The Solar-Reflective Characterization of Building Materials

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Abstract. The here presented data, referring to the basic publication [25], could be useful for practical applications at building materials. Thereby, the governing factor is the albedo or the related values, respectively. Moreover, a mainly proposed determination method guarantees precise and well defined values of the solar absorption coefficient, due to its direct measuring of the thermal behaviour of sample plates, while an alternative method is delivering less accurate but easier determinable albedo values. Based on this knowledge, some practical measures are proposed.

1. Introduction

In the context of the current climate discussion, local *microclimates* and the phenomenon of the so called *urban heat islands* represent considerable topics implying real chances for improving the microclimatic conditions by artificial measures. Such measures affect pavements, fronts and – in particular – roofs, being customarily called »cool roofs«. Hitherto, some appropriate efforts have already been made, mainly in the USA and in Canada, or are provided in future [1].

Luke Howard [2] was the first to provide evidence that air temperatures are often higher in the city of London than in its surrounding countryside. But only after the Second World War, this issue was taken up [3], while a series of investigations followed sampling the temperature distributions of many cities, and considering different influences such as surface geometry, wind convection and water transfer. For being able more precisely explaining the surface boundary effects due to solar radiation particularly in cities, several mathematic models have been proposed, in recent times e.g. by Mills [4], Grimmond and Oke [5], Masson [6], Kusaka et al. [7], and Erell and Williamson [8]. A review about the application of urban climate research in the design of cities is given by Erell [9]. Besides these general aspects, the special situation in different cities has been described, e.g. in Hong Kong (China) [10], Malmö (Sweden) [11], Reykjavík (Iceland) [12], Singapore [13,14], Trento (Italy) [15], Utrecht (Netherlands) [16] and St. Louis (USA) [17,18].

But in spite of all these various and complex considerations, it shouldn't be forgotten that the governing influence for any microclimate – and generally for any climate modelling - is due to the *surface colouring* whereby bright colours engender a minor warming-up in the presence of sunlight than dark ones. For describing this effect, the term »albedo« has been widely used so far. It is derived from Latin meaning »whiteness«, and was introduced by Johann Heinrich Lambert in his 1760 work »Photometria«, being commonly assumed as the colour-dependent *solar reflection coefficient*, normally indicated by *α*, concerning solar light and expressing the intensity-ratio of light being reflected by a surface compared to the incident light. A high albedo of a material surface – particularly of a roof - means that a large amount of the solar irradiance energy is reflected back to the surrounding atmosphere and, finally, to the Space, while only a low amount of the solar radiation energy is absorbed by the surface material leading to an only low enhancement of its temperature. However, the often used term »cool roof« is insofar misleading as it suggests a cooling-down effect, but indeed solely the warming-up of the roof is reduced. As a consequence, a high albedo of building materials, particularly of roofs, generally leads not alone to lower surrounding temperatures but also, at least when the isolation is insufficient, to lower indoor temperatures thus improving the comfort. Moreover, an individual benefit due to the reduction of air-conditioning costs may be ensured, as has been revealed in [19,20]. Some criteria for such materials have been recommended in [21,22,23,24].

Merely regarding the above cited work, the knowledge about this topic seems to be complete enough sparing further investigations. However, within the recent study [25] some inherent uncertainties and imprecisions have been revealed being worth to be emphasized. Hence, the intention of the present paper is briefly outlining the results of that basic study, focussing the requirements for building materials, and adding some special information.

2. Questioning Items and Alternative Approaches

According to [25], the following items are critically discussed, leading to the suggestions of alternative approaches:

- the desirable distinction between the terms »albedo« and »solar reflection coefficient«;
- the inaccuracy of the usual determination method for the solar reflection coefficient;
- the outline of an alternative method A by determining the solar absorption coefficient;
- the separate study of the cooling-down rates of warmed plates in a dark room; and
- the outline of an additional method B for determining the albedo.

The detailed descriptions of the methods are given in the next chapter. Therein, the mathematical analysis methods for the results are only described for the simplest case, while the complete formulations are elucidated in [25].

The desirable distinction between the terms »albedo« and »solar reflection coefficient«. With the definition of the term »albedo« some ambiguities arise, for, strictly speaking and regarding its true meaning, the albedo value should not be an absolute one but a relative one, namely being related to a white surface. However, in the former literature such a distinction is not made. Rather, the terms »albedo« and »solar reflection coefficient« are used as synonyms. Moreover, one finds the further apparent synonyms »spectral reflectance«, »optical reflection«, »reflection of direct radiation« and »reflectivity«. Since, as will be explained below in detail, the empiric determination of the albedo allows applying an easier method than that one which is necessary for determining the solar reflection coefficient, herewith a distinction of the two terms is suggested, using the abbreviations a_s for the albedo and α_s for the solar reflection coefficient.

The inaccuracy of the usual determination method for the solar reflection coefficient. When solar light comes upon the surface of a solid body, a part of it will be absorbed by the body leading to a gradual warming-up of the body, while the residual part of the light will be reflected but exhibiting another colouration and thus being transformed. The ratio of the radiant power of the incident light and the reflected light, given in Wm^{-2}, defines the solar reflection coefficient. As a result of this transformation, the light does not only change its colouring but also its character in such a way that its intensity gets dependent on the distance to the surface, as it is the case for scattered light. Hence, this kind of reflection is not the same as the reflection which occurs at the surface of a mirror. As would seem natural, the solar reflection coefficient is usually determined by measuring the intensity of the reflected light, compared to the simultaneously measured intensity of the incident light, the two measuring instruments (»pyranometers«) being aligned diametrically. For avoiding an interference with the thermal radiation of the irradiated body, the instrument being used for measuring the reflected light must not be sensible for that kind of radiation (wavelength-range 280-2800 nm). This method is described in the ASTM Standard E1918-06, and it is usually applied in »albedometers«. However, the measurement of the intensity of the reflected light is problematic because of its above mentioned distance dependency, so the accuracy of this method must be queried.

The outline of an alternative method A by determining the solar absorption coefficient. Within the present approach, not the reflected but the *absorbed radiation* is determined (or the »solar absorption coefficient« $\beta_{s,}$ respectively), namely by measuring the temperature courses of coloured quadratic plates (10 x 10 x 2 cm^3) with a known thermal specification when sunlight of a known intensity comes vertically onto these plates. They are embedded in Styrofoam, covered with a thin transparent foil acting as an outer window to minimize erratic cooling by atmospheric turbulence, and equipped with centrally positioned Hg-thermometers. Thereby, the colorations as well as the plate material may be varied. As a preferred reference material, aluminium is used being optimal due to its high heat-conductivity and high heat-capacity leading to a low heating rate and a homogeneous heat distribution. For enabling a correct orientation, the plate modules are positioned on an adjustable carrier (Fig. 1). During the warming-up time of preferably 30 minutes, the equilibrium temperature is normally not reached, but the heating-rate can easily be determined by graphically assessing the initial slope of the time-temperature curve. For being able to calculate the heat energy being absorbed by the plate, its thermal admittance (i.e. its area-specific heat-capacity) must be known. It may be taken from literature, or must be determined by a calorimeter. For determining the intensity of the sunlight, an appropriate commercially available electronic instrument may be used (»pyrheliometer«). Finally, the solar reflection coefficient may be simply calculated by the equation $\alpha_s = 1 - \beta_s$. Moreover, the albedo for a certain colour may be calculated by determining the ratio of the solar absorption coefficient of that colour and the solar absorption coefficient of a white surface.

But there is a further reason for using this method: Any climate modelling doesn't mainly operate with the solar reflection coefficient but actually with the solar absorption coefficient, assuming that $\beta_s = 1 - \alpha_s$, since the energy absorption of the Earth surface is primarily relevant to the energy budget, and not the reflected energy. So, by the conventional method, a calculated value is inserted given by the reflection coefficient, and not a directly measured one as it is the case with this method However, the disadvantage of this method is the requirement of samples which match the real conditions.

The separate study of the cooling-down rates of warmed plates in a dark room. The longer the shining on endures, the warmer becomes the irradiated plate. However, since a warmed material emits heat to the surrounding insofar its temperature is rising, the warming-up process, owing to the irradiation, is interfered by a simultaneous cooling-down process until a limiting temperature is reached where both rates are equal. For studying the cooling-down behaviour, separate measurements have been made with preheated plates in a darkened room. Thereby, the measurements being reported in [25] yielded that the cooling-down rate is independent of the surface-colour but – of course – dependent on the thermal admittance of the plate. If certain boundary conditions are fulfilled (constant atmospheric temperature, and relatively thin plates with a high thermal conductivity), the cooling-down process can be exactly expressed by a mathematical equation. Moreover, a stringent arithmetic combination of the warming-up and the cooling-down process was found allowing to model the temporal energy transfer occurring between a solid surface layer and the contiguous air, and thus to study the influence of the colour and of the thermal admittance of the plate. Since the cooling-down behavior is independent of the surface coloring, there is no need to carry out such measurements each time – except for confirming the results.

The outline of an additional method B for determining the albedo. The caloric method A permits a quite exact determination of the relevant key values, as well as a mathematic description of the basic processes. However, it requires an accurate preparation of well-defined samples of the relevant material and the availability of the convenient equipment, being thus not suitable for field-measurements. Therefore, additionally an easy device is proposed exhibiting both requirements. However, instead of the pyranometer for measuring the reflected radiation operating in the range of 280-2800 nm as being recommended in the quoted ASTM Standard E1918-06, a normal *light-meter* is used, operating in the visible light range and being customary for photography and delivering the measured values in lux. Naturally, that would solely allow the determination of *relative albedo-values,* i.e. being related to a white surface, but they may be compared with the albedo-values which have been evaluated by the caloric method. Since only the visible light is affected, temperature and wind are irrelevant. However, the measurements must always be made from the same position while the solar irradiance must be constant, which may be checked by a »pyrheliometer«. Nevertheless, the precision of this method may not be high, the more so a mirror-like reflection may occur. Fig. 18 shows an appropriate assembly for an albedo-measurement by a light-meter, using a white plastic-coated wooden board (60 x 70 cm) which has been painted with the respective colour. For this comparison, exactly the same colours were applied as for the previous experiments using method A. For being able to adjust the board perpendicularly to the solar radiation by regarding the shadow, a small coloured bar (from aluminium) is attached near the bottom edge of the board. The inclination angle of the board depends on the time of the year and of the day, and was in this case about 25°. For avoiding the interference by its shadow, the light-meter has to be positioned laterally.

3. Results and their Discussion

The greater part of the results concern method A, as being outlined above and shown in fig. 1. The detailed description of the apparatus, alike the mathematical analysis, is given in [25]. The warming-up experiments were carried out using small coloured quadratic plates (10 x 10 cm^{-2} and about 20 mm thick) from different materials (aluminium, wood, brick and stone) when sunlight of a known intensity (approx. 1000 Wm^{-2}) was coming perpendicularly onto these plates. As already mentioned, the cooling-down turned out being independent of the surface colour, thus for the relevant experiments – being separately carried out in a dark room -, only the plate material had to be changed, but not the colour. For studying the influence of the surrounding atmosphere, some additional measurements have been made in the absence of covering thin foil.

Aluminium (subsequent abbreviation: al) was used as a basic reference material. Moreover, the behaviour of spruce-wood (wo), brick (br) and stone (st) was studied. The wood plates were slightly thinner than the aluminium plates (17.5 mm instead of 20 mm). The brick-plates were sawed out from fresh red brick-pieces (being not weathered), being considerably thinner than the alumiunium plates (only 14.5 mm thick); and the (single) stone-plate (st) was also sawed out from a natural granite boulder found in the Swiss Alps. The mass variance of the plates within a measurement series was minimal.

The following colours have been applied (being not specified more precisely):

white (wh)	bright brown (lb)	vanilla (va)	bright blue (bl)
bright green (gr)	brick-red (re)	dark brown (db)	black (bk)

As it is obvious from the time-temperature-diagrams in the figures 3 and 4, for one thing, the warming-up rates significantly depend on the colouring of the plates, and, for the other thing, the rates are generally larger in the case of wood than in the case of aluminium. This phenomenon may easily been explained by the lower heat-capacity of wood compared to that one of aluminium. However, as the detailed evaluation yields, the warming-up rates of wood is somewhat smaller as it would be expected due to its heat-capacity. This may be explained by its reduced heat-conductivity diminishing the heat distribution within the plate, probably leading to an enhanced surface temperature (being not identical with the measured temperature). Finally, in particular considering the cases for dark brown and black coloured wood, the warming-up curves are not strictly linear, that which is a consequence of the release of heat by radiative emission.

The time-temperature-diagrams in the figures 5 and 6 compare the behavior of similarly colored aluminium- and brick-plates. They are computationally derived from measured data using a mathematical model, given in [25], revealing the reaching of limiting temperatures after a certain period. Due to their lower heat capacity, the warming-up rates of the brick plates are larger than these of the aluminium plates, as expected. However, it is remarkable that the limiting temperatures are independent of the heat capacity but solely dependent on the surface coloring, besides of additional influences as – in particular – the temperature and the convection of the surrounding atmosphere.

Fig. 7 shows a modelled sequence of a warming-up during 30 minutes, and a cooling-down during 90 minutes, comparing blackened stone and brick. Due to its larger heat capacity, the stone plate warms up more rapidly than the brick plate, but reversely it cools down more rapidly, too.

In Fig. 8 the different herewith determined solar absorption coefficients β_s are compared, while fig. 9 shows the respective albedo values a_s. Since the absorption coefficient for black is 0.85, and that one for white 0.24, the maximally hereby achievable improving factor (being called in [25] »solar color factor«) is approx. 3.5. Moreover, the comparatively high solar absorption coefficient of bright green should be noted, confirming the experience of the ineffectiveness of »green roofs« [1].

Finally, in figure 10 the two methods A and B are compared, exhibiting a satisfying accordance.

For illustrating these data, three further pictures are added. So, in fig. 11 a crude red-brick is compared with a pained one, exhibiting the same bright brown color as it has been applied for the measurements. The comparison of the values of the respective solar absorption coefficients yields a solar color factor of approx. 1.8. When weathered bricks are regarded instead of crude ones, this factor will even be much larger, probably up to 3.

4. Conclusions

In spite of the quite complex conditions prevailing in reality - being also determined by outer parameters such as the location of the object, the seasonal and the diurnal variation of the solar altitude, and the atmospheric conditions implicating clouds, haze, rain, wind etc. -, the here presented correlations and data, referring to the basic publication [25], could be useful for practical applications for building materials. Thereby, the governing factor is the albedo or the related values, respectively, determining the limiting temperature at a constant solar irradiance. The proposed determination method A guarantees obtaining precise and well defined values of the solar absorption coefficient, due to its direct measuring of the thermal behaviour of sample plates, while the alternative method B is delivering less accurate but easier determinable albedo values. The discussed items are not focussed on a particular scope but they are generally relevant, independent of the architectural styles. So it’s a question of a novel philosophy considering the albedo as a significant aspect for buildings, implicating to take the measures being adequate for any situation. However, some general aspects and practical measures may be mentioned here:

- First of all, any surface being exposed to direct solar insolation, particularly at roofs, should be provided as bright as possible (»cool roofs«). However, aesthetic aspects may be regarded, too, allowing individual variations. But for roofs, bright brown or bright grey should be preferred (whereby various shades of colour are feasible) while for fronts even brighter colours are desirable, preferably white, bright grey or bright brown for stony ones, and bright brown (and not dark brown!) for wooden ones. But »green roofs« are - from this point of view - not desirable, as the here presented results confirm.
- Transparent surfaces are heat traps. This concerns windows, as well as glass fronts. While for windows bright shutters should be provided, glass fronts, in particular black ones, are obviously untoward.
- The loveliest buildings are of limited value when they weather shortly. This is also the case for gable roofs which often are neglected. That must definitely change, preferably by protecting them with a varnish. Aged bricks should prior be refined.

Besides these material features, a further factor has to be mentioned even if it shall be hardly controlled in spite of its artificial character: namely the topology of cities, i.e. its skyline and the »macro roughness« of the Earth surface. Thereby, high buildings enlarge the surface leading to an enhanced absorbance of solar radiation.

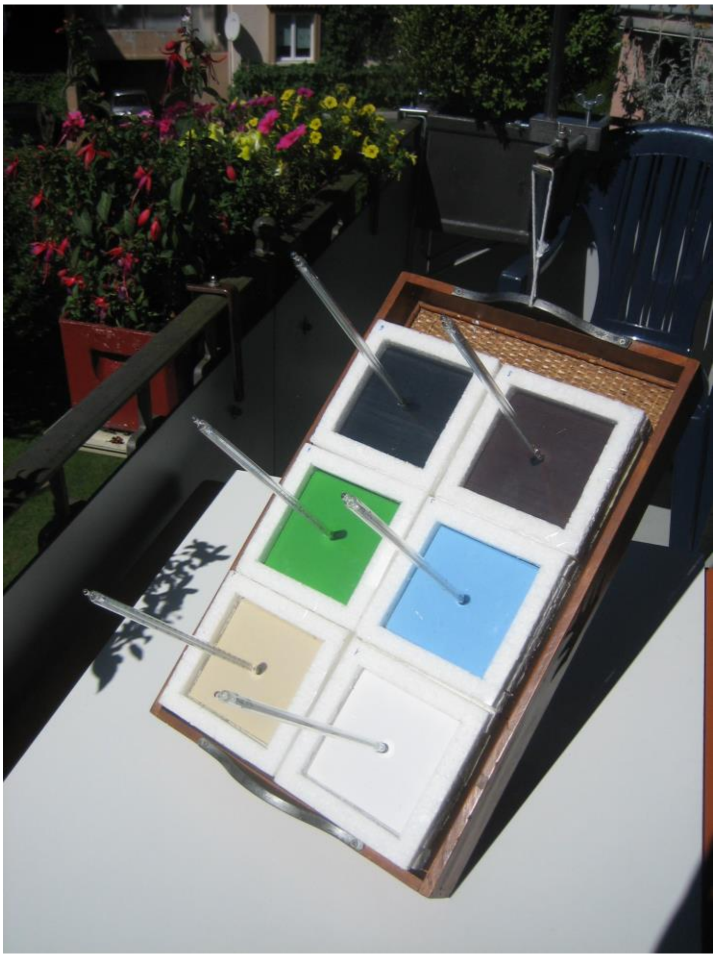

Figure 1: Panel comprising six modules (method A)

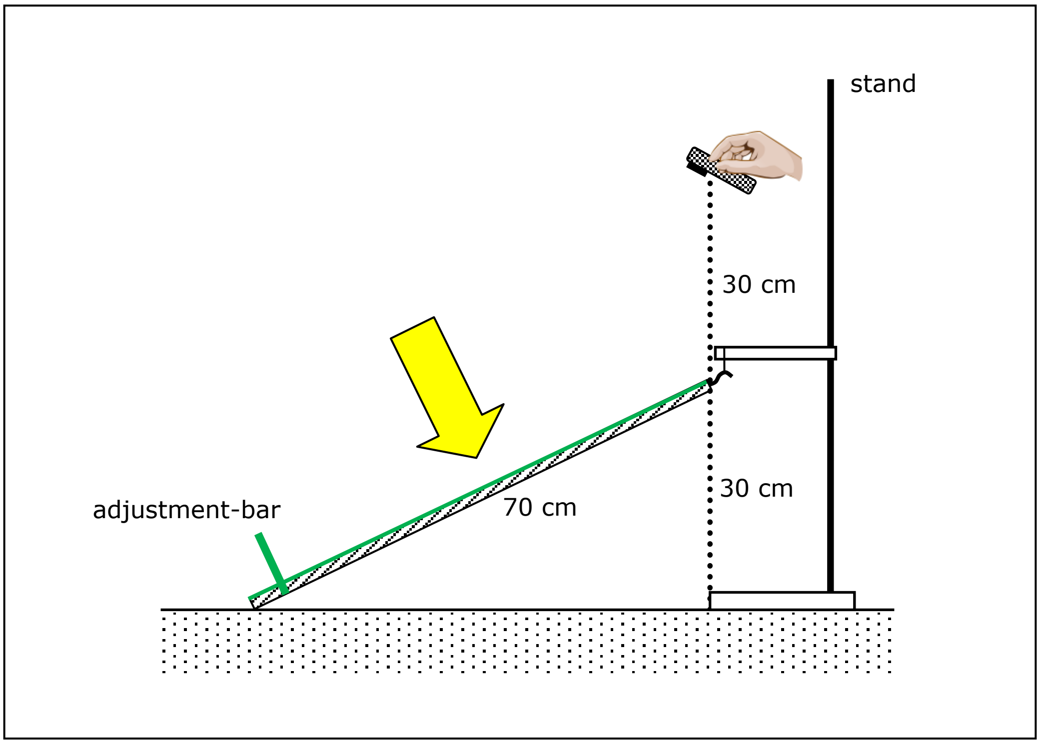

Figure 2: Assembly for the albedo-measurement by a light meter (method B)

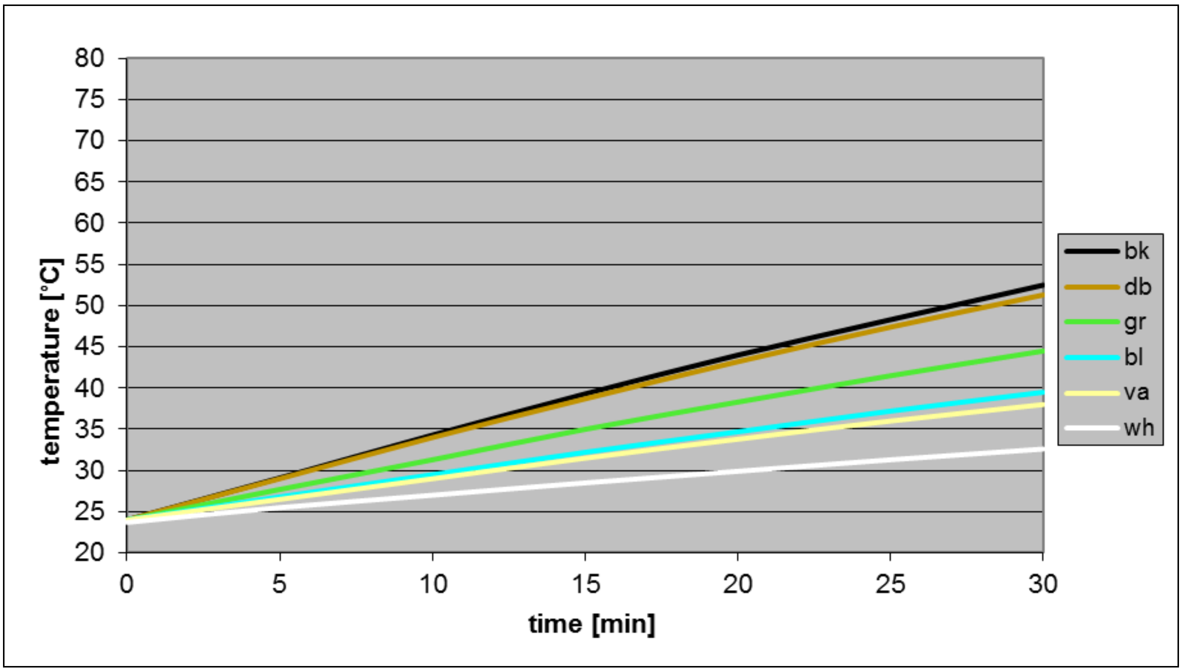

Figure 3: Warming-up of aluminium at 1040 Wm^{-2} (method A).
Initial slopes [°/min]: wh 0.31 / va 0.52 / bl 0.58 / gr 0.77 / db 1.02 / bk 1.08

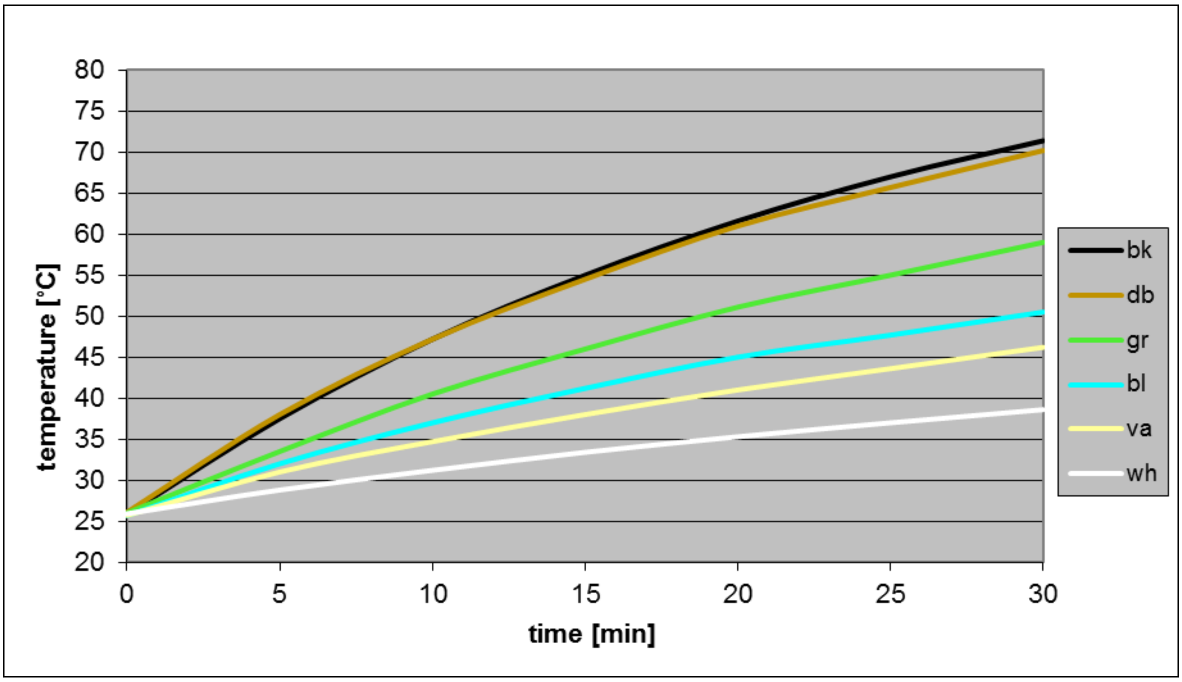

Figure 4: Warming-up of wood at 970 Wm^{-2} (method A).
Initial slopes [°/min]: wh 0.60 / va 1.02 / bl 1.20 / gr 1.57 / db 2.35 / bk 2.45

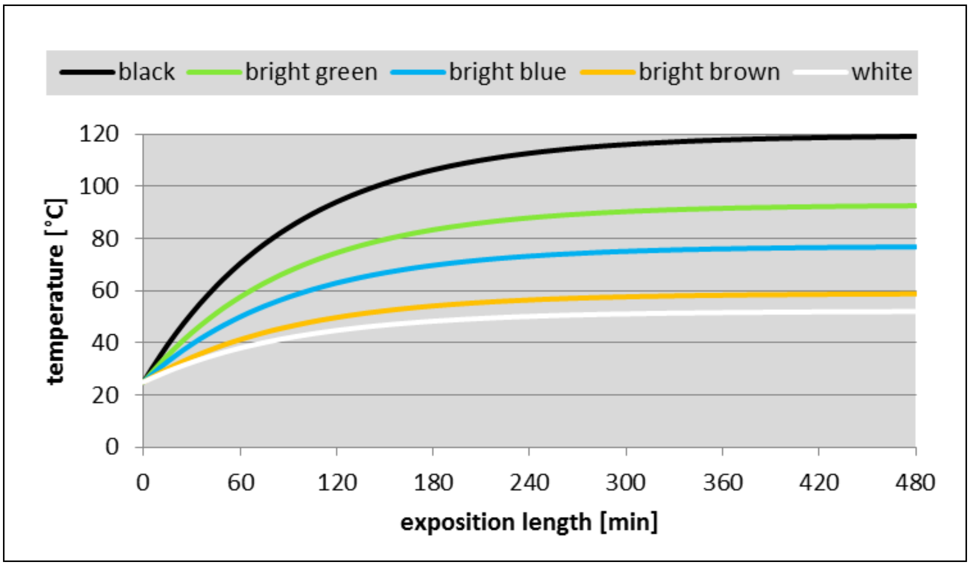

Figure 5: Temperature courses at differently coloured aluminium-plates

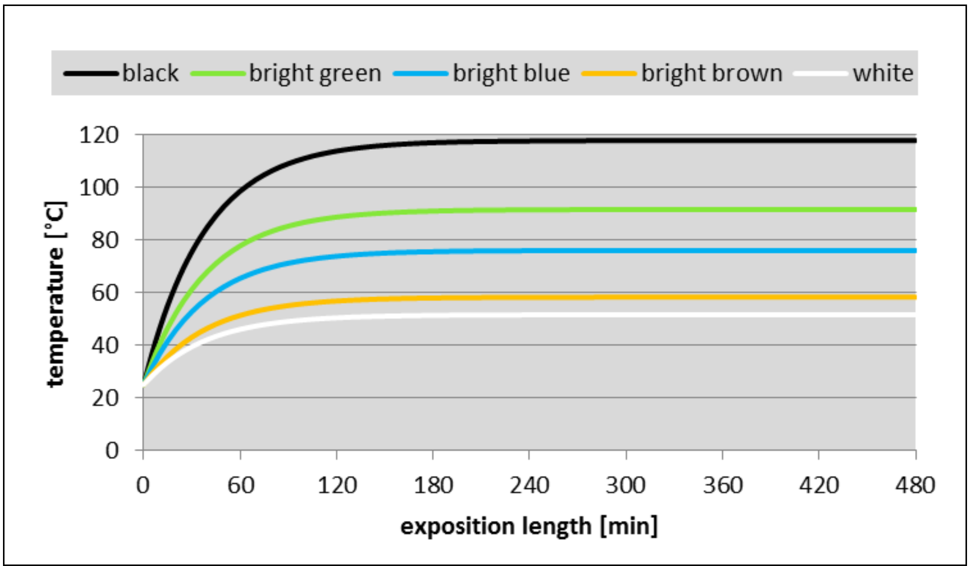

Figure 6: Temperature courses at differently coloured brick-plates

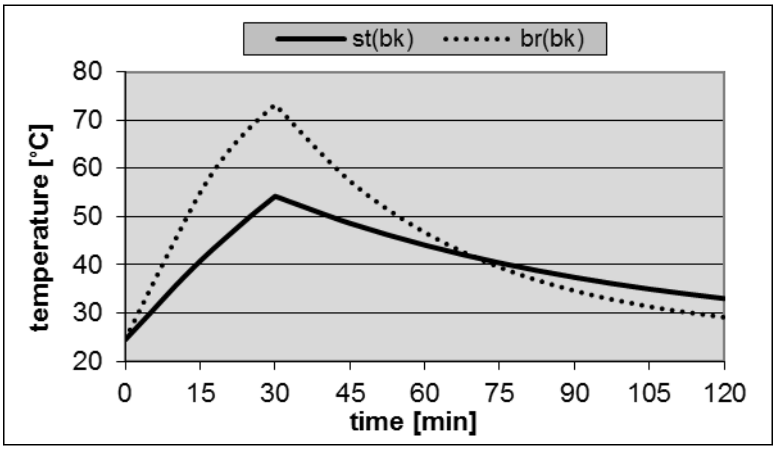

Figure 7: Two-step combination for stone (st) and for brick (br), both bk

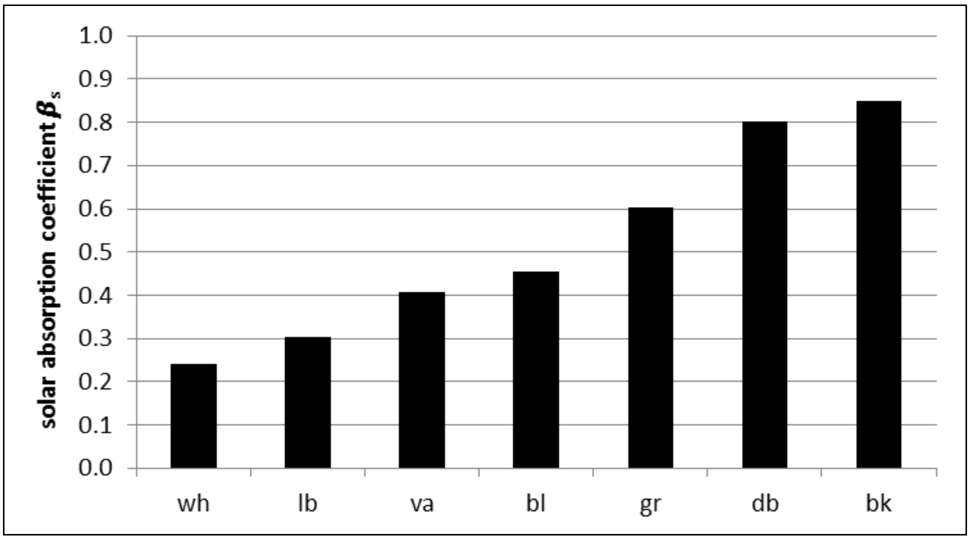

Figure 8: Solar absorption coefficients β_s on aluminium

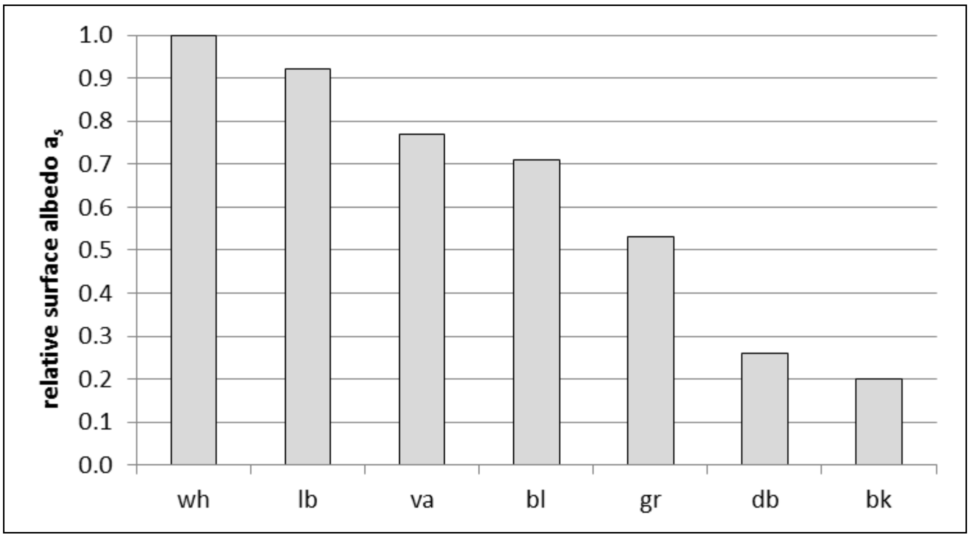

Figure 9: Relative surface albedos a_s on aluminium

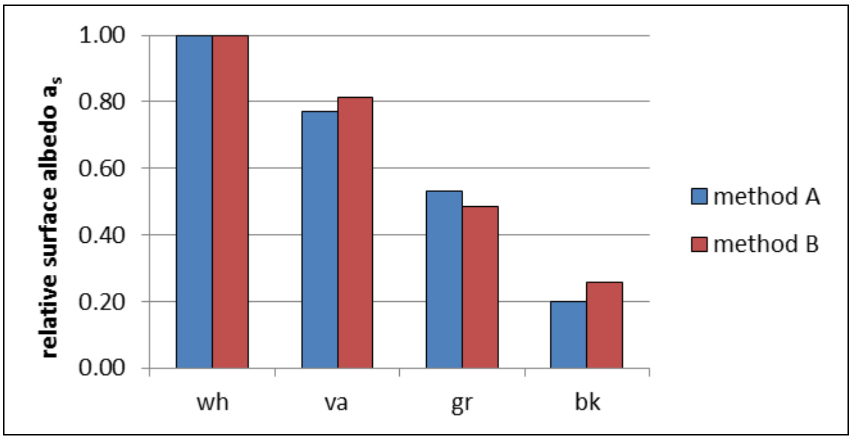

Figure 10: Method-comparison by means of the albedo-values

Figure 11: Crude red-brick (β_s = 0.53; a_s = 0.61) and painted one (bright brown, β_s = 0.30; a_s = 0.92)

Figure 12: Weathered and replaced bricks on a roof

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