluation of deformation state due to temperature variations on photovoltaic panels surface and mapping of related thermal expansions were carried out.

Paper is a part of a work concerning thermal performances of photovoltaic modules [3]. In working conditions, photovoltaic cells are subjected to a thermal gradient between the two sides of the panel, due to solar radiation. The aim of the present work is to prevent damaging of different components by identifying the most strained points.

Experimental methodology is the same as in previous works [2, 3]. It consists in laboratory extensometric measurements on specimens front side, the one directly exposed to the sun in working conditions. Four different photovoltaic modules were subjected to temperature cycles into a climatic chamber and deformation measurements were carried out employing strain gauges, glued on the samples surface. Electrical strain gauges are constituted by metal single grid on a plastic support. In order to eliminate extensometric grid influence, relative measurements were carried out, using a reference material (titanium silicate), whose thermo-physical properties are known. The thermal expansion coefficients were calculated, for each panel, on eight significant points, selected on front side, and the corresponding deformations, induced by thermal variation, were then evaluated. Finally, considering geometric and materials symmetry of samples, maps of thermal expansion on the specimens surface were drawn.

Laboratory tests provided the deformation state of photovoltaic panels at standard working temperatures (20÷60°C) and are preliminary to outdoor measurements, where thermal conditions are uncontrolled and variable.

NOMENCLATURE

F	gain factor of the strain gauge (-)
T	temperature (°C)
t	time (h)

Greek Letters

α	coefficient of linear thermal expansion (°C^{-1})
β	thermal coefficient of resistivity (°C^{-1})
ΔT	thermal variation (°C)
$\Delta\varepsilon$	strain variation between sample and reference material or thermal output (-)
ε	deformation (-)

Subscripts

G	grid
R	reference

S	sample
ΔT	thermal

EXPERIMENTAL METHODOLOGY

Samples and Facility

Four samples of photovoltaic modules were examined, with different dimensions, shapes, cells (mono-crystalline or poly-crystalline silicon), protection and support materials (*Plexiglas*, *Tefzel*, *Tedlar*), with or without frame. In particular, sample *PV1* has *Plexiglas* front sheet with high thermal expansion coefficient, whereas samples *PV2*, *PV3* and *PV4* are provided with transparent *Tefzel* and aluminium frame; only *PV2* has poly-crystalline silicon cells. Photovoltaic panels were furnished by different companies and more detailed descriptions were given in [3].

In previous experiences each sample was verified at electrical insulation and functionality with different resistances, before and after accelerated aging process, by thermo-hygrometric stress in climatic chamber; they showed regular performances in each check.

Experimental facility consists in a climatic chamber, sensors and acquisition devices for deformation and temperature measurements and was described in [2] and [3].

Deformation measurements methodology is based on extensometric theory. Single grid electrical strain gauges were chosen; previous measurements, carried out with rectangular three grid strain rosettes, showed in fact an isotropic behaviour in each point [3].

After control of samples in order to verify absence of defects, strain gauges were glued on eight different points, one for each channel of the acquisition unit, on the photovoltaic panels front side (Figure 1).

Strain gauges arrangement was determined in order to evaluate thermal performances of photovoltaic modules in all the parts that compose the front side. Therefore the eight strain gauges were placed in significant zones, such as geometric centre and edges of photovoltaic cells placed in, gaps uncovered by cells, metallic conductors for electrical connections, etc. The arrangement of strain gauges on samples is shown in Figure 2.

In order to measure the actual temperature on the specimens front side, type *PT100 DIN-A* thermo-resistances were used (accuracy: ± 0.15°C at 0°C and ± 0.35°C at 100°C). Contacts between thermo-resistances and surfaces were obtained with thermo-dissipative paste [3].

Experimental Methodology

Strain gauges fixed on the photovoltaic panel are subjected to a deformation in the sensor grid, due to the thermal variation on the sample surface; as electrical resistance increases, deformation increases too. Finally, being the module free from ties, sample is thermally expanded without strain variations.

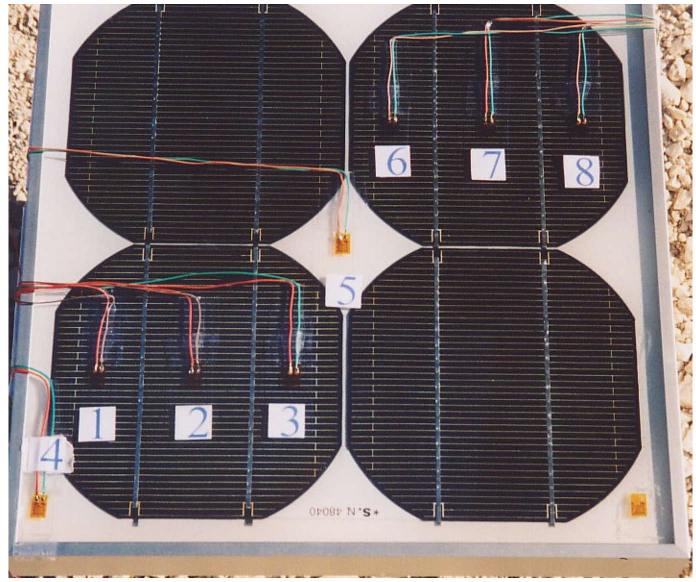

Figure 1: Strain Gauges glued on *PV3* Sample.

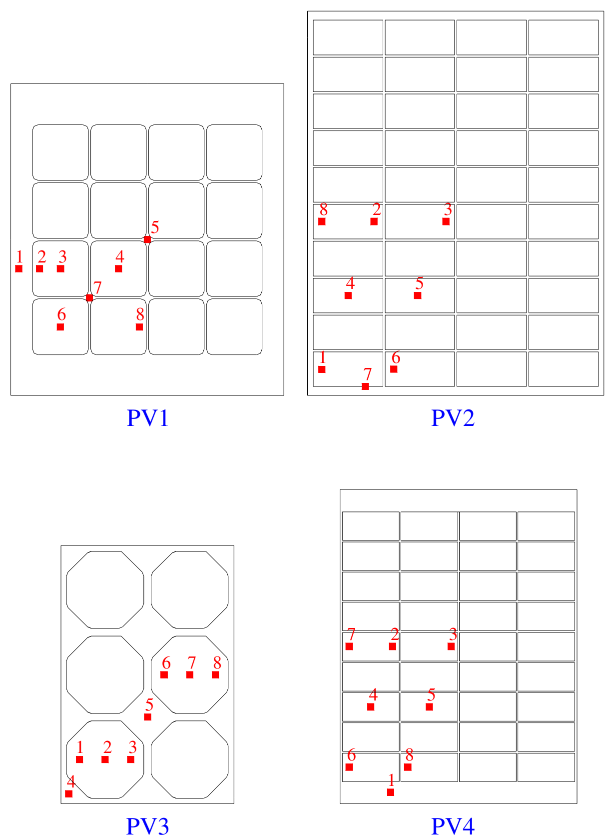

Figure 2: Arrangement of Strain Gauges on Samples Surface.

Thermal expansion coefficient of a sample can be calculated knowing the strain gauge gain factor F and measuring both specific variation of electrical resistance $\Delta R/R$ and temperature difference ΔT.

The electrical resistivity of metallic grid varies with temperature; its thermal expansion coefficient is different from the one of sample, so extensometric grid is also mechanically deformed.

Calculation of samples real deformations was possible using twin strain gauges (same type and same manufacture), glued one on photovoltaic module and one on a silica-titanium bar, the thermal expansion coefficient of which is known. A relative measurement is carried out, in order to purge data from error due to grid thermal expansion [2].

Strain gauges were connected to acquisition unit according to the *1/2 Wheatstone bridge* model [2], for a direct reading circuit. Tests were carried out in the climatic chamber and permitted to evaluate for each sample the thermal expansion coefficient in the eight significant points of the sample. Considering a temperature variation ΔT, the thermal expansion coefficient is given by [2]:

$$\alpha_S = \alpha_R + \frac{\varepsilon_{(G/S)} - \varepsilon_{(G/R)}}{\Delta T} = \alpha_R + \frac{\Delta\varepsilon}{\Delta T} \quad (1)$$

where α_R is $0.03\cdot10^{-6}$ °C^{-1} in the thermal range –45°C ÷ +175°C.

Before deformation measurements, check of strain gauge signal stability and elimination of residual stress were carried out [2, 3].

Deformations measurements were carried out in climatic chamber, where a typical temperature cycle in working conditions was simulated:

– 4 hour maintenance at 20 °C;
– 6 hour heating from 20 to 60 °C;
– 4 hour maintenance at 60 °C;
– 6 hour cooling from 60 to 20 °C;
– 4 hour maintenance at 20 °C.

Previous tests [2] showed that maintenance periods of 4 hours assure uniformity of temperature on the samples and between samples and air into the climatic chamber. Besides, heating or cooling with $\Delta T = \pm40$°C in 6 hours allow to repeat thermal variations reproducing the same conditions without hysteresis cycles, that is to say without residual deformations.

Experimental data were employed to estimate the thermal expansion coefficients and the corresponding actual deformations of the samples without grid influence. The obtained results represent average performances of the specimens at uniform temperature, as the thermal conditions can be controlled into the climatic chamber, but exclude the influence of other important factors, first of all the absorption coefficient for solar radiation of the different materials.

After the calculation of thermal expansion coefficients from Eq. (1), the deformations induced on photovoltaic modules surface were determined. In an elastic body, a temperature variation ΔT produces a thermal deformation $\varepsilon_{S,\Delta T}$ defined by [3]:

$$\varepsilon_{S,\Delta T} = \alpha_S \cdot \Delta T \quad (2)$$

The thermal deformations were calculated for each sample on the basis of the strain gauge measurements.

Finally, thanks to samples symmetry and strain gauges arrangement, maps of thermal expansion state on the specimens front side for working temperatures were drawn.

RESULTS

Tests were carried out from December 2004 to February 2005 in the Thermo-Technical Laboratory of the Department of Industrial Engineering, University of Perugia.

The photovoltaic panels were subjected at least to three thermal cycles into the climatic chamber and similar performances were observed for each one.

In Figure 3 an example of deformation trend in the eight points selected on *PV1* sample is given: figure shows measured thermal output $\Delta\varepsilon$ vs. time t, during a 24 hours thermal cycle.

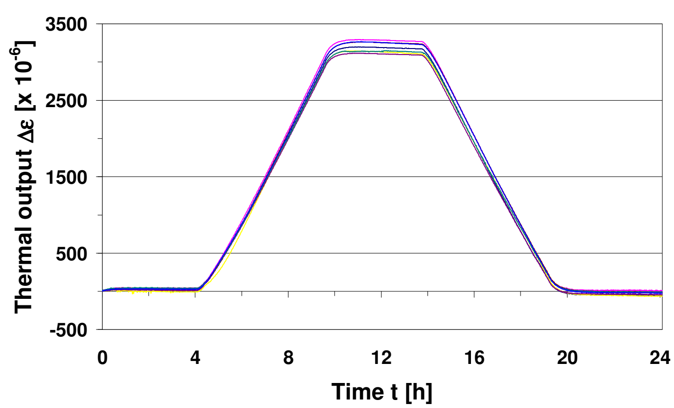

Figure 3: Thermal Output $\Delta\varepsilon$ vs. Time t during a 24 Hour Thermal Cycle on *PV1* Sample.

The corresponding surface temperature T vs. time t is drawn in Figure 4: data were measured on *PV1* sample during the same cycle and are averaged values of the thermal conditions in the different points on specimen front side; the thermo-hygrometric parameters are in fact rigorously controlled into the climatic chamber.

Experimental results are shown in Table 1: for each sample thermal variation ΔT, coefficient of linear thermal expansion α_S and thermal deformation $\varepsilon_{S,\Delta T}$ concerning the eight tested points during a 24 hours thermal cycle are reported.

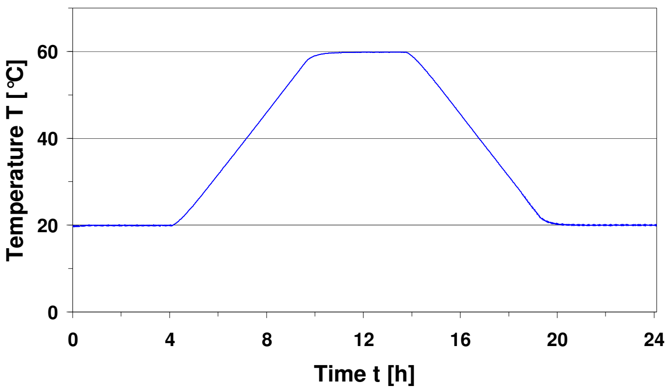

Figure 4: Surface Temperatures T vs. Time t during a 24 hour Thermal Cycle on *PV1* Sample.

Table 1: Experimental Results in the Selected Points on Samples Surface: ΔT [°C], α_S [x 10^{-6} °C^{-1}], $\varepsilon_{S,\Delta T}$ [x 10^{-6}].

Point	Sample							
	PV1		*PV2*		*PV3*		*PV4*	
	ΔT=39.79°C		ΔT=39.99°C		ΔT=40.05°C		ΔT=40.04°C	
	α_S [x 10^{-6} °C^{-1}]	$\varepsilon_{S,\Delta T}$ [x 10^{-6}]	α_S [x 10^{-6} °C^{-1}]	$\varepsilon_{S,\Delta T}$ [x 10^{-6}]	α_S [x 10^{-6} °C^{-1}]	$\varepsilon_{S,\Delta T}$ [x 10^{-6}]	α_S [x 10^{-6} °C^{-1}]	$\varepsilon_{S,\Delta T}$ [x 10^{-6}]
1	80.2	3191	7.7	309	8.4	338	9.2	367
2	81.9	3258	8.0	321	8.2	330	8.6	343
3	79.4	3158	9.5	381	8.3	331	8.2	329
4	74.0	2946	9.2	368	9.0	360	8.7	348
5	78.1	3107	7.3	293	7.8	313	8.1	325
6	81.1	3226	8.5	340	8.4	337	9.7	387
7	78.2	3111	8.2	330	8.1	326	8.7	347
8	81.4	3240	8.2	327	8.1	326	8.3	333

Maps of thermal expansion coefficient α_S are sketched in Figure 5 (*PV1* sample), Figure 6 (*PV2* sample), Figure 7 (*PV3* sample) and Figure 8 (*PV4* sample). Measured temperatures were uniform on the photovoltaic modules surface into the climatic chamber, so thermal deformation $\varepsilon_{S,\Delta T}$ is proportional to the corresponding coefficient α_S, according to (2); deformation maps have the same trend.

Results show that:

- sample *PV1* (Figure 5): protection front sheet has a higher thermal expansion coefficient than other samples ($74.0 \cdot 10^{-6}$ °C^{-1} ÷ $81.9 \cdot 10^{-6}$ °C^{-1}). Deformation state is characterized by low values on the barycentres of the four central cells. Map shows increasing values of deformations near the edges and the centre of the panel;

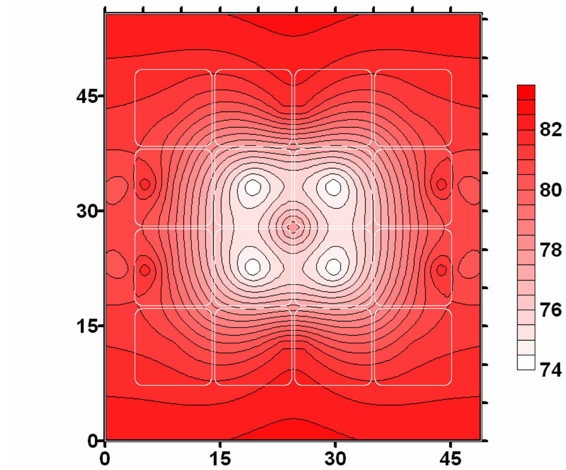

Figure 5: Map of Thermal Expansion Coefficient α_S on *PV1* Sample Surface [x 10^{-6} °C^{-1}].

- sample *PV2* (Figure 6): deformations (thermal expansion coefficient: $7.3 \cdot 10^{-6}$ °C^{-1} ÷ $9.5 \cdot 10^{-6}$ °C^{-1}) are characterized by:
  - four absolute minimum values near the medium point of smaller sides;
  - four relative minimum values near the corners;
  - absolute maximum value on the geometric centre of the panel;
  - four relative maximum values along the longer sides;

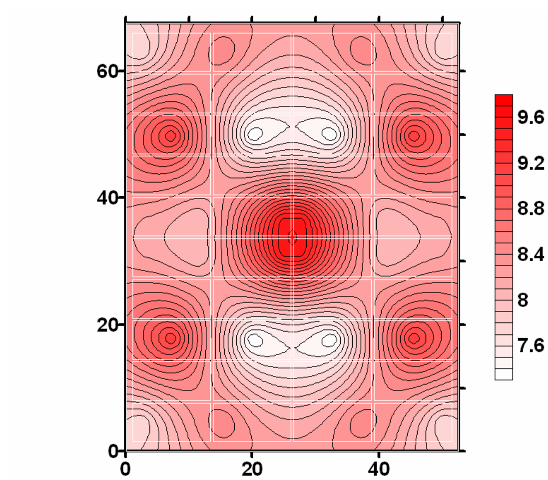

Figure 6: Map of Thermal Expansion Coefficient α_S on *PV2* Sample Surface [x 10^{-6} °C^{-1}].

– sample *PV3* (Figure 7): thermal expansion coefficient has minimum values ($7.8 \cdot 10^{-6}$ °C^{-1}) on two central zones, both on the upper and the lower part, where there aren't photovoltaic cells; on the contrary, the maximum value ($9.0 \cdot 10^{-6}$ °C^{-1}) is near the four corners of the panel. In the central zone the sample has medium deformations;

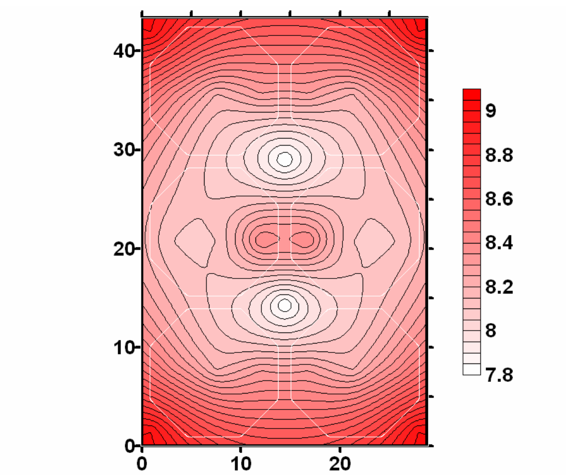

Figure 7: Map of Thermal Expansion Coefficient α_S on *PV3* Sample Surface [x 10^{-6} °C^{-1}].

– sample *PV4* (Figure 8): deformation state is characterized by maximum values near the four corners ($9.7 \cdot 10^{-6}$ °C^{-1}) and minimum values ($8.1 \cdot 10^{-6}$ °C^{-1}) along the longitudinal axis of the panel. Minimum deformation values involve almost all the central zone of the module.

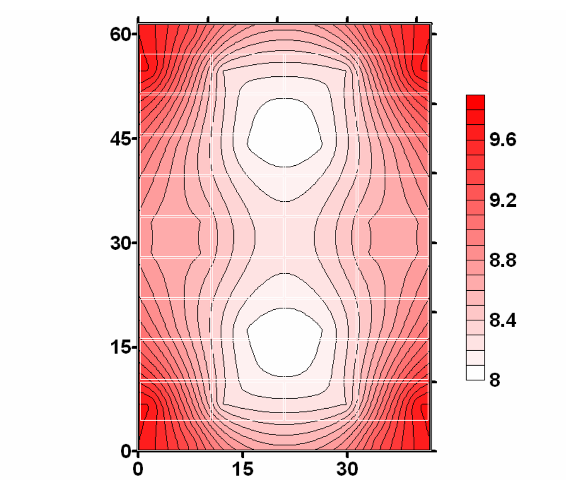

Figure 8: Map of Thermal Expansion Coefficient α_S on *PV4* Sample Surface [x 10^{-6} °C^{-1}].

CONCLUSION

Photovoltaic panels are subjected to thermal stress due to solar radiation, variable on different points of the module, which produces a particular deformation state. Thermal expansion may have negative consequences for the cells, according to materials assembling.

Experimental evaluation of deformations induced by thermal stress and mapping of deformation state on the panel front side, directly exposed to the sun in working conditions, was carried out with strain gauges measurements in climatic chamber.

Measurements were carried out by means of electric circuits, according to *½ Wheatstone bridge* model.

Analysing the experimental results, it may be concluded that sample *PV1* has a deformation state in the range $74.0 \cdot 10^{-6}$ °C^{-1} ÷ $81.9 \cdot 10^{-6}$ °C^{-1}, while samples *PV2*, *PV3* and *PV4* have lower values ($7.3 \cdot 10^{-6}$ °C^{-1} ÷ $9.7 \cdot 10^{-6}$ °C^{-1}). In particular, about the deformation surface trend:

– sample *PV1*: surface has a higher thermal expansion coefficient than other samples and it is characterized by minimum deformation values on the central cells;
– sample *PV2*: deformation state is very peculiar; map shows that thermal expansion coefficient has absolute maximum value on the panel centre and relative maximum values near the longer sides, but far from the corners;
– other samples, *PV3* and *PV4*, are characterized by very similar performances. They have similar materials and geometric characteristics of *PV2*, but mono-crystalline instead of poly-crystalline silicon; maps show that low and medium deformation values are present on central zone and maximum values near the corners of the panels; in particular, *PV3* has minimum deformation values where there aren't photovoltaic cells.

Measurements showed that thermal deformations on photovoltaic panels surface were not critical. Such a performance could be due to uniform conditions of temperature into the climatic chamber. State of thermal stress on photovoltaic modules will be estimated in following outdoor tests, in the real working conditions.

The methodology developed in the present paper allows to evaluate the most critical conditions and to avoid possible structural damages on photovoltaic cells. The methodology of deformation measurements can be applied to different kind of materials, employed in many fields of modern buildings.

REFERENCES

[1] F. Asdrubali, C Buratti, C. Simoncini: "Airborne sound insulation and absorption of noise barriers with photovoltaic modules", 17th International Congress on Acoustics ICA 2001, Rome, September 2001.

[2] C. Buratti, S. Ortica: "Experimental data of thermal expansion coefficient on artistic glass", 1st International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics HEFAT 2002, Kruger International

Park, South Africa, April 8-10 2002.

[3] C. Buratti: "Experimental data on the thermal behaviour of photovoltaic panels: measurements and strain and stress evaluation", 2nd International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics HEFAT 2003, Victoria Falls, Zambia, June 23-26 2003.

[4] AA. VV., "Energia dal Sole", ENEA-ISES Italia.

[5] L. Fedele, "Stato dell'arte delle fonti energetiche nuove e rinnovabili in Italia", ISES Italia.

[6] G. Comini, G. Cortella, "Energetica generale", SGE editoriali.

[7] A. Bosio, "Sistemi energetici", SGE editoriali.

[8] C. Mencuccini, V. Silvestrini, "Fisica II - Elettromagnetismo Ottica", Liguori.

[9] R. Baldacci, "Scienza delle costruzioni", UTET.

[10] V. I. Feodosev, "Resistenza dei materiali", MIR.

[11] F. P. Branca, "Misure meccaniche", ESA.

[12] G. Minelli, "Misure meccaniche", Patron.

[13] K. Wellinger, "Caratteristiche e prove dei materiali", PEM.