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Climate and Decay: The impact of the urban climate on built landscape

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Abstract

This paper focuses on the impact of climatic forces on built landscapes through time. It explores the initial results of a research project at the Technische Universität Berlin (TU Berlin) exploring the dynamics of change to built landscapes through time. The impact of climatic processes on built landscape is determined by the level of climatic exposure together with the form of the structure itself and the properties of the materials used such as surface finish, albedo and heat storage capacity. Climate is however not a constant factor, it follows cyclical rhythms for example from morning to night and seasonal change, which are often disturbed by unpredictable incidents such as storms and other extremes. This leads, together with other ageing factors such as usage and maintenance, to surface patination and eventually to deterioration and decay.

Workshops were held in cooperation with the climatology department at the TU Berlin over a one year cycle aimed at exploring the impact of climatic processes (e.g. temperature, humidity or solar radiation) by `mapping´ the traces of weathering on built landscape elements in various materials. A thermal imaging camera, hygrometer and other diverse climatic instruments were utilised to gain detailed readings from the objects themselves and their surrounding contexts. The results enable climatic impacts on various structures and materials to be determined and points of design and constructional vulnerability to be identified. The data resulting from the workshop enables a detailed interpretation of the visible signs of decay from the research case studies, and a deeper understanding of the causative processes involved.

These research results will be presented in the form of case studies, illustrating and analysing the impact of climatic agents on built landscape.

Built landscapes undergo constant dynamic change due to exposure to environmental forces, the processes of use and misuse, and the intensity and frequency of maintenance and repair. One of the key factors in designing and detailing durable projects is in understanding the climatic parameters of the specific location. Climatic agents such as precipitation, wind, sun, humidity and temperature highly influence the performance of landscape architecture works. This is due to the physical distress caused, for example, by repeated cycles of wetting and drying, freezing-thawing, wind, and fluctuations of temperature. These processes occur in repeated cycles; from daily cycles (e.g. temperature, precipitation) to seasonal cycles (summer, autumn, winter, spring) throughout the entire lifecycle (cradle, grave) of the project [FIG 1] [1]. The intensity, frequency and variability of these climatic agents dictate the extent of climatic impact over time. In order to counteract these agents construction materials can be enhanced through finishing (e.g. polishing) and the application of surface coatings (e.g. paint, impregnation).

The effect of these climatic agents leads to a process of patination and, if disregarded, subsequently to deterioration. The visible signs of climatic decay are for example greying, cracking, roughing, surface soiling and spontaneous vegetation growth, which can lead in the long term to a reduced load- bearing capacity and destruction. Through analysing these traces of time on the surface of built landscape the aggressive agents influencing change can be identified and frequently occurring areas of conflict identified.

This paper presents initial research results of a research project at the Technische Universität Berlin (TU Berlin) focused on monitoring the development of built landscapes through time. The results will be presented in the form of case studies, illustrating and analysing the impact of climatic agents on built landscape.

The main climatic agents identified during the course of the research are **temperature, relative humidity, precipitation, direct sunlight** (ultraviolet radiation - UV) and cycles of **freeze-thaw**.

Temperature and relative humidity levels determine the level and rate of biodeterioration, corrosion, rot and atmospheric staining [2: p 20]. These fluctuations can also cause severe damage due to thermal material expansion and contraction. Furthermore, temperature variations induce thermal stress generating a thermal gradient between the exposed upper surfaces and the surface below which can lead to cracking (e.g. concrete) and/or deformation (e.g. asphalt) [2: p 5]. This is particularly problematic for large components (e.g. large concrete surfaces) or constructions that do not allow for the necessary expansion through expansion joints [3: p 29, 4: p 29].

Exposure to direct sunlight (ultraviolet radiation) results in the UV degradation of UV-unstable materials [4: p 96-98]. UV degradation and weathering cause the natural processes of greying, cracking and warping of wood [4: p 98], synthetic surfaces often discolour and become brittle [Fig. 2a, 2b] [5: p 151].

Shaded locations allow for a reduced rate of evaporation and cooler temperatures which leads to increased levels of humidity and biological growth [Fig. 2c, 2d] [6: p 24, 7: p 154].

Precipitation (rain, sleet, snow, hail, drizzle etc.) is a major climatic agent and transporter of airborne sediments (e.g. particulate matter). The surface flow of precipitation on built elements is highly influenced by the object form, material and surface properties. Furthermore, ground proximity is a particularly major influence due to rising moisture from the soil and splashback which reaches a height of up to ca. 30cm. Materials with a higher water absorption capacity (e.g. sandstone) are particularly subject to intensive cycles of wetting and drying, freezing and thawing [3: p29, 2: p 2] and also to the formation of substrate suitable for plant growth [Fig. 2d] [6: p 22]. Water flow patterns on the surface result in the relocation of propagules and other sediments often leading to stains from colonies of cyanobacteria [8: p 625].

Precipitation also influences the ground beneath the construction by entering the substructure and groundwater table [2: p 15]. Soils that are prone to volume change are particularly problematic for the built environment; periods of drought may cause **soil shrinkage** which can cause structural subsidence, prolonged periods of rain can lead to **soil expansion** (heave) which may lead to structural damage. [2: p 20].

Wind causes direct stress to the structure and also transports airborne pollutants (e.g. industrial, marine pollutants, vehicular traffic) and sediments [2: pp 6-7]. The deposition of airborne dust, dirt, pollen, and other atmospheric contaminants on the surfaces of built elements leads to **surface soiling** [Fig. 3a, 3b]. Factors that contribute to soiling and staining include the material properties (e.g. chemical composition, water absorptivity and porosity), degree of exposure, surface roughness (structure) and wetness [8: p 623]. This deposition is increased on the lower-velocity lee of vertical elements such as walls, edgings and at the base of street furniture as well as on structured surfaces and in the corners, joints, gaps of built works. Surfaces that are vulnerable to frequent wetting or where surface moisture is continually present are particularly prone to soiling. This process not only highlights the surface structure but also surface imperfections through time.

Another major climatic influence is the frequency and intensity of **freeze-thaw cycles.** Frost induces stress in the material itself which can lead to cracks, surface scaling and roughness. Severe frost-thaw cycles can also cause frost heave leading to cracking, structural damage or subsidence. This is due to an upward volume expansion of soil caused by the freezing of moisture, the melting of this frozen soil can then lead to a weakening of the bearing capacity of the substrate [9: p60].

The climatic factors mentioned above also have a major influence on the **location**, **spread** and **rate** of growth of **spontaneous vegetation growth**. The growth is focused on niches, corners, joints and cracks of the built environment that have the ideal climatic, moisture and soil conditions for the specific species [Fig. 3c, 3d]. Norbert Kühn defines spontaneous vegetation as` ... all plants that develop without intentional Horticultural input .... It grows at no financial cost, is authentic and is always appropriate to site conditions´ [10: p 47].

Surface growth is mainly initiated by bryophytes, lichens, algae and fungi that are largely not detrimental to the material itself and contribute to the development of surface patina. This can however lead to more damaging species of vegetation taking hold such as trees and woody plants that may damage the construction through acids produced by the roots, direct contact, and physical penetration by roots [6: p 25, 11: p 101]. In general, more aggressive woody plants and trees that can severely damage a construction require higher levels of substrate [12: pp 359-366, 6: p 24].The intensity of growth is determined by the availability and quality of rooting substrate, the exposure, moisture availability and the frequency of disturbances from use (trampling) and/or maintenance [Fig. 3c, 3d] [6: pp 16, 23, 13: p 5, 11: p 94]. Existing plant cover also protects against evaporation, sun exposure, and regulates relative humidity therefore supporting further growth [14]. Our research results show that damp, sheltered and shaded locations generally support more growth than exposed locations.

The reflection of short-wave solar radiation is termed albedo. Its value is expressed by the percentage of the total incoming radiation that is reflected, from total absorption (0%) to total reflection (100%) [15: p32]. Albedo is mainly influenced by the colour and brightness of a material surface and the intensity of sunlight (illumination) [16. p.35]. It is also influenced by factors such as surface roughness, the wavelength of the incoming solar radiation and its angle of incidence [16: p.52]. Due to the decreasing angle of incidence, the albedo value increases from the equator to the poles [16: p 35, 15: p32].]. Darker and rougher surfaces (lower albedo) lead to an increased absorption level, rapid heat transformation on the material surface, leading to increased evaporation and lower surface moisture [16: p 35,160]. Lighter and smoother surfaces (higher albedo) reflect more solar radiation leading to a reduction in surface temperatures. [15: p32]. This increased solar reflection from lighter surfaces can however have a negative effect on surface brightness (glare) and increase thermal stress/discomfort for pedestrians. [17: p 384]

These climatic agents are influenced by the degree of exposure, aspect (slope), relief, and the degree of sheltering of the structure by surrounding obstructions such as trees or nearby buildings [16: p 54]. The agents seldom act independently, more commonly they act in combination with one another. The following diagram divides the built landscape into three main climatic zones [Fig. 4]:

Open ground with no obstructions nearby is exposed to direct sunshine, frost actions, increased wind velocity and high levels of precipitation. These locations lead to an increased rate of drying, increased solar ultraviolet radiation, low humidity together with high precipitation and frost intensity. This climate is the most extreme and therefore aggressive for many materials; colours generally fade; synthetic materials become brittle, wood twists and cracks [Fig. 2a, 2b]. Direct exposure to sunlight and wind often lead to desiccation thus limiting the growth of spontaneous vegetation [18: p 31, 19: p 65]. Construction materials best suited to these areas are therefore tolerant to high levels of ultraviolet radiation, thermal expansion, cycles of precipitation, and frost-thaw. A relatively light surface (high albedo) is favourable in reducing surface temperatures and material stress (e.g. thermal expansion), very light surfaces should be avoided due to glare and thermal stress for pedestrians [17: p. 384].

Semi-open ground with low nearby obstructions is subject to moderate climatic exposure. The increased surface moisture through partial-shading (decreased rate of drying) together with increased deposition of airborne sediments increases the rate of spontaneous vegetation growth,

Sheltered locations with significant surrounding obstructions are generally protected from the direct actions of precipitation, direct sunshine and wind. These locations lead to a reduced rate of drying, increased humidity and therefore to an increased rate of biological deterioration [Fig. 2c, 2d]. Airborne organic matter and other sediments often accumulate in these lower-velocity areas leading to increased moisture retention and soil formation which in turn provides the perfect physical and hydric conditions for spontaneous vegetation growth [20: p13, 19: pp 63 - 80]. Construction materials for these areas should be resistant to moisture, biodegradation, quick drying and simple to clean. Unbound surfaces and paving with a high proportion of joins (e.g. setts) generally require increased maintenance in these areas.

Note: Due to the complexity of the interaction between climate and the built environment there are many special climatic locations, for example those influenced by up-draughts on facades, which are not covered by this simplified zoning diagram.

Case Studies

Workshops were held in cooperation with the climatology department at the TU Berlin over a one year cycle investigating the climatic impact on built landscape elements in various materials.

These were held as student field research activities using a thermal imaging camera, hygrometer and other climatic instruments. The data resulting from the workshop enables a detailed interpretation of the visible signs of decay from the research case studies, and a deeper understanding of the causative processes involved.

The research site was the forecourt of the architectural building of the TU Berlin. The space is oriented towards south east and comprises mainly of sealed surfaces with two planters containing shrubs and trees. The surface temperature and surface moisture were measured at 14 standpoints at regular intervals from 8am to 8pm. Air temperature, relative humidity and wind were recorded using a multi-functional instrument. A thermal imaging camera was also used to gain a greater coverage of readings from the objects themselves and their surrounding contexts.

The first summer recordings took place on 25.05.2016, a cloudy day on which the albedo effect, for example on dark and light paving slabs, was almost insignificant, which demonstrated the significant relationship between albedo and the level of sunlight. The field research was then repeated on a sunny summer day on 08.06.2016. Sanda Lenzholzer explains that on a sunny day at noon in central Europe an open surface can receive up to 1000 watts per square meter, compared to 500 watts on a cloudy day and a mere 100 watts in deep shade. [15: p31].

In the following section the summer workshop results from 08.06.2016 will be discussed together with the findings of the research project in order to explain the impact of climatic agents on vertical and horizontal elements of the built landscape. The air temperature was recorded on the TU Berlin rooftop weather station.

1. Vertical element: FREESTANDING CONCRETE WALL

The highest temperatures fluctuations were recorded on the most exposed surface at the top of the wall, whereas the more constant temperatures were distributed at the base. The recorded surface moisture was the lowest at 8pm due to the heat storage capacity of the material. As Darlington [13: p 17] observed, vertical elements lead to an interruption of horizontal air currents and therefore to increased deposition of sediments and propagules compared to horizontal spaces. He states that `In assessing the ecological potential of any wall, general considerations include its dampness, texture, thickness, inclination, orientation and position ...´ [13: p 5]. Thicker walls are capable of retaining more moisture and are therefore more prone to surface vegetation. [13: p 5].

The climatic evaluation of the wall is divided into three zones, the **Top**, **Face** and **Base**.

Top: This zone is characterised by extremes of wetting and rapid drying, the highest moisture and temperature fluctuations, and the accumulation of airborne substrates. The values at the top of the wall in full sun rose rapidly in the morning and reached up to ca. 16°C above the air temperature, cooling occurred after sundown. Particles accumulate on the horizontal surface at the top of the wall due to air currents, precipitation, surface erosion and transportation by animals (e.g. birds and ants), enabling biological growth. Wall copings are a form of constructive protection that reduce staining by shedding precipitation away from the face of the wall. The field research results show that copings are often not implemented, leading to many cases of surface staining.

Face: This area is characterised by the lowest levels of surface moisture, little staining and substrate deposition and rapid drying. The temperature of the face of the wall reached its peak of 31°C in the early afternoon, in the early evening it remained 11°C warmer than the surrounding air temperature due to the heat storage capacity of the material. The incline of the wall affects moisture and substrate retention, more vertical surfaces are predominantly dryer, and therefore fewer plants can establish [13: p 5, 8, 18: p 39]. The upper area of the wall face is influenced by the runoff of sediments from the top of the wall which often cause vertical biological staining (e.g. cyanobacteria, algae, mould) [8: p 625]. This process leads to a highlighting of the surface structure of the wall. Walls from individual units (e.g. bricks, stone, concrete) and vertically structured surfaces lead to a more even spread of surface soiling. Surface irregularities, for example due to production process faults such as the soiling of concrete formwork, can also become more visible through soiling. The bottom 20-30cm of the wall is strongly influenced by rising damp and the splashback of rainwater which often leads to soiling, biological growth, staining and material deterioration [8: p 629]. Surface soiling on smooth and light coloured surfaces (e.g. smooth exposed concrete) becomes especially visible.

Base: This is the wettest zone due to direct precipitation, runoff from the wall face and moisture rising from the soil due to capillarity [Darlington: p5]. Spontaneous vegetation growth is predominantly found at the base due to the increased levels of moisture, low evaporation levels due to shading, and the increased availability of rooting substrate [13: p5, 6: p20]. The substrate accumulates through the direct deposition of airborne particles or from being washed from the face and/or top of the wall by precipitation. This niche is seldom disturbed by human trampling and is particularly difficult to maintain, which often leads to an increased rate of growth.

2. Horizontal element: GRANITE PAVING SLABS, LIMESTONE SETTS, ASPHALT, TOPSOIL

The darker **granite paving slabs** and **limestone setts** had a consistently higher surface temperature and lower surface moisture than the lighter surfaces. Some lighter slabs with significantly rougher surfaces attained similar measurements to the darker surfaces; this

surface roughness leads to a reduced albedo. The highest surface temperature of ca. 50 ° C was reached at 2pm on the dark granite slabs on open ground, which was over 20 ° C above the surrounding air temperature. Therefore, materials and joints for exposed locations need to withstand the internal stress and expansion resulting from this extreme temperature variation, together with physical loading.
The higher pore volume of the gravel joints results in reduced maximum temperatures. Spontaneous growth mainly occurs in these joints where soil and moisture can accumulate, especially on shaded surfaces that are seldom disturbed by trampling and/or maintenance. Shading leads to reduced evaporation, an increase in surface moisture retention and reduced maximum temperatures, thus aiding vegetation growth [Figure 7] [16: p. 57]. The recorded surface temperature difference between sunny and shaded locations of limestone setts reached ca. 18°C at 2 pm, whereas the difference was down to ca. 2°C at 8pm.

The growth of paving vegetation is also dependant on maintenance regimes such as brushing or road salting. This vegetation is often maintained in a perpetually early state of succession due to trampling and limited soil accumulation [11: p99].

The recorded temperature of the exposed **black asphalt** surface (low albedo) reached a maximum of ca. 46°C in the early afternoon which was ca. 20°C higher than asphalt in a shaded location. These high temperatures can lead to a softening of the asphalt binder leading to deformation and rutting [21]. In the late evening the surface temperature was ca.10°C higher than the air temperature demonstrating its high heat storage capacity. The field research shows that repeated cycles of expansion and contraction often lead to surface cracks and the breaking of the adhesive bond with the peripheral edging which leads to spontaneous vegetation growth.

Low temperature and moisture fluctuations characterise the **soil surface** due to the high pore volume and moisture retention properties [16: p. 50]. The soil temperature rose to ca 10°C above the air temperature in full sun, in the full shade the temperature remained within ca. 3°C of the air temperature.

Conclusion

The initial research results display a great diversity of weaknesses due to climatic agents throughout public space in Berlin, some of which are depicted and discussed in this paper. The data resulting from the workshops enables the specific characteristics of climatic vulnerability on various structures and materials to be determined thus generating a wide range of detailed knowledge on project development. Landscape architects can combat these climatic agents through the optimisation of design, detailing, construction processes and maintenance regimes throughout the project cycle.

Climatic factors also have a major influence on the spread and growth rate of spontaneous vegetation. Maintenance operations should aim to halt the processes of succession to the early stages that are not harmful to the material or structure. Insufficient or incorrect maintenance can lead to the continued growth and succession of grasses and woody plants that can lead to deterioration and/or structural damage.

Factors such as the degree of exposure, relief and aspect strongly influence the intensity of microclimatic agents. This indicates the necessity for selecting the right material and surface finish for a particular geographical location. Furthermore, knowledge of the **specific climate factors** and the foreseen **level of maintenance and repair** are required. No two locations on a site are exactly alike; therefore different materials or surface treatments may be necessary to implement an object in various situations. For example, in an exposed open location a hardwood bench may well be treated with UV protection oil, for a sheltered location under lime trees a painted finish is most probably more appropriate.

Existing signs of climatic degradation also act as a `climatic indicator´, providing an expectation as to the type and extent of climate- induced deterioration. Therefore, regular monitoring of post-completion development together with the implementation of necessary design and/or technical alterations and/or maintenance strategy can avoid premature deterioration.

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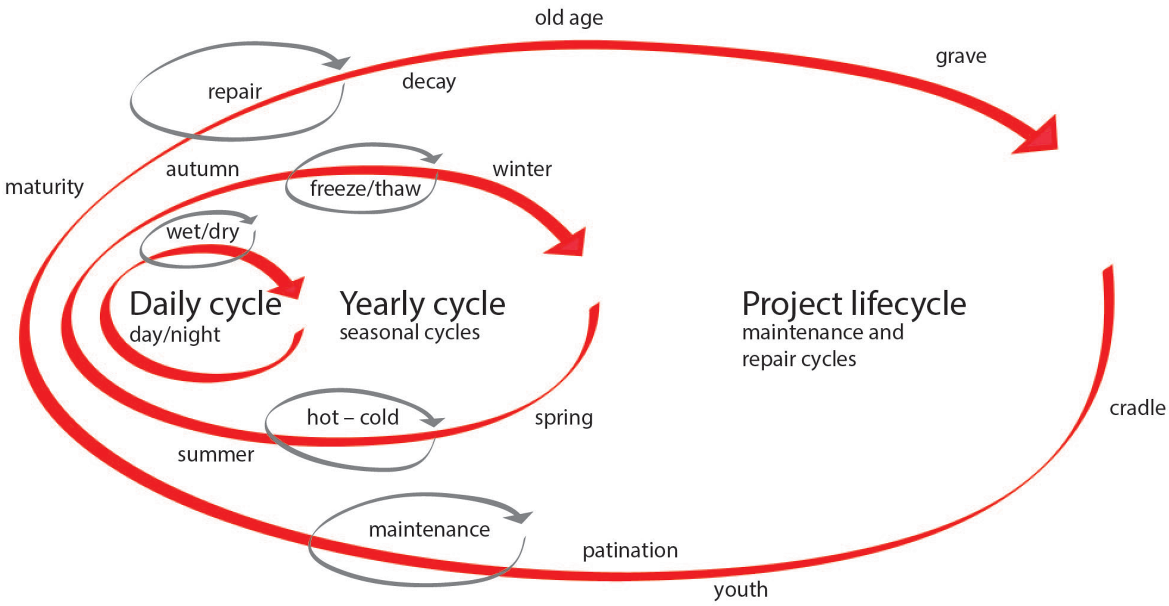

Fig. 1: The cycles of landscape transformation [Diagram: S. Colwill].

Fig. 2: a) Greying of wood (exposed location): time of competition/ 3 months later. b) Discoloration of synthetic surface (exposed location): year 1/ year 3. c) Comparison of strongly shaded locality and an exposed sunny location 2 years after completion. d) Water absorption increasing staining (sheltered location): year 8. [Photos: S. Colwill]

Fig. 3: a/b) Deposits of airborne sediments on concrete wall (exposed location): year 1 / year 10. c) Biological growth on wooden deck (sheltered location): year 17. d) Biological growth only on riser due to reduced trampling and maintenance (semi-exposed location): year 1 / year 7. [Photos: S. Colwill]

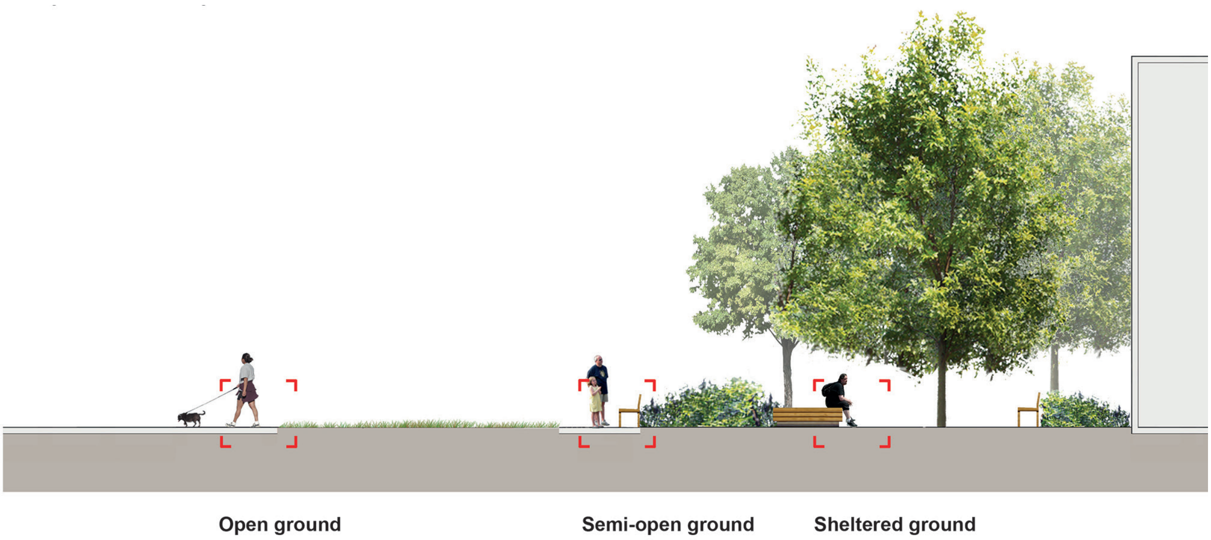

Fig. 4: The zones of climate exposure [Diagram: S. Colwill].

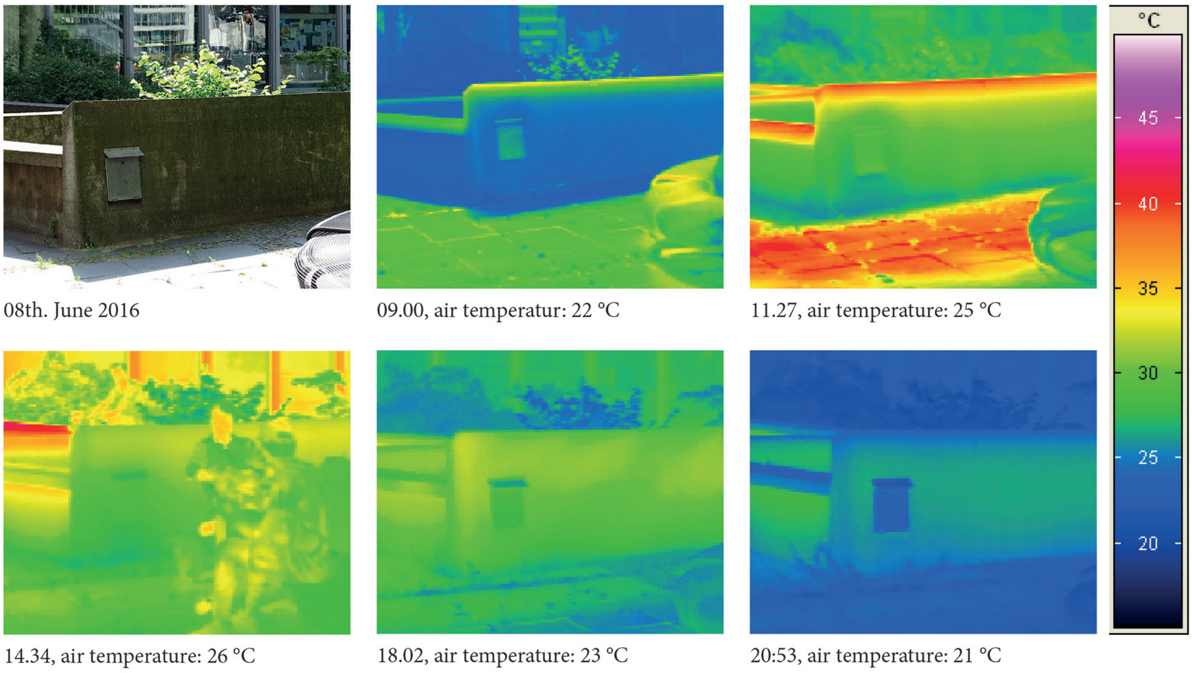

Fig. 5: Thermographic analysis of a freestanding concrete wall over a one day period. [F. Zwangsleitner]

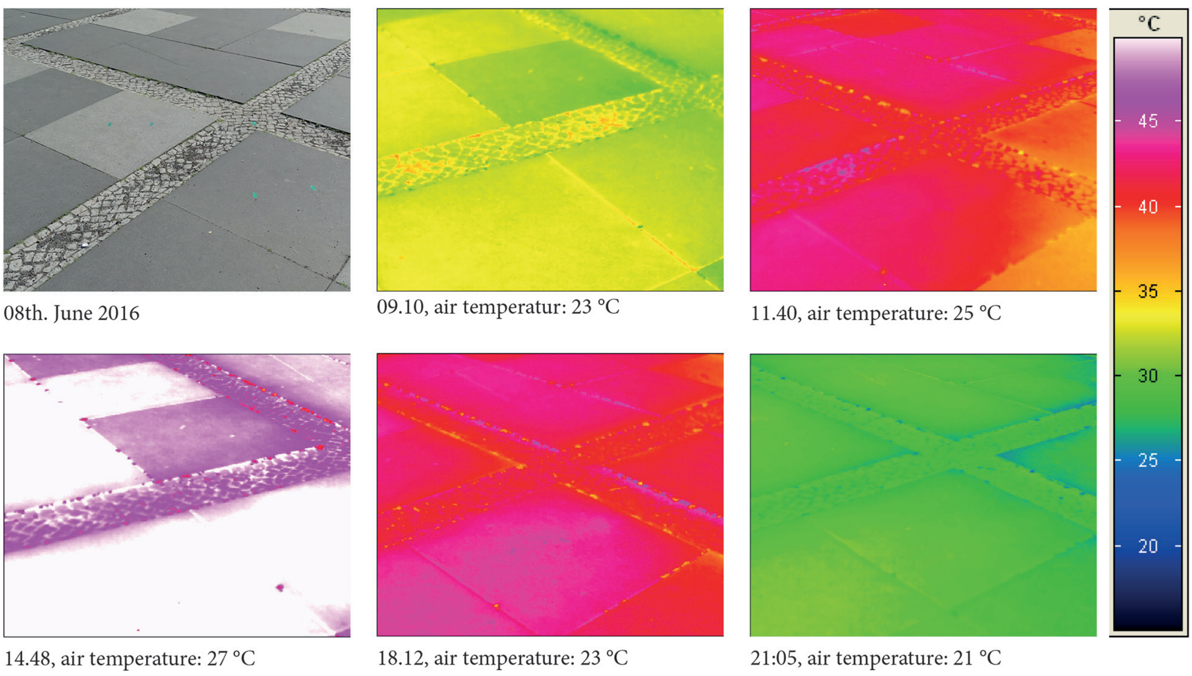

Fig. 6: Thermographic analysis of dark and light coloured granite paving slabs over a one day period. [F. Zwangsleitner]

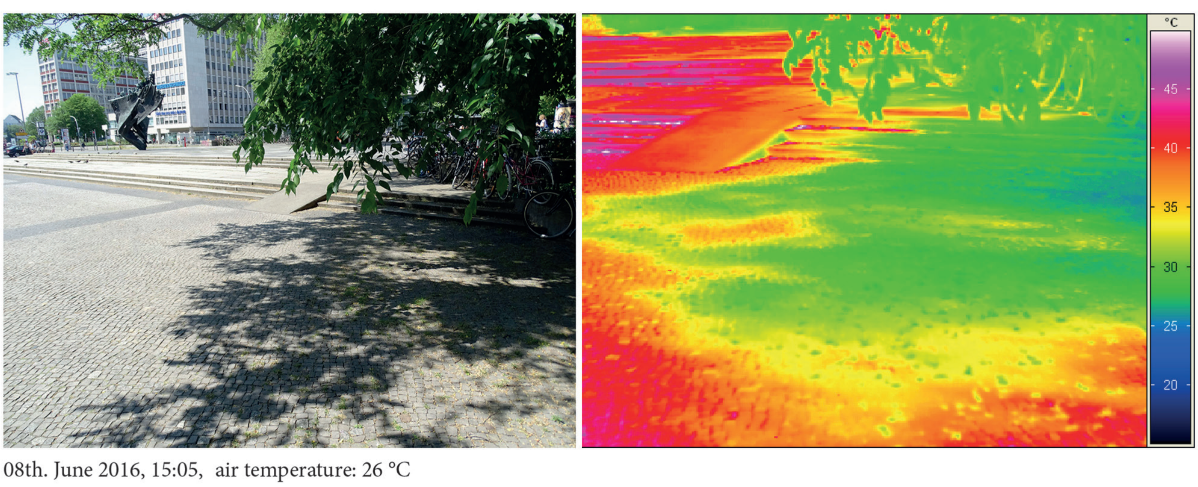

Fig. 7: Thermographic analysis showing the effect of light and shadow on limestone setts [Diagram: F. Zwangsleitner]