Experimental Study of the Properties of Thermal Insulating Materials and their Behaviour under Climatic Conditions and Artificial Ageing

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Abstract – The aim of this Master's Thesis is to explore the initial properties of the thermal insulating materials and systems which are most widely used in Greece and the ways that these are affected when exposed to accelerated environmental stress and artificial ageing. The materials under study were Thermal Insulating Materials and External Thermal Insulating Complex Systems (ETICS). Both were exposed to tests of ultraviolet radiation with simultaneous hydrothermal action, as well as cycles of freeze-thaw and salt spray tests. The properties–indices of the materials that have been checked and studied were optical analysis/visual evaluation, compressive strength, water absorption, change in material mass and thermal conductivity.

***Key-words:** accelerated environmental stress, thermal insulating materials, ETICS, artificial ageing, thermal conductivity*

I. INTRODUCTION

In this day and age, energy constitutes a unique, maybe the only one, indisputable Stock Exchange value. Therefore, reducing energy consumption acquires a very important role and buildings' thermal insulation is an important part of this project. In this respect, testing of the properties and the durability of thermal insulating products is one of the contemporary challenges in the struggle towards less energy consuming buildings.

The exposure of materials to permanent stress or to extreme conditions of stress causes their damage/fatigue. Therefore, there is a growing need for the development of laboratory methods and processes that can charge materials in ways that are equivalent to damage caused by natural ageing under environmental stress, as an alternative to time consuming tests of materials in real conditions.

The quest for models of artificial ageing has been at the forefront during the past few years. Daniotti, V. et al. (2013) report that a number of standard processes of accelerated ageing that evaluate the resistibility of various materials has already been developed. The aim of these (at least of their majority) is the evaluation of the appropriateness of materials used and not the prediction about the duration of the service life of their products (Daniotti, V. et al., 2008). According to Brennan and Fedor (1994) the interrelationship between the results of material damage after exposure to stress in a laboratory and those after natural exposure of materials to environmental stress possibly will remain forever controversial. And this is so because the duration of laboratory ageing procedures and their precision have competitive action.

In the following table (I) are set out some of the proposed methods of accelerated climatic ageing.

TABLE I
ACCELERATED CLIMATIC AGEING CYCLE METHODS

	Method	Observation of deterioration during/after the test	Equivalence to natural ageing
	NT Built 495	Visual evaluation	Not estimated
	J. Bochen	Open porosity and average pore radius of render	100 cycles equivalent to 1.5–2.7 years
	J. Bochen	Open porosity and average pore radius of render	100 cycles equivalent to 2 years
B. Daniotti	**Short-term**	Microscope analysis Water absorption Water vapour permeability Tensile bond strength of adhesive and base coat to insulator Render strip tensile IRT, SINa, SINb, TI CON RHst, degradation survey photos	Not estimated
	Long-term	Should be developed	
ETAG 004	**Heat-rain cycles (80cycle)**	Impact resistance Bond strength Water vapor permeability Visual evaluation	The whole service life
	Heat-cold cycles (5 cycles)		
	Freeze-thaw (30 (cycles)	Bond strength Visual evaluation	

Source : Griciute, G. et al. 2013

More specifically the accelerated stress due to solar radiation constitutes perhaps the most difficult part in the analogy between laboratorial and real conditions. The wavelength of ultraviolet electromagnetic radiation is approximately between 4 and 400 nm. UV radiation of wavelength of 290-400 nm reaches the Earth's surface and this is approximately the 10% of the emitted solar energy towards Earth (Kosmopoulos, P., 2007). Artificial sources of medium wave ultraviolet radiation (UVB) provide us with fast tests which may not always be accurate, fortunately being wrong on the safe side; they are too severe. On the contrary, the use of light sources that exclude wavelengths under 295 nm provide us with more precise results, however, the increased correlation is priced with a limited acceleration of ageing (Brennan, P. and Fedor, C., 1994).

II. Methodology

A. Materials

All materials under study bore CE and ETA (for ETICS) certification and their use is particularly widespread in Greece. More specifically, as far as thermal insulating materials are concerned, Expanded Polystyrene EPS80 and EPS200, Graphite Expanded Polystyrene EPS100 (GrEPS100) and Extruded Polystyrene XPS were selected. As far as ETICS are concerned, we selected all the aforementioned thermal insulating materials coated with a cement layer or with an elastic layer based on synthetic organic resin. The specimens were cubic measuring 40x40x40 mm.

An electric heated wire apparatus was used for the cutting of the specimens. Moreover, six specimens from each material and composition were used to perform all types of stress testings.

B. Expirimental Programme

The following (accelerated) environmental stress tests were selected:

- Solar Ultraviolet Radiation (UV) in increased temperature, alternating with cycles of humidity (Hydrothermal stress).

Due to the fact that our research included thermal insulating materials as well as External Thermal Insulating Complex Systems (ETICS), we followed variants of the following standards: ASTM D 4329, EN ISO 4892-1, EN ISO 4892-3 and ASTM G 154-00a.

The conditions of humidity were achieved by means of spraying water as is prescribed in ASTM G 154-00a and EN ISO 4892-1 and distilled water was used (EN ISO 4892-1 §5.3.2). The type of the temperature sensor was Black Panel Thermometer and it was constructed according to EN ISO 4892-1. The duration and the temperature of the stress test were decided according to Cycle A as described in ASTM D 4329.

The pattern of the stress test consists in seven hours and forty-five minutes (7h 45min) of exposure of the specimens to UV radiation (Emitted power spectrum: 315… 400 nm (UVA) – 13.6 W and 280… 315 nm (UVB) – 3.0 W) in temperature of 60° C (Black-Panel Temperature) followed by three hours and forty-five minutes (3h 45min) of conditions of humidity (condensation) in 50° C. Between these two stages intervenes a time span of 30 min in order to achieve a balance between the two conditions and in order to avoid any chance of thermal shock. That was due to the fact that our specimens concern materials of particularly restricted heat capacity and we considered the time span of two hours, which was prescribed by the standards, as excessive. Instead, the time span of 30 minutes proved sufficient for the temperature of the specimens to go down to 50° C.

In addition, we decided to reduce the timespan of specimen exposure to UV radiation and humidity by 15 minutes (15 mins) compared to the timespan patterns prescribed in standards, so as to achieve a larger number of cycles of stress test within the same time span (2 complete cycles every 24 hours). The total duration of the stress exerted on the specimens was eighty days (80 d) or, in other words, 160 complete cycles of UV stress tests were conducted. In order to perform the process that is described above, we constructed the chamber/apparatus that is portrayed in figure 1, so that it could provide the conditions that are required by the aforementioned standards as well as what is described in ASTM G 151-97.

Figure 1. – Constructed Chamber/Apparatus for UV Stress Test

- Freeze-Thaw Cycles

In this case we applied a variant of methodology B as prescribed in standard ASTM–C666/C, according to which the freezing takes place in air (dry environment) while thaw takes place in water. This standard was preferred first because of the need for simultaneous stress of thermal insulating material and ETICS, second because of the especially harsh stress that it prescribes (Tobiasson, W. et al., 1999) and third, because of the alternative it offers in case an automated system for the freeze- thaw process is not available. The temperature during freezing approximated -18° C (±2° C), whereas during thaw it approximated +4° C (±2° C). The duration of the freezing stage was 4 h and thaw lasted 4 h so that every single cycle lasted 8 h. In sum, ninety (90) cycles of freeze- thaw took place.

- Salt Spray (Fog) Testing

During the testing in alkaline environment to which the specimens of all materials under test were exposed, a salt spray/fog chamber (VSC/KWT 450 Vötsch) was used. ASTM B117-73 standard was applied. The testing lasted a hundred and twenty days (120 d) and the solution that was used consisted of 5% NaCl by weight (wt%) of water in deionised water. The temperature during the salt spray testing was 35° C (+1.1-1.7 C).

C. Testing of Properties – Indices

The properties that were checked as indicators of assessment of materials' durability against environmental stress tests in which they were subjected, are:

- Visual Inspection – Optical Evaluation

For the observation and monitoring of the specimens, a stereomicroscope Leica MZ75 with an especially adapted digital photographic camera and an image analysis and processing software were used. This way, it was attempted to minimize the subjective intervention of human perception and monitoring. The appearance of cracks-discontinuities—defects and any changes in the porosity were quantified as well as counted digitally before (for reference purposes) and after the testings. The defects that were taken into consideration were differentiations sized over seven (7) pixels which corresponds to a size of 150 mm. During the analysis, adjacent discontinuities, the outline of which presented at least four connections with other adjacent ones, were unified.

- Compressive strength

The test was conducted according to standard EN 826 (compressive strength for 10% deformation-σ10%) with the use of the electromechanical system of testing INSTRON 5960. The compression strength testing was carried out only for the specimens of thermal insulating materials.

- Thermal Conductivity factor «λ»

The calculation of the thermal conductivity factor «λ» was conducted according to the methodology proposed by P. Bison and E. Grinzato ("Fast estimate of solid materials thermal conductivity by IR thermography" 2010) with the use of a thermoelectrical device (Peltier) and a JADE 510 – CEDIP medium wavelength infrared camera. The specimens were cut in dimensions of 40x40x10mm in order to achieve the required ratio between the surface of the slab and the thickness.

- Short-term water absorption

The test was conducted according to standard EN 1609.

- Change in mass

The check of the change in the mass of the specimens was conducted by means of weighing them and comparing the average weight values of the various types of specimens. This procedure took place after their being kept under the appropriate conditions so as to achieve approximately the same percentage of humidity.

III. Selected Results

In table II are to be found, as an indication, the aggregated results that have arisen by the visual evaluation of the specimens after their UV and Freeze-Thaw testing.

TABLE II
VISUAL EVALUATION

VISUAL EVALUATION DIFFERENTIATION (%) - UV				
%	EPS80	EPS200	GrEPS	XPS
INSULAT. MATERIALS	7.14%	5.74%	4.74%	3.51%
ETICS ELAST. COATING	0.60%	0.84%	0.75%	0.61%
ETICS CEMENT COATING	0.31%	0.76%	0.85%	0.73%

VISUAL EVALUATION DIFFERENTIATION (%) - FREEZE-THAW				
%	EPS80	EPS200	GrEPS	XPS
INSULAT. MATERIALS	1.70%	1.63%	2.40%	1.66%
ETICS ELAST. COATING	2.90%	2.71%	3.59%	3.78%
ETICS CEMENT COATING	35.81%	35.05%	24.33%	33.74%

It can be noted that the coated materials (ETICS) remained optically almost intact during the given duration of UV testing - at least, this is the case regarding the scale/extent of our inspection. The thermal insulating materials presented an increase in the porosity of their surface. In addition, it should be noted that discolouring and obvious photodegradation on their surface were observed.

After the Freeze-Thaw testing, ETICS with cement coating presented extensive damage even complete degradation of the cement coating. The respective numerical data do not present clearly the extent of damage, because it, as already mentioned, was extensive; the surface of the coating did not remain solid and it could be extracted from the specimen very easily (separation of the coating from the underlying layer which was comprised of adhesive material and glass fibre mesh, was observed). This failure appeared in all specimens, without exception, regardless of the thermal insulating material used in the ETICS components. However, in the specimens with ESP80 as a thermal insulating component, the failure was observed with more delay and it could be described as marginally less extensive than in the rest of the specimens checked, rendering them, nevertheless, non-functional.

Therefore, it is reasonable to assume that the thermal insulating component influences the durability of ETICS and one of the reasons for the final failure is the fact that the ETICS complex end product is non isotropic. The failure appeared after 10 Freeze-Thaw cycles and the phenomenon was almost complete before the completion of the first 30 cycles. Therefore, for this specific case, the criterion of the 30 cycles that are necessary according to directive ETAG 004 on the certification of the resistibility of material in Freeze-Thaw, is deemed sufficient.

Figure 2. Etics Specimens with Cement Coating Failure

Table III provides the percentage variation of compressive strength of the thermal insulating specimens after the environmental strain testings.

TABLE III
COMPRESSIVE STRENGTH

COMPRESSIVE STRENGTH VARIATION (%)				
%	Virgin (Kpa)	UV	FT	SLT
EPS80	106.07	90.79%	98.53%	102.60%
EPS200	205.51	93.91%	98.66%	101.88%
GrEPS	117.65	89.94%	99.31%	101.66%
XPS	286.70	97.28%	96.36%	99.90%

As it is observed, all the materials presented significant reduction in the measured compressive strength after their exposure to UV radiation. Regarding the stress testing in freeze-thaw cycles all the materials presented a slight reduction in compressive strength. Eventually, after the salt-spray test all the materials presented a slight improvement of their compressive strength except from the extruded polystyrene XPS which remained unaffected.

The explanation for this could be the intrusion of salts in the porous component of the thermal insulating materials which, by means of the formation of crystalline structures, reduced porosity and reinforced the structural grid of the polymer. Extruded polystyrene was not affected maybe because of its restricted porosity.

As far as thermal conductivity is concerned, its determination was done by means of a thermographic monitoring of heat flux with the method already described (Figure 3).

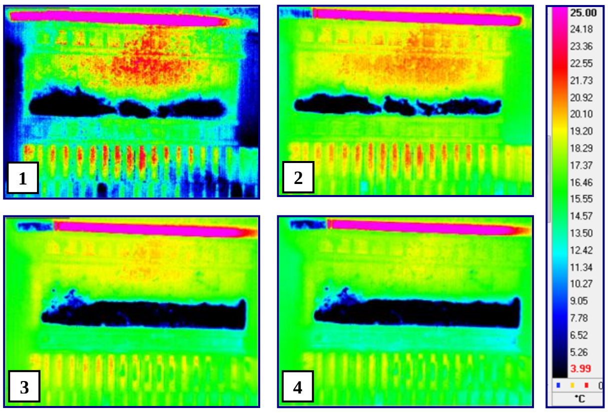

Figure 3. Thermographs of a specimen.
We can notice the Transition from the Unstable Heat Flux Phase (1-3) to Stable Heat Flux Phase (4)

Concerning the influence of the strain tests on thermal conductivity of materials, the results are to be found in figure 4 and in Table IV.

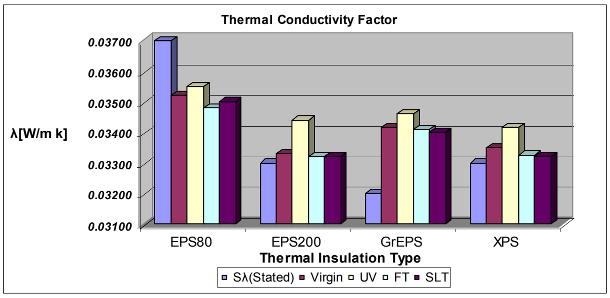

Figure 4. Thermal Conductivity "λ" Graph

TABLE IV
THERMAL CONDUCTIVITY "λ" VALUES

THERMAL CONDUCTIVITY FACTOR "λ"					
[W/m K]	S_{λ}(Stated)	Virgin	UV	FT	SLT
EPS 80	0.03700	0.03520	0.03550	0.03480	0.03500
EPS 200	0.03300	0.03330	0.03440	0.03320	0.03320
GrEPS	0.03200	0.03415	0.03460	0.03410	0.03400
XPS	0.03300	0.03350	0.03415	0.03325	0.03320

An increase of the thermal conductivity factor "λ" was observed in all thermal insulating materials after their exposure to UV, which suggests failure of either their material or their cellular structure. Worse behaviour (higher "λ" increase) was presented by materials with a denser structure (EPS200, XPS).

In addition, a slight or marginal reduction of thermal conductivity after the testing of the materials in Salt Spray and Freeze-Thaw cycles were observed. An explanation for this could be the formation or the deposition of salts on the specimens' surface and the caging of air in the specimens' mass.

On the whole, it would be reasonable to assume that the impact of the Freeze- Thaw and the salt spray testing on factor "λ" was negligible.

Concerning the measurement of water absorption of materials, we observed an increase in water absorption in all cases except from that of extruded polystyrene after its exposure to UV radiation which resulted in reduction. It is possible that the deposition of disintegrated material restricted the spaces between cells and this way short-term water absorption was reduced. The respective results are set out in Table V.

TABLE V
SHORT TERM WATER ABSORPTION

SHORT TERM WATER ABSORPTION (wt%)				
	Virgin	UV	FT	SLT
EPS 80	41.08%	35.84%	66.47%	65.61%
EPS 200	23.22%	25.65%	25.57%	60.31%
GrEPS	15.88%	21.61%	61.90%	43.48%
XPS	7.81%	22.52%	14.10%	22.90%

The generally increased values of water absorption that were observed could be explained on the basis of the increase of material surface.

As far as short term water absorption of ETICS is concerned, the measurements did not present any regularity and the only worth noting observation is that the measured values of the specimens of all systems under test call for a freeze-thaw testing according to directive ETAG 004 (Short Term Water Absorption).

Finally, regarding the change in mass of the specimens of thermal insulating materials, we could observe a noticeably similar behaviour of specimens of expanded polystyrene EPS80 and EPS200 during various tests, with a 5% reduction during exposure to UV radiation and material mass increase after salt spray test; the material mass of ESP200 specimens remained almost unchanged during freeze-thaw tests and there was a slight material mass increase in the case of ESP80 specimens. In general, all materials presented a loss in mass after their exposure to UV radiation with greater loss in mass in the case of Graphite Expanded Polystyrene and less in the case of XPS. The loss in mass is partly due to loss in material.

Graphite polystyrene increased its mass after Freeze-Thaw tests (due to salts deposition that had been observed also during visual inspection) whereas it is also the only material that presented a very short reduction or fixity in mass during salt spray tests. Possibly, the presence of graphite microparticles prevented the absorption of NaCl. EPS showed the fewest percentage changes in mass. The respective results can be found in Table VI.

TABLE VI
MASS VARIATION

SPECIMEN MASS VARIATION (%) (40X40X40 mm)				
	Virgin	UV	FT	SLT
EPS 80	100.00%	95.91%	101.18%	105.37%
EPS 200	100.00%	94.65%	99.88%	105.04%
GrEPS	100.00%	93.33%	104.38%	99.03%
XPS	100.00%	98.89%	98.59%	102.36%

IV. CONCLUSIONS

The following conclusions-remarks are to be drawn by the present study:

All thermal insulating materials presented vulnerability when exposed to UV radiation with simultaneous hydrothermal stress, and this was evident in the reduction of their compressive strength, loss in their mass as well as the increase of the thermal conductivity factor «λ».

Cycles of Freeze-Thaw stress tests affect mainly the mechanical properties of thermal insulating materials.

ETICS with cement coating failed the Freeze-Thaw cycles test and displayed general structural failure.

The compressive strength of thermal insulating materials appears reinforced after their exposure to salt spray tests.

As a result of the aforementioned remarks we can draw some more general conclusions, a number of which can be of practical usage. The UV radiation impact on the exposed thermal insulating materials and the ageing-declining of their properties (increase of thermal conductivity, reduction of compressive strength and loss in mass) lead us to the following proposals:

During storage of materials, especially if this is needed for a long period, a place that ensures protection from sunlight should be selected. It would be useful to define relative specifications/standards for the whole distribution network of thermal insulating products. The use of suitable packaging material that protects the thermal insulating material from UV radiation (e.g. foil reflecting film) could be a good solution during its transport and its short term storage by suppliers with no appropriate storage facilities available.

Care should be taken during construction for the protection of thermal insulating materials which remain exposed for long time intervals. This can be achieved by means of covering the buildings' façade, especially when long intermissions of works are necessary. In addition, a construction method that could solve the problem would be the use of ETICS when the construction of the building in stages has been planned and as a result thermal insulating materials would be left exposed for a long time. A typical example is the case of incomplete buildings after the stage of the construction of their load-bearing structure which is made of reinforced concrete and the attached panels of thermal insulating materials are left exposed and unprotected for many years in a row. Maybe the adoption of some kind of time limitations in this case would be a step in the right direction.

ETICS exposure to UV radiation calls for further study since, even though no failure was observed, still there were some minor faults. It would be interesting, especially for construction purposes in earthquake-prone countries like Greece, to conduct thorough research in ETICS exposure to earthquakes after UV radiation (of course by means of a broader range of specimens).

Regarding ETICS after tests that were conducted within the framework of the present research, the following are proposed:

The use of final cement coating is not recommended in regions where significant temperature variations are noted and especially in regions with low temperatures because it does not display the durability required in such conditions.

The categorisation of ETICS products-systems and the indication of the conditions under which their use is suitable (obviously after relevant tests and certifications have been conducted) are proposed. The identification of products eligible to be used in ETICS according to ETAG 004 on the basis of Pass/Fail criteria, in some cases may prove unsatisfactory. In addition, in other cases it may cause unreasonably high cost because it may require properties which are not necessary in the region of a specific building construction. For instance, the use of the aforementioned cement coating would be an appropriate and cost-efficient solution in a seaside area where extremely low temperatures are never noted.

Eventually, the impact of Salt spray test appears to be beneficial for the compressive strength of thermal insulating materials by reinforcing the structural grid of polymers by means of the formation/deposit of crystalline structures and this maybe can be utilized in some ways. On the contrary, the retention of salts in the mass of thermal insulating materials and their consequent lock-in after their coating can prove damaging both for the coating layer and the load-bearing structure. Therefore, the protection of thermal insulating materials, both during storage and construction in seaside areas, is considered as absolutely essential.

However, regarding the increase of compressive strength which was observed after the salt spray test of the thermal insulating materials by means of the supposed incorporation of salts in their mass, we have to observe, that, if it is further confirmed, it could be applied in an extensive range of instances of use regarding products like: EPS embankments, EPS geofoam and soil/foundation insulation for the halting of frost ingress.

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