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Building Materials for Cities and Climate Change – a Material Catalogue with Recommendations

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Abstract. High urban density with heat accumulating materials and sealed surfaces can cause heat stress and reduced nocturnal cooling in summer. Appropriate building materials may contribute to the mitigation of this effect. The research project evaluates building materials for façades and outer surfaces (ground) on the resulting urban microclimate and on factors like glare, acoustics and embedded energy. The present publication focuses on the impact on the microclimate. The analysis comprises the simulation of forty-seven data sets in a microclimatic model with ENVI-met. The results show that during daytime the PET for the whole neighborhood ranges between 30.1 and 36.4 °C. Choosing a bright instead of a dark color can lower the PET between 0.2 and 1.0 K. Dark colored metal sheets may cause turbulences which lead to a reduction of the PET between 2.0 and 3.8 K (compared to a bright metal sheet). However, this effect may not be reproducible under varying boundary conditions. During night-time, the resulting span of ambient temperatures between the materials reaches 21.4 to 22.0 °C (level 1.7 m). The temperature difference between the materials at the level of 10.7 m (for night ventilation) is found to be approx. 0.3 K and can be considered irrelevant.

1. Aim of research and background

One of the most tangible effects of climate change in everyday life is an increase of instances of strong heat stress in the built urban environment during summer. The use of materials for façades and other outer surfaces, which do not exacerbate the microclimate of urban environments, can be one integral part of a tool box for climate resilient cities. However, the choice of external building skin and other outer surface materials will usually not only address microclimate, but also other aspects such as glare, acoustics, embedded energy and longevity. When assessing materials in an early planning stage, decision makers must have relevant information readily available.

This project addresses this need by providing a material catalogue that assembles data on thermal properties, optical and spectral characteristics, life cycle data and more as well as the effect on the microclimate. Crucial individual parameters themselves can be identified and compiled by a comprehensive literature research. However, the complex multi-scale interaction effects can only be assessed by using sufficiently detailed microclimate models which take into account the urban energy



balance. The present publication addresses the simulations performed for the case study site in an urban neighborhood in Basel (CH, Figure 1).

2. Scientific Methodology

Representative materials used in a contemporary urban environment are selected. The chosen materials cover a wide range as the following numbers illustrate (for abbreviations see Figure 3):

- specific heat: 450 (“W_lc_sandwichpanel”) to 1610 (“W_fal_wood”) $J*(kg*K)^{-1}$
- solar reflectance index (SRI): 3 (“fal_PV_mineral_wool”) to 100 (“W_refl_coating_b”)
- albedo: 0.16 (“fal_PV_mineral_wool”) to 0.81 (“W_refl_coating_b”)

The materials of the outermost layer of the building skin or the ground are assigned to typical construction systems. Because ENVI-met possesses a limitation for construction layers per building element the layers from outside up to the insulation layer are considered relevant. Different coloring of materials is considered by assigning characteristics for light, intermediate and dark colors. This differentiation leads to forty-five data sets. Either the material for the walls or the ground are changed for each case. The albedo for the unmodified material is set to 0.30 for roofs and walls (approximation for roof tiles) and 0.18 for the ground (approximation for weathered asphalt). The change of color due to ageing, soiling or bleaching is not explicitly taken into account. However it can partially be roughly estimated by comparing results from the three “color levels” used.



Source: <https://map.geo.bs.ch>

Figure 1. Location in Basel.

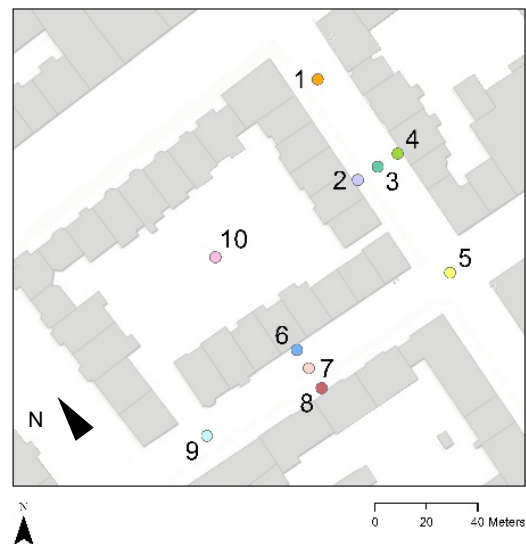


Figure 2. Placement of sensors.

Table 1. Initialization parameters used in ENVI-met for the simulations. hum = humidity

Parameter	Value	Parameter	Value
Initial atmospheric θ	21 °C	Wind speed at 10 m above ground	1.4 m/s
Specific hum. at 2'500 m	7 g water / kg air	Wind direction (°, clockwise from 0:N)	140°
Relative hum. 2 m above ground	50 %	Soil θ / hum. at 0-20, 20-50 and >50 cm	19.9 °C / 75 %
Roughness length z_0 (m)	0.01	θ_i in the buildings	19.9 °C

The simulations are performed with ENVI-met 4.4.5 [1], a software that simulates the dynamic interaction between buildings and soils in an urban environment with the atmosphere. The program calculates a steady state condition with certain initial parameters (Table 1) as a basis for the transient simulation. The urban situation shown in Figure 1 is modeled three-dimensionally, however with flat

roofs and a surrounding albedo of 0.3, representing an urban context. The simulation model cannot take ventilated air layers in construction systems into account. Such air layers are treated like a closed cavity and are given a constant thermal conductance. Ten sensors positioned as proxies for pedestrians at relevant locations are defined and provide vertical profiles (Figure 2). The analyzed heights of the sensors are 1.7 m (height of head) and 10.7 m (level for night ventilation). Weather data from Basel for a heat wave in the first week of August 2018 is used. The microclimate is characterized during daytime by the physiological equivalent temperature (PET) and during nighttime by the ambient temperature (θ_a). PET takes into account all relevant factors on the human thermal comfort, including meteorological parameters (insolation, air temperature, wind and humidity), human behavior and the energy balance of a person (including e.g. sweating). A sequence of three days with high ambient temperatures (whole period: $\theta_{a,max} = 34.8$ °C on the third day at 2 pm, $\theta_{a,min} = 17.5$ °C on the first day at 4 am) and a clear sky is simulated. On the third day, two points in time are analyzed: 2 pm (θ_a 34.8 °C) and 4 am (θ_a 21.2 °C). A PET between 29 °C and 35 °C can be rated as “warm”, causing moderate heat stress, a PET of > 35 °C is rated as “hot” causing strong heat stress [2]. Because the microclimate of the whole neighborhood is of interest, the mean of all ten sensors is analyzed.

3. Results

The analysis comprises 10 data sets for the ground and 35 data sets for walls. The walls are split into five construction types: cavity walls “cw”, plastered insulation walls “pi”, walls with reflective coating “refl_coating”, lightweight construction “lc” and facing with (ventilated) air layer “fal”.

Figure 2 shows the resulting PET at 2 pm. The construction systems for the ground lead to PET values between 33.5 °C and 33.9 °C. The lowest PET stems from the ground material “G_concrete”, the highest PET is caused by “G_grass”. During night-time, the temperature level is lower and the difference is even smaller ($\theta_a = 24.1 - 24.2$ °C). When comparing θ_a at the levels of 1.7 m and 10.7 m above ground only a very small difference caused by the materials is found (0.0 - 0.1 K).

For all wall construction systems the PET at 2 pm ranges between 30.1 (“W_lc_glass_blind_d”) and 36.4 °C (“W_pi_brick_aerogel_d”). During night-time at a height of 1.7 m θ_a ranges between 21.4 °C (“W_lc_glass”) and 22.0 °C (“W_fal_fibre_cement_d”). At 10.7 m the range of θ_a is between 21.5 (“W_lc_glass”) and 21.9 °C (“W_fal_fibre_cement_d”). Looking at the different construction types for the walls the following observations are made:

- There are three subtypes of cavity walls “cw”: Brick walls with air or a core insulation in-between the two layers and a concrete wall with core insulation. Daytime: These constructions reach PET values between 33.1 °C (“W_cw_brick_ci”) and 36.1 °C (“W_cw_concrete_ci”). Night-time: The brick wall with bright surface and air between the both brick layers (“W_cw_brick_air_b”) leads to the lowest θ_a of this group (24.1 °C). The highest θ_a stems from the same wall type with a dark surface. The difference between the wall-types is small at 0.3 K.
- Walls with plastered insulation “pi” fall into four sub-categories: Two brick walls with a cladding of either insulating plaster or aerogel and two concrete walls with mineral wool or EPS insulation. Daytime: The wall causing the highest PET (36.4 °C) in the neighborhood is the brick wall with dark plaster and aerogel (“W_pi_brick_aerogel_d”), the one featuring the lowest PET (34.8 °C) is the concrete wall with bright plaster and EPS insulation (“W_pi_concrete_eps_b”). Night-time: The temperature difference between the wall types is small (0.4 K). The highest θ_a results from “W_pi_concrete_mineral_wool_d”, the lowest from “W_brick_aerogel_b”.
- In the lightweight construction “lc” category, basically two sub-types are investigated: a sandwich panel with different colors and a glass façade with or without a blind. Daytime: Surprisingly, the highest PET at 34.5 °C stems from the bright sandwich panel (“W_lc_sandwichpanel_b”), the lowest PET at 31.0 °C is caused by the dark sandwich panel (“W_lc_sandwichpanel_d”). Night-time: The glass façade has the lowest θ_a (21.4 °C) and the

dark sandwich panel (“W_lc_sandwichpanel_d”) has the highest θ_a (21.8 °C). Thus, the temperature difference at night is 0.4 K.

- Reflective coatings, daytime: The dark reflective color on an uninsulated brick wall (“W_refl_coating_d”) results in a higher PET (33.6 °C) than the bright color (“W_refl_coating_b”, 35.5 °C). Night-time: There is no significant difference between the colors ($\theta_a = 21.7$ °C).
- The wall constructions “facing with air layer” (fal) cover six different types of cladding. Daytime: Generally, they cause a PET in the neighborhood in the range of 31.0 °C (“W_fal_metal_d”) and 35.9 °C (“W_fal_green_wall”). Night-time: The lowest θ_a is found for the PV-façade (“W_fal_PV_mineral_wool”, 21.7 °C). The highest θ_a is caused by fibre-cement cladding (“W_fal_fibre_cement_d”, 22.0 °C). The temperature difference between the constructions at night-time is 0.5 K.

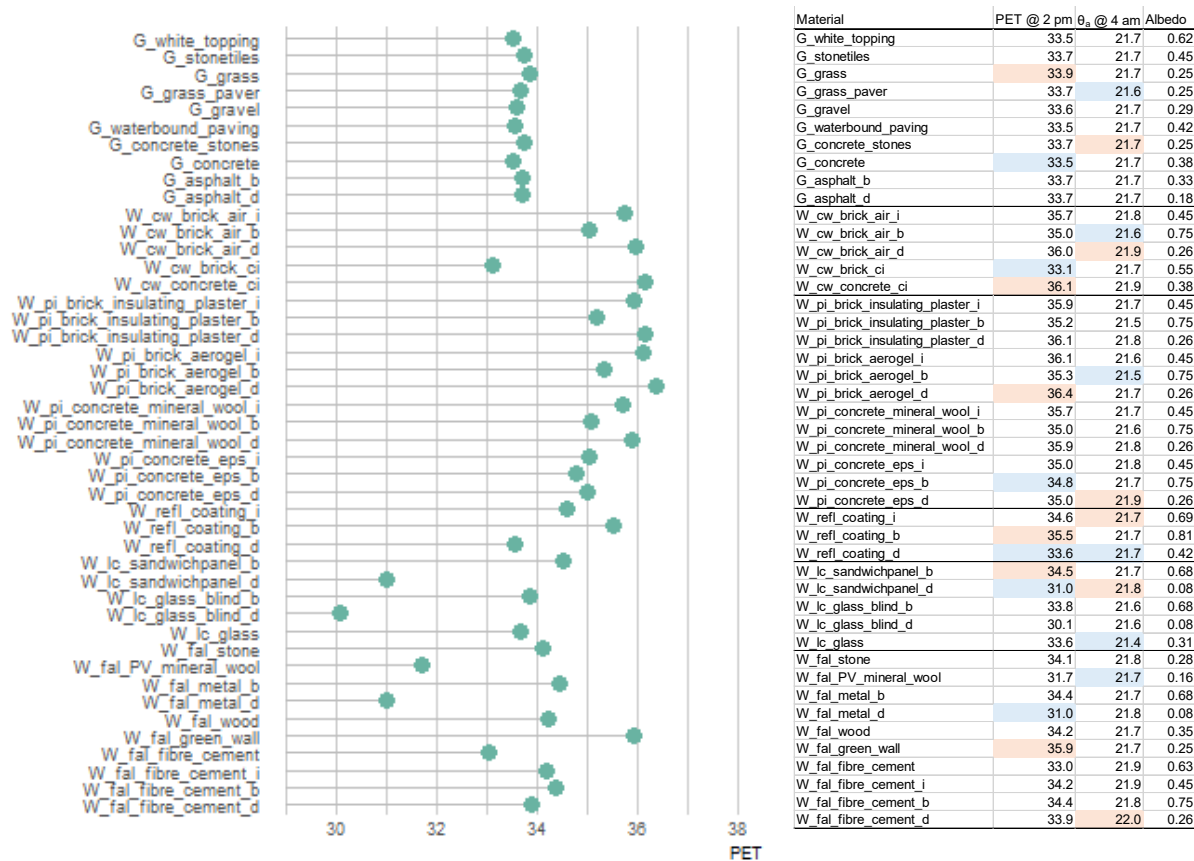


Figure 3. Results for the PET at 2 pm at a height of 1.7 m. Abbreviations: G = ground, W = wall, cw = cavity wall, ci = core insulation, pi = plastered insulation, lc = lightweight construction, fal = facing with air layer, i = intermediate, (α = 0.45), b = bright (α = 0.75), d = dark (α = 0.26), refl = reflective color (i: α = 0.69, b: α = 0.81, d: α = 0.42), Color code: blue = min, red = max

In the preceding paragraph, the analysis of the mean of the ten receptors is given. The variance between the receptors can be characterized by the standard deviation and the difference between the minimum and the maximum PET/ θ_a for each material: The standard deviation of PET at 2 pm (at 1.7 m) ranges between 2.5 K (“W_fal_metal_b”) and 3.7 K (“W_pi_brick_aerogel_d”) with an average at 3.0 K. The largest PET difference of 11.5 K between the receptors is found for “W_pi_brick_aerogel_d”, the smallest of 8.0 K for “W_lc_glass_blind_d”. The mean of all differences

at 1.7 m is 9.5 K. During the night-time, the θ_a spread is much smaller with a standard deviation between 0.0 K and 0.1 K. The maximal difference is 0.4 K.

4. Discussion

The construction systems for the ground result in a narrow bandwidth of PET with 0.4 K difference. It seems that the thermal inertia of the ground equalizes big differences.

The most striking phenomenon is the fact that for some construction systems the bright color results in a higher PET than the dark color. The construction systems in question are listed in Table 2. Besides the reflective coating and the fiber cement cladding they are all metal sheets in combination with either an insulation layer or air. The analysis of the wind speed reveals that for the dark colored metal sheets the wind speed in the neighborhood increases. Thus, high surface temperatures of the dark metal sheet seem to cause turbulences – which basically can be expected to a certain extent due to induced thermals – that lead to a lower PET (difference to bright color 3.9 – 4.9 K). For the reflective coating and the fiber cement the PET difference between the bright and the dark color is < 2.7 K. The difference in wind speed is very small (reflective coating) or even slightly inverse for the bright color (fiber cement). Consequently, there must be other reasons not explored herein. For wall types “pi” with higher PET due to dark colors (“W_pi_concrete_mineral_wool_b” and “_d” and for “W_pi_concrete_eps_b” and “_d”), the corresponding wind speed is always smaller (0.02 m/s).

Table 2. PET, max and min θ of the ground and wind speed at 2 pm in the yard , max θ of all walls

Construction	PET (°C) receptor 10	Max θ of all walls* (°C)	Max**, Min*** θ of ground in the yard (°C)	Wind speed at 1.7 m, receptor 10 (m/s)
W_refl_coating_b / _d	43.0 / 40.3	43.3 / 43.4	40.0±0.5; <20.8 / 39.5±0.5; <20.8	0.06 / 0.08
W_lc_sandwichpanel_b / _d	40.6 / 36.7	43.3 / 43.3	39.7±0.5; <20.8 / 37.8±0.5; <20.8	0.07 / 0.11
W_lc_glass_blind_b / _d	40.5 / 35.6	43.0 / 43.0	39.5±0.5; <20.8 / 35.8±0.5; <20.8	0.08 / 0.64
W_fal_metal_b / _d	41.4 / 36.7	43.2 / 43.3	39.7±0.5; <20.8 / 37.9±0.5; <20.8	0.07 / 0.11
W_fal_fibre_cement_b / _d	41.3 / 40.9	43.3 / 43.3	39.7±0.5; <20.8 / 39.6±0.5; <20.8	0.08 / 0.07

Restrictions by graphical interface ENVI-met: * = the surface θ of single walls seems not to be accessible in a straightforward way, ** only a temperature span is given, ***no exacter min θ is edited.

Construction systems “facing with air layer” (fal) should cause lower temperatures than for example the construction systems “plastered insulation”, especially during night-time. The rationale here is that the air layer in the “fal” type is naturally ventilated (buoyancy driven) and the outermost layer thus “cooled”. However, the simulation results do not reflect this: the highest temperatures for all walls are featured by “W_fal_fibre_cement_d”. As mentioned in section 2, ENVI-met considers the air layer simplified as an insulation layer ($\lambda = 0.025 \text{ W (m K)}^{-1}$). Therefore, the simulation results for these constructions represent the worst case with “no ventilation”.

Generally, plants are thought to contribute to an agreeable microclimate. Despite this, grass on the ground (“G_grass”) and green walls (“W_fal_green_wall”) yield the highest PET in their respective material group. This is due to the fact that the simulated period is at the end of a heat wave, where the ground and the wall are desiccated. It can be assumed that in a more humid period or with a permanently watered green wall the resulting PET would be lower.

The simulations focus on the microclimate outside of buildings. Although for most of the examined constructions the interior climate in the buildings is disconnected from the outside climate by an insulation layer and doesn’t influence the outside temperatures of the wall, it is desirable that the interior temperature is realistic. The initial temperature inside (θ_i) is 19.9 °C (Table 1). As a simplification ENVI-met considers each building block as one hollow building unit without any internal mass (no separating walls or floors). In addition, ventilation and solar gains are not taken into

account. In one exemplary block (Figure 1: block enclosing the yard with receptor 10 in a u-shape) θ_i reaches 26.5 °C at the end of the simulation period. This is a reasonable result.

Initially, in the simulation the soil/ground has a temperature of 19.9 °C. At the end of the simulation period (last hour) the temperature range in the whole neighborhood is between 19.9 °C and 27.8 °C (depth: 35 cm, ground type: reference, $\alpha = 0.18$). These values can be compared to available measurements of soil temperatures in two villages (depth: 35 cm, rural area, 01.08.2018) close to Basel [3]: In Brislach and Therwil 20.5 °C and 21.4 °C were recorded, respectively. The lower value from the simulation results shows good agreement with the measurements. Taking the urban context of the simulation scenario into account, the higher value also seems reasonable.

5. Conclusion

Out of the 45 construction systems/coloring scheme combinations analyzed, 32 cause a PET below 35 °C, pointing towards a moderate heat stress. 13 systems cause a PET > 35 °C, thus pointing towards strong heat stress. During daytime (2 pm) it is found that the ground materials “only” cause a PET difference of 0.4 K in the microclimate of the neighborhood. Mean PET values for all receptors range between 33.5 °C and 33.9 °C. The results found for grass must be taken with caution, because the end of a heat wave is analyzed where the evaporation effect is virtually inexistent. In the group “cw”, the brick wall with core insulation causes the lowest values in the neighborhood (PET 33.1 °C). In the group with “pi” the concrete wall with EPS and bright color causes the least heat stress (PET 34.8 °C). In the groups of “lc” and “fal” the sandwich panel and the metal cladding with dark colors both cause a very low PET. This result and the low PET for dark blinds must be treated cautiously: it is unlikely that in all circumstances such strong wind turbulences will reduce the heat stress reliably. The difference between the highest and the lowest PET for all walls is found to be 3.2 K. Applying bright versus dark colors is found to cause a difference in the PET values between 0.2 and 1.0 K. In case of local wind turbulences (e. g. found for dark metal claddings) the difference between dark and bright colors ranges between 2.0 and 3.8 K (dark metal = lower PET). During night-time (4 am) the difference between all walls is 0.8 K (1.7 m) and 0.3 K (10.7 m).

Even though the overall effect between the materials seems small, it is worthwhile to take the microclimate into account while designing spaces. Small differences as part of an overarching concept can contribute to a better microclimate in the city and to less heat stress. When broadening the perspective and complementing the microclimate assessment with other aspects it will likely be found that a material which performs well concerning the microclimate might have other drawbacks. The multi criteria assessment of building materials will be shown in a later publication.

6. Abbreviations

α = Albedo (-); λ = thermal conductivity (W (m K)⁻¹); PET = physiological equivalent temperature (°C); θ = temperature, θ_a = ambient temperature (°C), θ_i indoor temperature (°C),

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