Greenroof potential to reduce temperature fluctuations of a roof membrane: A case study from Estonia

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ABSTRACT

This paper analyses the temperature regime of a light weight aggregates (LWA)-based greenroof in comparison with a modified bituminous membrane roof. The measuring period was from June 2004 to April 2005. Both seasonal and daily results showed that in Estonian climatic conditions, an extensive greenroof is sufficiently capable of protecting the roof membrane from extreme temperatures. In the summer period, the 100-mm-thick substrate layer of the greenroof significantly decreased temperature fluctuations compared with the bituminous roof surface. In autumn and spring the substrate layer protected the base roof's membrane from rapid cooling and freezing. It also provided effective thermal insulation in winter. In addition, measurements showed that the surface of the LWA media in the greenroof heats and cools more than the surface of the bituminous roof; however, its influence on temperature in the substrate layer was not considerable. Indexes to characterize greenroof's temperature effects are proposed.

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1. Introduction

Greenroofs have been increasingly investigated in order to determine how they could improve the quality of the urban environment. Greenroofs consist of the following layers: a waterproofing membrane, a drainage layer, a filter membrane, a substrate layer and plants. The composition and thickness of the substrate layer is decisive. One benefit of greenroofs is to protect the base roof membrane against solar radiation, thus lowering its temperature and also minimizing temperature fluctuations. Research has confirmed that greenroofs also have the following benefits: the ability to reduce urban stormwater runoff problems, reducing the total runoff by retaining part of the rainfall and distributing the runoff over a long time period [1–5]; the ability to reduce the pollution of urban rainwater runoff by absorbing and filtering pollutants [1,5–7]; helping to keep buildings cool in summer and also to reduce a building’s energy consumption by direct shading, evaporative cooling and additional insulation [8–13]; improving air quality by catching a number of polluting air particles and gases, including smog. The evaporation and oxygen-producing effect of vegetated roofs can contribute to the improvement of the microclimate. Considering the above-mentioned benefits, it may be concluded that greenroofs can thereby mitigate the urban heat island effect [14,15]. Planted roofs also provide food, habitat and a safe habitat for many kinds of plants, animals and invertebrates [16]. Greenroofs can also mitigate noise pollution [17]. In city centres, where access to green space is negligible, greenroofs create space where people can rest and interact with friends or business colleagues. Greenroofs provide a psychological benefit because of their appearance, which differs greatly from ordinary roofs. Therefore, aesthetic value is the most apparent benefit of vegetated roofs [17].

An exposed roof membrane absorbs solar radiation during the day and its temperature rises, while in the evening its surface temperature drops. Daily temperature fluctuations create thermal stresses in the membrane and reduce its durability. The greenroof blocks the solar radiation from reaching the membrane, thus lowering its temperature and also minimizing temperature fluctuations. The life span of the membrane of a conventional roof is usually 20–25 years, but it is believed that a greenroof membrane may last twice as long.

Some investigations have been performed concerning the temperature regime of greenroofs, in which the main research topic was temperature fluctuations in greenroofs and reference roofs. Much more research has been done to investigate greenroofs’ heat transfer and the ability to reduce buildings’ energy consumption by other researchers. Thorough research has been done by Liu and Baskaran from the National Research Council in Ottawa, Canada [18]. During the 22-month observation period (860 days), Liu and Baskaran found that the membrane temperature of the reference bituminous roof exceeded 30 °C for 342 days, was above 50 °C for 219 days and above 60 °C for 89 days.
In comparison, the membrane under the greenroof only exceeded 30°C for 18 days, and never reached 40°C. The temperature fluctuation in the exposed membrane of the reference roof had a median of 42–47°C. The greenroof reduced the temperature fluctuation in the roof membrane to a median fluctuation of 5–7°C throughout the year. Bass and Baskaran [9] showed the results of the same roof temperature profile monitoring on typical days in different seasons. On a typical summer day the membrane temperature on the reference roof reached 70°C, but the membrane temperature on the greenroof fluctuated at around 25°C. On a typical winter day without snow coverage, the temperature on the reference roof fluctuated from −15 to 10°C depending on the air temperature, while at the same time the membrane temperature on the greenroof remained relatively stable between 1 and 5°C. Wong et al. [15] found that surface temperatures measured under different kinds of vegetation were much lower than those measured on hard surfaces. The maximum temperature of the hard surface and under all kinds of plants was 57 and 36°C, respectively.

The objective of this paper is to analyse how a light weight aggregates (LWA)-based greenroof functions in local weather conditions, as a result of observing an existing greenroof in Tartu, Estonia. The task was to assess the temperature regime on the greenroof’s surface and in the greenroof’s substrate layer, and to compare those with a modified bituminous membrane roof.

2. Materials and methods

2.1. Site description

The studied greenroof was established in May 2003 and is situated near the city centre of Tartu, Estonia (58°22'40"N, 26°44'07"E). It consists of the following layers: a modified bituminous base roof, a plastic wave drainage layer (8 mm), rock wool for rainwater retention (80 mm) and a substrate layer (100 mm) with LWA (66%), humus (30%) and clay (4%). The reference roof is a modified bituminous membrane roof; the distance between the roofs is approximately 350 m. Both the non-fertilized greenroof and the reference roof have no slope and the same area (120 m²). The length of the greenroof is 18 m, and its width 6.60 m; its height from the ground is 4.5 m. The brick building (with 300 mm clay bricks), covered by the greenroof, is a one-storey printing-plant (Ecoprint) annex to a three-storey office building (stone house with wood weatherboarding impregnated with natural paint; with a conventional flat roof). During the measurement period, the amount of plant cover was 45% of the whole roof area. The most common plant species were Sedum acre (planted and seeded; covers 55%), Thymus serpyllum (20%), Dianthus carthusianorum (5%), Cerastium tomentosum (all seeded; 3%) and also Veronica filiformis (occasional species; 7%). This was the best possible roof to study, considering the presence of a suitable reference roof in the vicinity. Although the size, aspect and slope of the reference roof were similar to those parameters of the greenroof, there are still some differences behind the roofs’ conditions, such as snow cover thickness in winter, which depends on wind direction.

2.2. Sampling and analysis

The measuring period was 10.06.04–25.04.05. The temperature was measured every 15 min using sensors Pt1000JGB/E, produced by Evikon MCI (Estonia), and recorded with data logger R0141, produced by Comet System Ltd. (Czech Republic). Data processing was performed using MS Excel. On the greenroof the temperature was measured using MS Excel. On the greenroof the temperature

<table>
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<th>Table 1</th>
<th>Explanations of abbreviations used in figures</th>
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<tr>
<td>Abbreviation</td>
<td>Explanation</td>
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<td>GR at 100 mm</td>
<td>Temperature measured at the depth of 100 mm in the substrate layer of the greenroof</td>
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<td>GR at 50 mm</td>
<td>Temperature measured at the depth of 50 mm in the substrate layer of the greenroof</td>
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<td>GR surface</td>
<td>Temperature measured on the LWA surface of the greenroof</td>
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<td>RR surface</td>
<td>Temperature measured on the surface of the reference bituminous roof</td>
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<td>Air</td>
<td>Temperature measured at 1 m above the greenroof</td>
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was measured in two places: at the eastern and western side of the roof. The temperature was measured both on the surface of the roof and at 1 m above the roof, and also at a depth of 50 and 100 mm in the substrate layer. Because the greenroof’s bituminous membrane of the base roof was inaccessible, temperature measuring at the depth of 100 mm in the substrate layer was the best possibility to investigate temperature regime in the greenroof. As the greenroof’s surface was mainly covered by LWA (plant cover was only 45%), the surface temperature expresses the temperature of the LWA. On the bituminous roof the temperature was measured on the surface and at 1 m above the roof. As the temperatures of both sides of the greenroof were similar, for comparison with temperatures on the reference roof only the results of the eastern side are used. In February and March, however, when snow cover on the western side was thicker and similar to that of the reference the results of that side were used. The air temperatures above the roofs were similar, and therefore these are used in comparison. Inside the building equipped with the greenroof temperature was not measured. Explanations of abbreviations used in figures are shown in Table 1.

2.3. Statistical analysis of data

The normality of temperature data was checked using the Lilliefors and Shapiro–Wilks tests (STATISTICA 7.0 software). Most of the temperature values (except for the air temperature measured at 1 m above the greenroof) were not normally distributed. For the analysis of these data we used non-parametric statistics (e.g. the Spearman Rank Order Correlation). For normally distributed temperature differences, parametric statistics (average and standard deviation values and Pearson correlation) were applied. The level of significance of α = 0.05 was accepted in all cases.

3. Results and discussion

3.1. Temperature regime in the entire measurement period

Fig. 1 illustrates daily average temperature values. In summer (June–Mid-September), the daily average temperature values of the greenroof’s substrate layer were lower than those on the surface of the reference bituminous roof. In winter the temperature relations were similar due to the snow cover.

In the winter period the amplitudes of average daily temperatures (the difference between daily maximum and minimum temperatures) were highest on the surface of the greenroof, as it was warmed by the sun and cooled down at night (Fig. 2). Surprisingly, the amplitude of the surface temperature of the reference bituminous roof was even smaller. This clearly demonstrates that the surface of the LWA greenroof should be...
seasonal and daily differences between the temperature values of different measuring sites are significant (see Sections 3.2 and 3.3).

The Spearman Rank Order Correlation between the temperature values measured over the whole study period in different sites was highly significant ($p < 0.001$), showing $R$ values between 0.97 and 0.99 (Table 2). At the same time, the median values of temperature series over the entire period did not differ significantly (Fig. 3). However, some seasonal and daily differences between the temperature values of different measuring sites are significant.

The monthly variation of average daily temperature amplitudes (Fig. 4) clearly illustrates that throughout almost the whole study period, temperatures on the LWA surface of the greenroof fluctuated significantly more than on the surface of the reference bituminous roof. The differences were more remarkable in summer and decreased in autumn and winter. In summer the amplitudes of the air temperature were also lower than on the surface of roofs, but in winter above the snow cover the air temperature fluctuated significantly more than that of the roofs.

In the warmer period the sum of temperatures by months (Fig. 5) was higher on the surface of the reference bituminous roof, because it warmed during the daytime and stayed warmer than the greenroof's surface at night. The sum of the temperatures of the greenroof's substrate layer was smaller in those months because the temperature did not rise as much and remained stable. The sum of its temperatures was, however, greater than on the roofs, but in winter above the snow cover the air temperature fluctuated significantly more than that of the roofs.

In the autumn season, when the substrate layer was warmer than the surfaces that cooled down at night. In winter more fully covered by plants in order to avoid such considerable heating. Nevertheless, the high-temperature increase on the surface of the greenroof did not considerably influence the temperature in the greenroof's substrate layer, where temperature values were much lower and stable. Average amplitudes in temperature in the greenroof's substrate layer, where temperature surface of the greenroof did not considerably influence the heating. Nevertheless, the high-temperature increase on the surface of the greenroof was much more fully covered by plants in order to avoid such considerable heating. Nevertheless, the high-temperature increase on the surface of the greenroof was much more fully covered by plants in order to avoid such considerable heating. Nevertheless, the high-temperature increase on the surface of the greenroof was significant.

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Fig. 1. Daily average temperature values during the entire measurement period (10.06.04-25.04.05).

Fig. 3. Variability of temperature series.

Fig. 2. Variation of the amplitudes (difference between the maximum and minimum values) of daily average temperatures.

Fig. 4. Monthly variation of average daily temperature amplitudes.

Table 2: Spearman rank order correlation coefficients ($R$) of measured temperatures ($p < 0.001$)

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<tr>
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<th>Air</th>
<th>Reference roof surface</th>
<th>Greenroof surface</th>
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<tr>
<td>Reference roof surface</td>
<td>0.98</td>
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<td>Greenroof surface</td>
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<td>Greenroof at depth of 100 mm</td>
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temperatures fluctuated much more on the surface of the greenroof, and therefore the sum of the temperatures was higher, as the other investigated temperatures were more stable.

On contrary to Fig. 3, the monthly mean values of temperature differences between different measuring sites (Fig. 6) are remarkable and in some cases (summer season versus winter season) significant. The greatest differences were observed between the greenroof’s substrate layer and the surface of the greenroof, although due to high standard deviation values these differences were not significant.

3.2. Temperature regime in different seasons

In this part we compare temperatures in the greenroof’s substrate layer at the depth of 100 mm and on the surface of the bituminous reference roof. Decreasing temperature fluctuations in summer is one important reason why a greenroof is necessary. Especially in tropical countries, this effect plays an important role [12,15], but it can also be significant in the temperate zone [10]. In the summer period (10.06.–22.09.2004), measurements in Estonia showed that the greenroof’s substrate layer efficiently reduced temperature fluctuations. On sunny days the surface of the reference bituminous roof heats up to two times more than the greenroof’s substrate layer, which has almost the same temperature as the air. The number of days in the summer season in which the temperature exceeded 30 °C was 53 for the bituminous roof, but only 7 at the depth of 100 mm in the greenroof’s substrate layer.

In autumn, temperatures did not change much due to cool and cloudy weather. The surface of the reference bituminous roof cooled down more than the greenroof’s substrate layer. The temperature in the substrate layer did not decrease below zero. Thus the substrate layer protects the base roof membrane from rapid cooling and freezing.

In the winter season, the temperature in the greenroof’s substrate layer was a couple of degrees higher than on the surface of the reference roof, except when the snow cover was thin due to ablation by snowstorms. The reference roof was covered by a thicker snow layer, which kept the surface temperature relatively stable. At the end of February the snow cover on the greenroof increased and the temperature in the substrate layer was higher than on the surface of the reference roof. On winter days, the insulating effect of the snow cover is apparent. However, the greenroof’s substrate layer provides important additional thermal insulation.

In the first part of the spring season (20.03.05–25.04.05), the temperature on the surface of the reference roof fluctuated considerably due to daily sunshine and night frosts, whereas in
the greenroof’s substrate layer the temperature was more stable. Daily temperature courses of the substrate layer in this period show a change from the stable winter–spring (frozen) regime into the summer regime with bigger fluctuations. The effect of temperature isolation is highest during periods when the roof surface heats up in the daytime and freezes at night.

3.3. Temperature regime in typical days of each season

On a typical sunny summer day, the surface of the bituminous roof heats up in the morning and cools down in the evening (amplitude 35.1 °C). The greenroof's substrate layer significantly decreased daily temperature fluctuation (amplitude 13.8 °C). The temperature at the depth of 100 mm rises slowly until afternoon, and then begins to fall just as slowly (Fig. 7). At a depth of 50 mm the temperature runs in the same direction, but is higher before noon and lower in the afternoon. The LWA's surface heats up and cools down faster (amplitude 40.1 °C) than the surface of the bituminous roof, remaining coolest at night. Although LWA surface heating in the daytime and cooling in the evening involves corresponding changes in substrate temperature, the latter fluctuates notably less, and thus the base roof is protected from extensive temperature fluctuations. Since in summer the LWA's temperature fluctuates even slightly more than the temperature of the bituminous membrane, the careful establishment of vegetation is recommended. These results are similar to the results of research performed by Bass and Baskaran [9], although in their study the membrane temperature on the greenroof fluctuated about 7 °C less than in our study, probably because of differences in the location of sensors.

Fig. 6 shows temperature fluctuations on the surfaces of the estimated roofs on a sunny–cloudy summer day. Such temperature fluctuations have a negative impact on the roof membrane, and may cause damage if they occur too often. The greenroof’s substrate layer reduced temperature fluctuations on the surface (30 °C) by 20 °C. At a depth of 50 mm, the temperature was more affected of temperature fluctuations on the surface than at a depth of 100 mm. Thus a 100-mm-thick substrate layer is sufficient to protect the roof membrane against such temperature fluctuations.

On a cloudy autumn day temperatures did not change much (Fig. 9). The highest values were registered for air temperature, whereas surface temperatures were stable, decreasing below zero at night on both roofs. At the same time, temperature at a depth of 100 mm decreased to only 2.5 °C at night.
On winter days, all temperatures under the 200-mm-thick snow cover are stable (Fig. 10). However, all of the roof types showed a similar temperature pattern. Similar results have been found in a study carried out by Bass and Baskaran [9] on a typical winter day when roofs were covered with a 200-mm-thick snow layer. Air temperature fluctuated between $-20$ and $-10\,\text{°C}$;
however, the temperature of the roofs’ membranes remained steady (average 2.0 °C).

On the greenroof the thickness of the snow cover was different: on eastern side of the roof (GR1) it was 70 mm and on the western side (GR2) 200 mm. While under the 200 mm-thick snow cover the temperatures were stable, under the 70 mm-thick snow cover the temperatures were more affected by air temperature. For example, on 9 March at 15.00 all measured temperatures, including air temperature, were on average −2 °C. For the next morning at 5.00 the air temperature had fallen to −15 °C, the temperatures on the GR2 side were stable around −2 °C, but the temperatures on the GR1 side had fallen to −6 °C. Thus on winter days a sufficiently thick snow cover is recommended; in addition to protecting the base roof membrane, it also protects plants against freezing damage.

On a typical melting spring day the temperature on the surface of the greenroof, where snow had recently melted, rises to 15 °C. In the evening the surface cooled down rapidly and at night it froze (Fig. 11). In the frozen substrate layer of the greenroof, where snow had recently melted, rises to 15 °C. Thus on winter days a sufficiently thick snow cover is recommended; in addition to protecting the base roof membrane, it also protects plants against freezing damage.

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3.4. Indexes characterizing temperature effects of the greenroof

Indexes for characterization of greenroof’s temperature effects are shown in Table 3. These are based on comparison of mean seasonal temperatures of measuring sites of the greenroof with the reference roof and the air above the greenroof. Different indexes reflect temperature effects in different seasons. For instance, indexes I–II reflect differences of the greenroof layers with the air above the roof. In our studies, the greenroof accumulated some heat over the whole year, except spring. On the other hand, Index V shows the cooling effect of the greenroof in summer and may correlate with energy saving values. Therefore, indexes indicate two effects of the substrate layer of the greenroof; cooling effect in warm period and heat storage effect in cold period. In summer period investigated greenroof acted as passive cooling appliance of the printing plant and reduced the yearly cost for conditioning by 500 EEK m⁻² ($50; $1 = 10.08 EEK, in May 2008; personal communication by Mr. Juhan Peedimaa, the chief of the Ecoprint office from 19 May 2008).

4. Conclusions

The measurements presented here showed that a greenroof can provide a base roof with effective protection against the influence of intensive solar radiation. In the summer period the greenroof studied significantly decreased temperature fluctuations compared with the bituminous roof. In autumn and spring the substrate layer protected the base roof's membrane from rapid cooling and freezing. It also provided effective thermal insulation in winter. Thus a 100-mm-thick substrate layer that is entirely covered by plants successfully mitigates the influence of weather on the roof membrane. The surface of the LWA media in the greenroof heats and cools more than the surface of the bituminous roof. Although its influence on temperature in the

![Fig. 11. Temperatures in different measuring sites on a melting spring day (27.03.05).](image-url)

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<td>Mean seasonal temperatures (°C) at different measuring sites of the studied roofs and main proposed indexes for characterization of greenroof’s temperature effects</td>
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<td>Seasons</td>
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*Seasons: summer: 10 June–31 August; autumn: 1 September–30 November; winter: 1 December–25 March; spring: 26 March–25 April.

* Measuring sites: 1—GR at 100 mm; 2—GR surface; 3—RR surface; 4—air at 1 m above the GR.

* Indexes: index I—GR at 100 mm/air at 1 m above the GR (1:4); index II—GR surface/air at 1 m above the GR (2:4); index III—GR surface/GR at 100 mm (2:1); index IV—GR surface/RR surface (2:3); index V—GR at 100 mm/RR surface (1:3).
substrate layer was not considerable, plant cover must be well
developed and cover at least 80% of the surface. We can definitely
say that even with a low percentage of plant cover, greenroofs can
reduce the overheating of air in cities. This is in contrast to the
modified bituminous roof, which is completely covered by a heat-
absorbing coat. In cities there are many previously constructed
buildings with flat roofs that could be covered with plants, but it
would be ideal if most new buildings had vegetated roofs.

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