Radiative properties of polymer coatings from the point of view of energy conservation

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Abstract

The importance and contribution of the radiative properties of polymer-based exterior building materials to energy conservation are discussed in this work. The high hemispherical absorptances and the high monochromatic absorptances between 3000–4200 Å wavelengths of all polymers are introduced. We have tried to determine the reason for the high absorptances and examined the possibility of reducing this property. This is especially necessary for buildings in a hot climate which are covered with polymers with high absorptances and need excessive energy for cooling. Magnified surface photographs were taken and atomic compositions of three polymers and one ceramic samples were determined by scanning electron microscopy. The bond types of polymers and the dissociation energy of these bonds were theoretically examined. The results indicate that the high absorptance is a result of the breaking of single bonds especially between C–C, C–O and C–H. In the domain of this study it was impossible to prevent the bond cleavage. Therefore it is advisable to avoid the use of carbon-based polymer exterior coatings in hot climates.

1. Introduction

Investigations to economically maintain thermal comfort in buildings have increased recently. Mathematical expressions modelling the heat transfer through the building envelope have been developed [1–4] and various simulation programs have been produced [5–8]. Also, in some research, the correlation between theoretical values obtained from simulation programs and the values measured at the experimental buildings has been examined [9–11]. In all cases, mathematical models and simulation programs which generally require long computer times, determine the thermal behaviour of the preselected component for the cross-section of a building. The properties of materials are included in these expressions only as a coefficient or as a constant value. The materials selection and the physical properties of materials (specific gravity, specific heat, heat transfer coefficient, absorptance, etc.) have an important effect on the heat transfer

and energy conservation, but they are outside the scope of these investigations. Baleynaud *et al.* are interested somewhat in these subjects, as expressed in ref. 10 in which a new simulation program was explained. However, the material included in their work may be improved.

In refs. 12–15, it was cited that the radiative properties of exterior building materials have an effect on the energy consumed to maintain thermal comfort inside buildings. It was also explained that the amount of energy conservation provided by the selection of materials may vary widely depending on the radiative properties of materials and the solar energy potential of the site [13]. However, the average value of the energy conservation as a result of the rational selection of an exterior coating may be accepted as 30% [10, 13]. This amount is not an insignificant figure nowadays, considering the cost of energy and the increasing environmental problems related to domestic heating during winter months.

The radiative properties of materials, naturally, depend on their inner structure (chemical com-

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position, atomic bonds, crystalline order, energy levels of electrons, etc.). No investigation has been published on the effect of the inner structure of materials on their radiative properties and energy conservation, to the authors' knowledge. In ref. 14, a large difference between the absorptances of ceramic and polymer-based exterior coatings in the UV region (3000–4200 Å) was reported but the reasons for the difference in absorptances have not been given. Also the effect of the difference in absorptances on energy conservation was not examined.

In this work, the effects of the inner structure of carbon-based polymer exterior coatings (polyvinyl acetate and polyacrylate) on the radiative properties are examined. The possibilities of changing the radiative properties with improvements in the inner structure are also determined by experimental and theoretical considerations. The advantages and disadvantages of the radiative properties of polymers in cold and hot climates are explained.

Radiative properties of polymers

The radiative properties of some traditional ceramic (gypsum and lime) and some commercial polymer materials (polyvinyl acetate, polyacrylate and alkyds-oil modified polyesters) produced as exterior coatings are shown in Fig. 1 [14]. The absorptances have been calculated from the re-
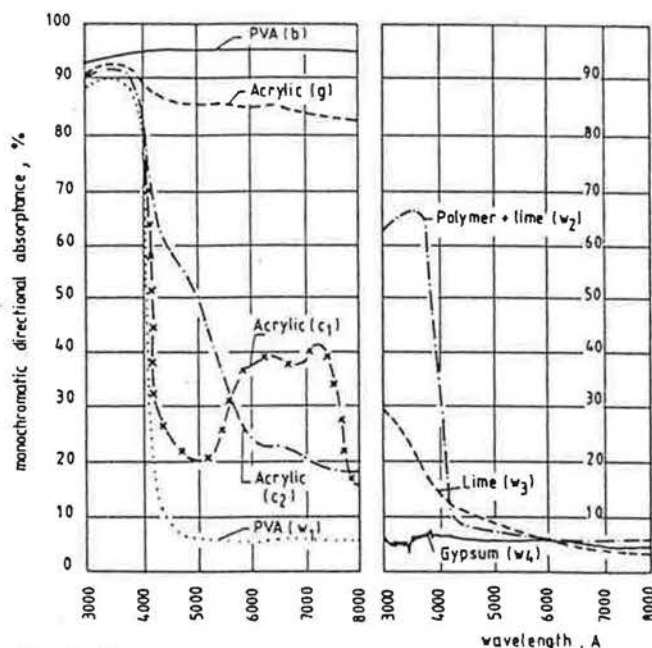
flectances measured by a Perkin-Elmer Lambda 9 and 330 model spectrophotometer with an integrating sphere. The measured wavelengths range from 3000 Å to 8000 Å. From the curves in Fig. 1 it can be seen that the monochromatic absorptances of ceramic surfaces are almost constant between 3000–8000 Å (gypsum ≈ 5%, lime ≈ 10%). On the other hand, the monochromatic absorptances of all polymers between 3000–4200 Å (in UV region) are approximately 0.90 in spite of their different colours, surface properties and chemical compositions, and may differ widely from the absorptances between 4200–8000 Å. The hemispherical absorptances in the solar spectrum (between 3000–30000 Å) of white polymer-based coatings may reach 40% [14].

Experimental procedure

Surface photographs magnified ×100 and ×500 of four commercial-type coatings (polyvinyl acetate, polyacrylate, polyacrylate + lime and pure lime) have been taken by scanning electron miroscopy (SEM). Their colours according to the Munsell Atlas are 0–9.5/0, 17.5–9/4, 0–9/0 and 20–8.5/0.5, respectively.

Atomic composition analysis of the surfaces has been carried out by means of SEM and the program assisting the SEM on the surface photographs of samples magnified ×100. If any heterogeneous region was observed during SEM examination, atomic composition analysis was realized for each heterogeneous region. However, SEM and the program cannot analyse the elements which are lighter than Na. It is obvious that the analysis capacity is satisfactory for the purpose of examining similarities in filler materials of polymer samples.

Results and discussion

The inner structure of the polymers affect the absorptances mainly due to the following reasons:
— atomic order;
— chemical composition of filler materials used to conserve the polymer;
— atomic bonds.

All polymers have high absorptances between wavelengths of 3000–4200 Å, therefore the property which causes this behaviour is expected to prevail for all polymer samples.

The magnified surface photographs taken by SEM to examine the similarities in inner structure are shown in Figs. 2–5. The photograph of a polyvinyl acetate (PVA)-based commercial coating is pre-

Fig. 1. Absorptances of some traditional ceramic and commercial polymer materials; (b) = black, (g) = gray, (w) = white, (c) = colourful.

sented in Fig. 2. A fairly homogeneous and amorphous inner structure is observed as expected. However, on the photographs of a polyacrylate-based commercial coating in Fig. 3, very small crystals are observed throughout the heterogeneous structure. The photographs of another commercial coating consisting of acrylic and lime are shown in Fig. 4. The amount of polymer in this sample is very low. Small crystalloids dispersed in the amorphous phase, which are Ca compounds, are seen on the photographs. In ref. 16, Chandra and Flodin explained this formation by a different crystallization process of $Ca(OH)_2$ in acrylic media. The inner structure of this sample, consisting of polymer and ceramic materials, is fairly complex. In Fig. 5, the photographs of a lime surface are seen. On the surface, the small crystals which are $Ca(OH)_2$ and $CaCO_3$ compounds are observed.

There is not any similarity in the atomic order (crystal order) of polymer samples: PVA has an amorphous structure while the others may have crystalline and amorphous structures together.

The atomic compositions of tested samples are given in Table 1. It is understood that Ca, Si and Ti with atomic ratios more that 10% are the filler materials in PVA. In the polyacrylic sample, Na and Cl locally have high ratios besides Ca, Si and Ti. In the sample consisting of acrylic and lime, only Ca has a high ratio, while the others generally have a ratio less than 5%. According to these results, only the ratio of Ca is similar between the filler materials of tested polymer samples. The high absorptances of polymers between wavelengths of 3000–4200 Å cannot be explained by the Ca compounds, because this behaviour does not exist in the lime sample which consisted of pure Ca compounds.
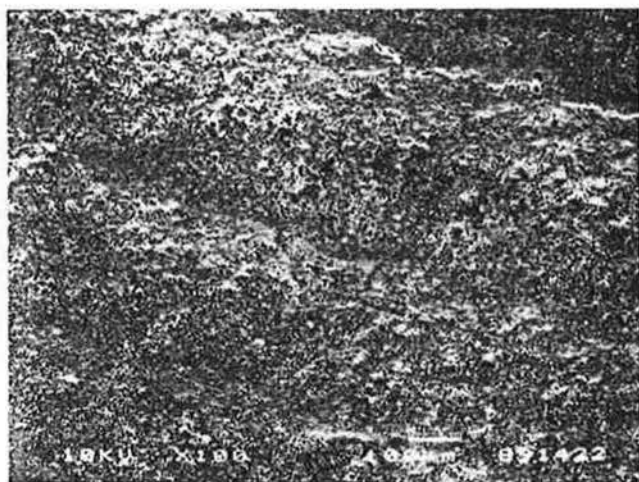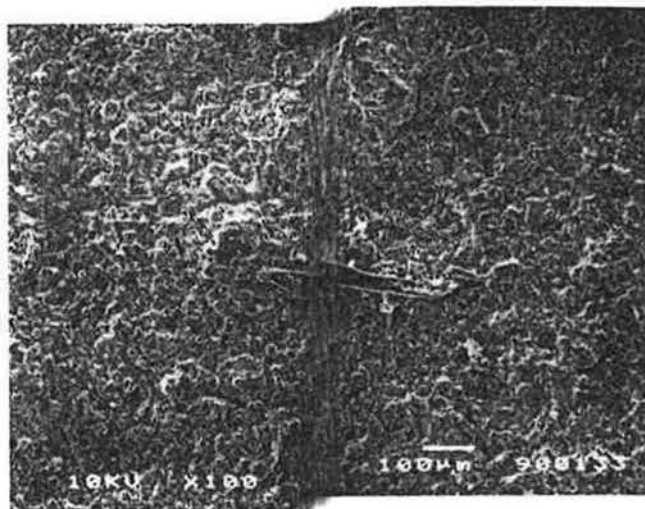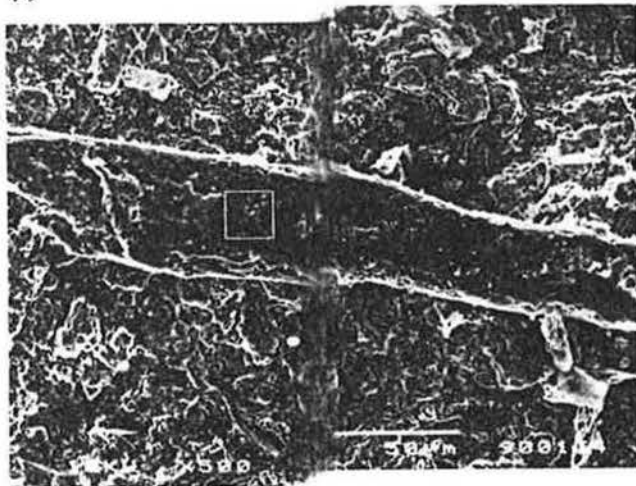

Fig. 2. Surface photograph of polyvinyl acetate-based exterior coating.


(a)

(b)

Fig. 3. Surface photographs of polyvinyl acrylate-based exterior coating.

Consequently, it is understood that the filler materials added to polymers or atomic compositions of samples cannot cause polymers to have high absorptances in the UV region.

Finally, we explored the effect of the atomic bonds existing in polymers on the absorptances. The chemical composition of tested polymers are as follows [17]:
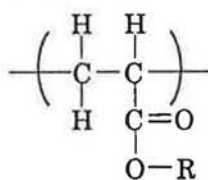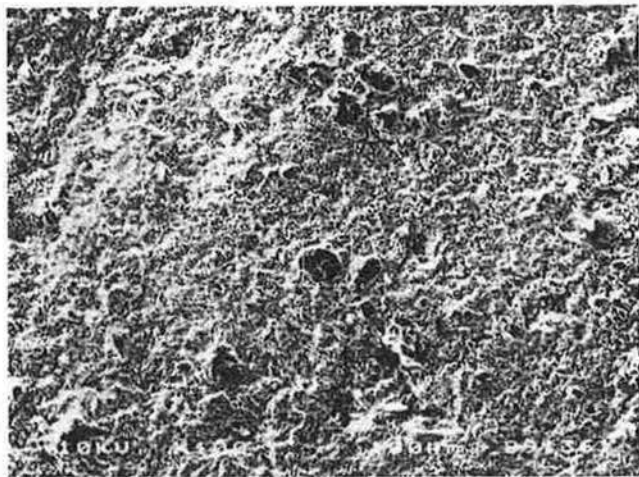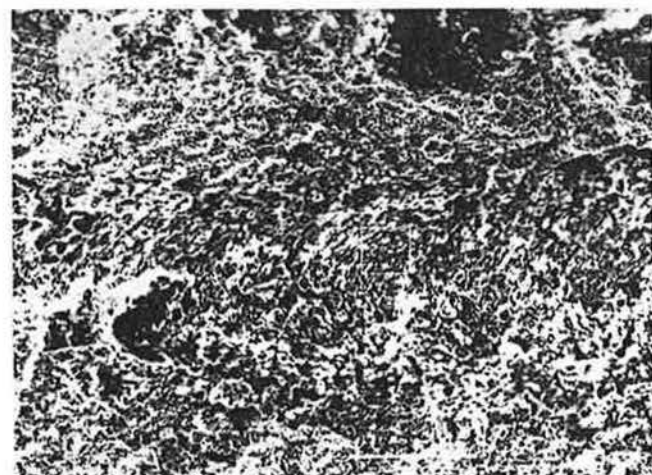

Acrylate
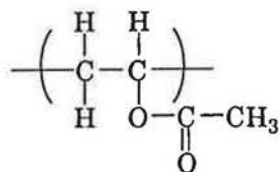
Vinyl acetate

The dissociation energies of these bonds and equivalent wavelengths are given in Table 2 [18,
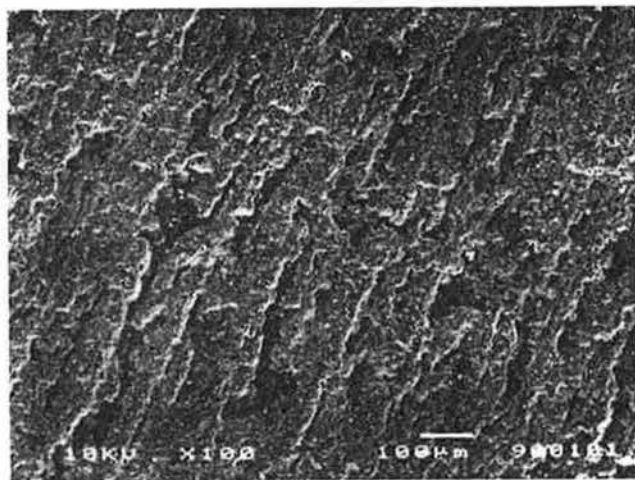
(a)

(a)

(b)

(b)
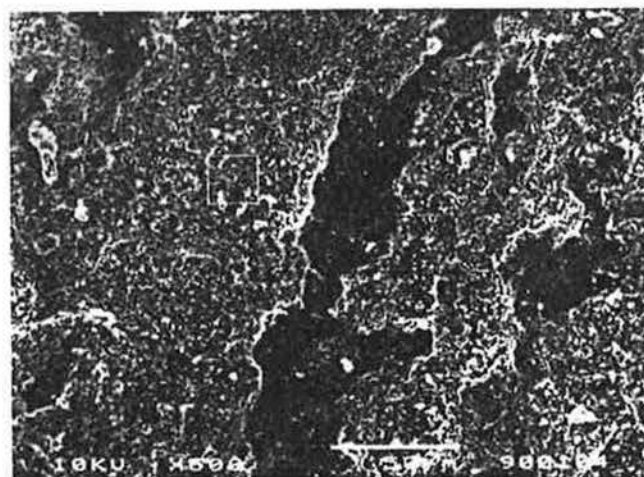
Fig. 4. Surface photographs of exterior coatings which consisted of acrylic and lime.

Fig. 5. Surface photographs of lime.

19]. According to Table 2, breaking any double bond requires energies equivalent to less than 3000 Å. Therefore, the high absorptances between 3000–42000 Å cannot be explained by the breaking of double bonds. On the other hand, energies between 3000–42000 Å break single bonds between carbon and other elements (Table 2). Owing to this phenomenon, the breaking of single bonds between C−C, C−O, C−H, C−Cl, C−N, etc., causes polymers to have high absorptances between 3000–4200 Å.

It is impossible to produce carbon-based polymers without the single bonds between C−C, C−O and C−H. Therefore, the high absorptances of polymers in the UV region cannot be reduced to any level which will be suitable for hot climates, by available techniques used in the production process. However, the amount of polymer in the coating affects the behaviour of the surface between 3000–4200 Å. If the amount of polymer is small, the absorptances of the surface in the UV region will still increase, but not reach 90% as observed on the curve of the polymer + lime (w_2) surface in Fig. 1.

In any case, building scientists should take the high absorptances of polymers into consideration, even if their colours are white, when using carbon-based polymer exterior coatings.

The high absorptances of all polymers cause polymer-based exterior coatings to have high surface temperatures. An increase of 0.05 in the hemispherical absorptance will cause an increase of 1 °C in the surface temperature when the surface is exposed to solar energy of 400 kcal/m^2h which is the approximate value representative of spring months in temperate climates [13]. Of course, an increase of 0.50 in the hemispherical absorptances will cause an increase of 10 °C in the surface temperature.

TABLE 1. Atomic compositions of samples

Samples	Atomic composition (%)										
	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe
PVA*	–	–	4.6	19.6	0.8	2.1	–	2.6	55.3	14.9	–
Acrylic-based	1.6	1.0	3.8	14.2	–	1.1	0.9	1.5	55.7	17.1	5.2
samples	15.1	4.5	4.0	7.9	–	8.4	20.1	1.6	29.7	5.6	3.0
	7.1	2.9	6.9	17.3	–	3.4	8.2	1.3	34.4	14.9	3.6
Lime	–	2.8	–	0.5	–	2.0	–	–	94.8	–	–
	–	4.3	–	0.3	–	2.4	–	–	90.0	–	3.0
Lime +	–	1.0	1.1	1.9	–	2.5	–	–	90.4	2.2	0.9
acrylics	–	5.9	3.0	7.6	–	4.2	–	–	75.9	1.7	1.6

*Only one point analysis is given for PVA because its surface is fairly homogeneous.

TABLE 2. Dissociation energies and the wavelengths

Bond	Dissociation energy* (kJ/mol)		Wavelength (Å)	
	[18]	[19]	[18]	[19]
C–C	347	370	3424	3211
C=C	–	680	–	1747
C–H	398	435	2985	2731
C–O	444	360	2676	3300
C=O	–	535	–	2221
C–Cl	327	340	3633	3494
C–N	343	–	3464	–
C–F	389	–	3054	–

*The values vary with the type of neighbouring bonds. For example, methane (CH_4) has 435 kJ/mol for its C–H bond: however C–H bond energy is about 5% less than this value in CH_3Cl and 15% less in $CHCl_3$ [18].

High surface temperature is useful in cold climates and during heating mode, because this causes lower heat transfer from inside to outside. When the surface with 0.20 hemispherical absorptance is taken as the reference surface, an increase of 1 °C in surface temperature will provide a 10% energy conservation in comparison with the reference surface, when the inside–outside temperature difference is 10 °C. En-

ergy conservation will be 100% if the surface temperature is 10 °C higher than the temperature of the reference surface [13]. In ref. 10, the sunlit side of the wall separating the center room from the sunspace was examined in the experimental dwelling with sunspace. The absorptances of the sunlit side range from 0.1 to 0.9 and thus, in this range, conservation of the energy consumed by a convector used to maintain thermal comfort in the centre room is 30%.

On the other hand, exterior coatings which have high surface temperatures are not desirable in hot climates and during cooling mode, because such buildings need more cooling energy because of the high temperature of their external surfaces. The difference, depending on the hemispherical absorptances, between the surface and the ambient temperature and the energy conservation percentages in comparison with the reference surface are given in Table 3 for some ceramic and polymer surfaces in a hot climate. Surface temperatures are calculated by the well-known sol-air temperature formula. In this formula, the amount of solar energy (I) and external film coefficient (α_e) are taken as 600 kcal/m²h and 20 kcal/m²h, respectively. The outside–inside temperature difference ($T_{os} - T_{is}$) is also taken as 15 °C. According to Table 3, any

TABLE 3. The comparison of white surfaces of different bases

Coating materials	Hemispherical absorptances	Difference between the surface and ambient temp. (°C)	Required energy for cooling* (%)	Energy conservation (%)
Gypsum (ceramic)	0.05	1.5	0.30R	70
Lime (ceramic)	0.10	3.0	0.40R	60
Polymer	0.40	12.0	Ref. value R	0

*This column is calculated by using the formula q_r/q_{gypsum} and q_r/q_{lime}; q is the energy consumption per area [13].

building covered with a polymer-based white coating will heat up more than one covered with a ceramic-based white coating, even if other properties are compatible with the air-conditioning requirements. The amount of energy used to cool a building which is covered with polymer-based materials will be 2.5–3.5 times greater than the amount needed to cool one which is covered with ceramic-based materials.

Conclusions

The effects of the radiative properties of exterior coating materials on the heat transfer and energy conservation are worthy of further investigation. Indeed, the behaviour of carbon-based polymer coatings are extremely interesting. All carbon-based polymers have 90% absorptances between wavelengths of 3000–4200 Å and thus hemispherical absorptances are also high. The principal reason for this behaviour is the existence of single bonds between $C-C$, $C-O$ and $C-H$. The reduction of high absorptances of this material is not possible since carbon-based polymers without $C-C$, $C-O$ and $C-H$ cannot be produced.

The external surface temperature of the building covered with polymers with high absorptances is also high. Therefore, architects working in hot climates should be careful when using polymer-based or polymer-added exterior coatings. This is because the building with polymer-based exterior coatings is heated more compared to one with the ceramic-based exterior coatings: therefore, more energy is needed to cool it. For this reason, architects should avoid the use of carbon-based exterior coatings in hot climates, even if their colours are white. There is no problem in cold climates; just the contrary, it is more suitable to use polymer-based exterior coatings instead of ceramic-based exterior coatings from the point of view of heat transfer and energy conservation.

Acknowledgement

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