Civil and Environmental Research, Vol.4 2013
Special Issue for International Congress on Materials & Structural Stability, Rabat, Morocco, 27-30 November 2013

Mitigation of the Urban Heat Island Effect by self-cooling Concrete Pavers

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Abstract. Worldwide an increasing migration from rural to urban regions can be observed. Hence cities are growing and as a result the building density and the land sealing rise. Concrete as commonly used building material in urban structures provides a high heat storage capacity. Therefore the microclimate in cities has become warmer than in the surrounding areas. This phenomenon is called Urban Heat Island Effect. To mitigate this situation a large scale application of self-cooling concrete pavers is an approach to reduce the urban heat island effect. Making use of evaporation enthalpy, this new type of pavements counterbalances the absorption of solar radiation and the subsequent transfer of heat to the surrounding environment. The typical double-layer structure of concrete paving stones can be maintained. The mass concrete acts as a water storage layer and is covered by a permeable face concrete. As the different requirements of these layers demand different concrete mixtures, they are developed and optimised for their respective functions. This paper presents some suitable no-slump concrete mixtures that combine a sufficient compressive strength as well as good water transportation properties for the above mentioned approach.

1 Introduction

World-wide the increasing surface sealing, building development and generally the expansion of urban areas lead to heat islands in the inner-city areas, particularly in warm and hot climate zones. The building materials act as a heat accumulator, so that at sunny days a temperature difference up to 10 K between the city and surrounding can be observed [1]. This so-called Urban Heat Island Effect (UHIE) is supplementary amplified by directly draining off the water into the sewerage, which prevents cooling by evaporation [2]. With increasing urbanisation the impact of this phenomenon grows. Economical as well as social consequences occur. At elevated temperatures more energy is needed for the air conditioning of the buildings. Both the costs for cooling and the consumption of resources are increasing. The well-being and the health of the population are also negatively affected at very high temperatures, so that the performance of the working people goes down and actually the mortality rate rises too [3].

2 Thermodynamic principle

The mechanisms of heat transfer outlined in Figure **1** are responsible for the heating of concrete paving stones. Solar radiation is absorbed by concrete pavers. Thus, the surrounding air exhibits a gradient of temperature. This produces density difference in the air, which yields convection. This is intensified by the wind.

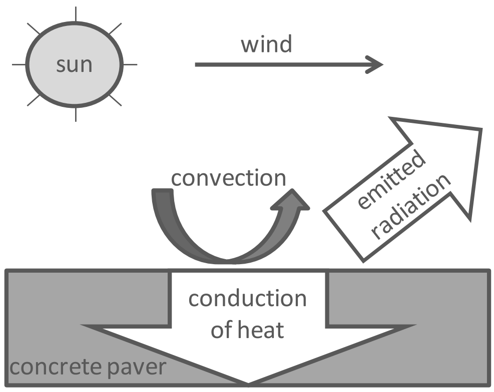

Figure 1: Scheme of the mechanisms of heat transfer.

In the concrete paver the heat transfer takes place by conduction and partly by emitted radiation from the stone. The intensity of the emitted radiation can be calculated with the Stefan-Boltzmann-Law (equation 1 [4]):

$$q = \varepsilon \cdot \sigma \cdot (T_s^4 - T_a^4) \quad (1)$$

Where:
ε = emissivity
σ = Stefan-Boltzmann-constant = 5.68 *10-8 W/(m²K4)
Ts = surface temperature [K]
Ta = environmental temperature [K]
High emissivity of concrete (ε = 0.94 [5]) declares the high intensity of emitted radiation. Due to the direct proportionality between emission and absorption, a higher amount of heat is stored by materials with high emissivity. Supplementary, with a value between 950 and 1200 J/(kg*K) [6] the specific heat capacity of concrete is relatively high while the heat conductivity for standard

concrete ($\lambda = 2.1$ W/(K*m) is low [7]). Thus the use of concrete generates a high capacity of heat storage. The surface temperature is incorporated into equation 1 to the fourth power. A decrease of 1 K of the concrete surface temperature already reduces the intensity of emitted radiation significantly. A well known approach to cool down a surface is already utilising for wine coolers. Stored water evaporates, if enthalpy withdraws from its surroundings, thus the surface temperature drops.
Thus, self-cooling concrete pavers should have the capability to store water, which can evaporate at elevated temperatures. The thus cooled surface reduces the air temperature above the sealed area. Hence, one approach to mitigate the Urban Heat Island Effect is the large-scale use of self-cooling concrete pavers in inner city areas.

3 Research objective and scope

Ordinary paving stones usually have a double layer structure- composed of face and mass concrete. Self-cooling concrete pavers (

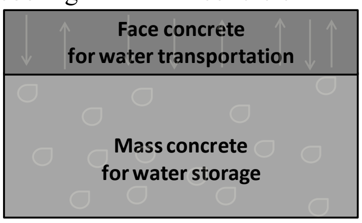

Figure 2) should have an optimized water transportation face layer and a mass layer for storing water. Though, appropriate properties as compressive strength, abrasion resistance or freeze-thaw resistance must not be negatively affected by this optimisation. At last the paving stones should also meet the aesthetic and economical requirements.

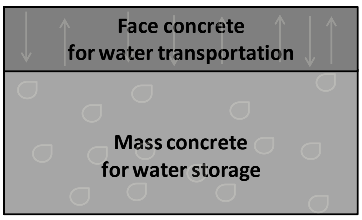

Figure 2: Scheme of the structure of the self-cooling concrete paving stone.

One solution to implement the described properties is the addition of viscose fibres to the face concrete mixture and the use of storage material (different granulates) in the mass concrete. This paper focuses on the influence on the surface temperature due to the different materials. Laboratory production of double layered paving stones is described and some results of the current research are shown.

3 Materials and sample production

3.1. Mixture for face concrete

For the basis no slump concrete with a maximum particle size of 4 mm was chosen. The water-cement-ratio (W/C) was 0.38. For the permeable face concrete fibres were added to the mixture to enhance the water transportation ability. Different fibres were used in an amount of 1, 2 and 3 % by volume. In previous research the compressive strength and the capillary water absorption of these mixtures were tested [8]. For further studies a mixture with 3 % by volume viscose fibres was chosen since it was found to be the best compromise between water transport and mechanical strength properties. The used viscose fibres possess a length of 6 mm and a density of 1.5 cm/m³.

3.2 Mixture for mass concrete

The same basic mixture was used for the face layer. For the mass concrete the incorporation of water storage material was essential. Therefore, parts of the aggregates were replaced by different materials with high water absorption: clay, waste materials (recycled concrete granulate, bottom ash), natural expanded materials (perlite, vermiculite) and materials of volcanic origin (vulkanite, lava stone and lava sand). The characteristic properties of the used materials are listed in Table 1.

Table 1. Overview of storage materials and their characteristics.

Storage material	Particle size [mm]	Particle gross density [g/cm³]	Water absorption after 24h soaking [vol.-%]
Fired clay (crushed)	0.5-1	1.310	27
Fired clay	0-4	1.280	20
Recycled concrete granulate	2-4	2.320	7
Perlite (fine)	0-1	0.098	49
Perlite (coarse)	0-3	0.117	39
Vermiculite	0-4	0.293	61
Bottom ash	0-4	1.180	38
Vulkanite (fine)	0.3-1	1.550	22
Vulkanite (coarse)	0.5-1.5	0.800	45
Light lave stone (ganulate)	0.63-2.0	2.490	9
Lave sand	0-1	2.710	5

The mixtures with fine perlite and recycled concrete granulate pointed out to be the best compromise out of the various storage materials shown in Table 1 in terms of the compressive strength and water absorption performance. Thus, these mixtures were selected for further research and testing.

3.3 Production of double layer testing samples

Double layer testing samples with dimensions of a typical paving stone (30cm x 30cm x 10cm) were produced on laboratory scale. For this purpose a mould was filled with no slump concrete and placed on the vibrating table. The mass was compacted on a vibration table in addition with an applied weight of m = 20.5 kg. The vibration of the table was 30 seconds with a frequency of f = 180 Hz. In contrast to the production in the factory the face layer was produced at first. After this first compaction of approximately 1 cm face layer the production of the thick layer with mass concrete under the same conditions followed unless for the last 15 s of compaction also the applied load was vibrating with a frequency of f = 50 Hz.

Supplementary to the mixture with viscose fibres, which was described in 3.1, a reference face mixture for comparison was chosen. For mass concrete three different compositions were mixed. Two mixtures include storage materials while the third is the reference one. Several combinations of the different layers were concreted and are shown in Table 2.

Table 2. Paving stone combination.

Notation	Face concrete	Mass concrete
V SP	Mixture with 3 vol.-% viscose fibres	Mixture with fine perlite
V CG	Mixture with 3 vol.-% viscose fibres	Mixture with recycled concrete granulate
R CG	Reference face mixture	Mixture with recycled concrete granulate
R RM	Reference face mixture	Reference mass mixture

The reference mixture was developed in a previous study, where standard mixtures for face and mass concrete from several paving stones producers were collected. These mixtures turned out to be the basis for this reference mixture.
After production the samples were stored for 24 h under a foil and afterwards stored uncovered in a climate chamber at T = 23 °C; RH = 50 %. After 28 days the paving stones were ground planar and divided vertically in two halves. Cylinder with a diameter of d = 70 mm were drilled out of one half, while the other half served as the sample for temperature measurements during radiation.

4 Testing Methods and Results

4.1 Compressive strength

The compressive strength of three cylinders of each double layer sample was measured according to EN 196- 1. Figure 3 shows the results of the test for every combination.

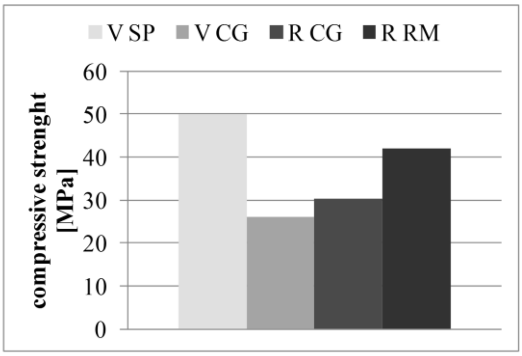

Figure 3: Compressive strength of different combinations

The tensile strengths requirements according to DIN EN 1338 are 3.6 MPa and for compressive strength approximately 38 MPa, respectively. This is met by combination "V SP" and "R RM". During the compaction, the stored water in the perlite was pressed out. The character of no slump was lost due to the higher amount of water, which was available for reaction with cement. A dense structure of mass concrete was yielded.
While the reference mixture has a typical no slump structure, the mixture with concrete granulates is more porous. Hence, the mixture "V CG" and "R CG" have a lowest compressive strength in this test series. The high porosity is not only due to the porous concrete granulate. The compaction method is a further reason for the more than 10 MPa lesser compressive strength compared to the reference. The compaction factor was calculated for the mixtures and listed in Table 3. The compaction of the face concrete was neglected at this point due to the small dimensions. Hence, the compactions factor is the ratio of the measured density of the mass concrete and the calculated density of the mass concrete. The differences are noticeable.

Table 3. Compactions factors

Combination	V SP	V CG	R CG	R RM
Compaction factor [%]	111	81	80	89

4.2 Capillary water absorption

The capillary water absorption was measured according to DIN EN 13057. Three samples for each combination were placed on bearing devices in a box. The box is filled with water until the devices are under water as shown in Figure 4. Immersion depth should amount to (2 ± 1) mm. After defined time steps the sample weights were measured and noted.

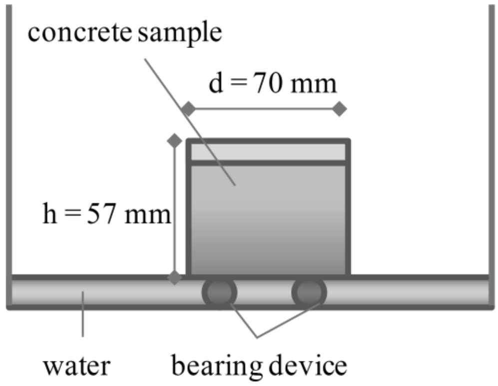

Figure 4: Scheme of the capillary water absorption test

Self-cooling concrete pavers require a high amount of capillary water absorption to transport the water for evaporation from the core to the top. The time dependent capillary water absorption is shown in Figure 5 for each combination.

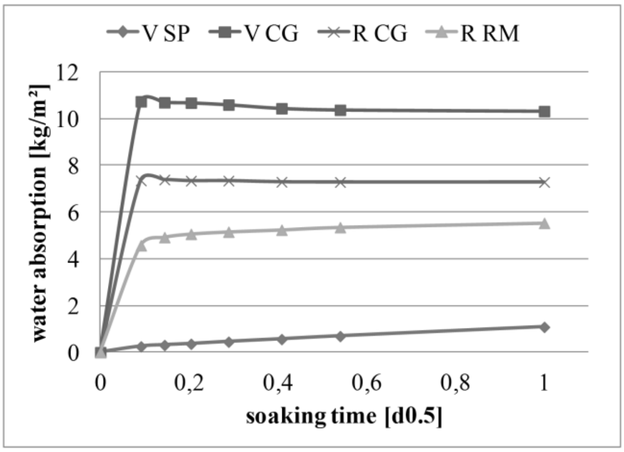

Figure 5: Time dependent capillary water absorption

The results of the capillary water absorption show an opposing trend compared to the compressive strengths. The combinations with the porous concrete granulates have higher water absorption due to the capillary pore size. Addition of fibres to face layer increase the water absorption markedly. On the one hand it could be explained by the soaking ability of viscose fibres and on the other hand by a porous zone, which forms around the fibres.

4.3 Cooling Effect Tests

Good water transportation properties are assumed, but for the efficiency of self cooling concrete pavers the cooling effect is essential. Thus a testing method for this effect is needed. Therefor one paving stone (h = 57 mm, a = 140 mm, b = 218mm) of each combination was saturated with water. Afterwards the samples were irradiated with infrared-heaters for 6 hours. During the radiation the surface temperature was measured continuously by thermocouples on the surface. For a better demonstration of the temperature differences infrared thermography was used.

Figure 6 shows thermal images of the four water saturated stone samples after a radiation of 3 hours. The thermocouples measured the surface temperature on the top layer, which is the fibre concrete or the reference concrete in this setting. While the sample a) and b) has the same face layer, the surface temperature differs. The same results is given for the samples c) and d) with the reference face layer. This suggests that the face layer only plays a minor role for the influence of the surface temperature after 4 hours radiation. To verify this, the samples were turned. The test was repeated with the mass layer on the top. The samples were water saturated again before radiation. The surface temperatures were measured from the top layer, which was the mass layer in this case. The thermal images are shown in Figure 7 for this position.

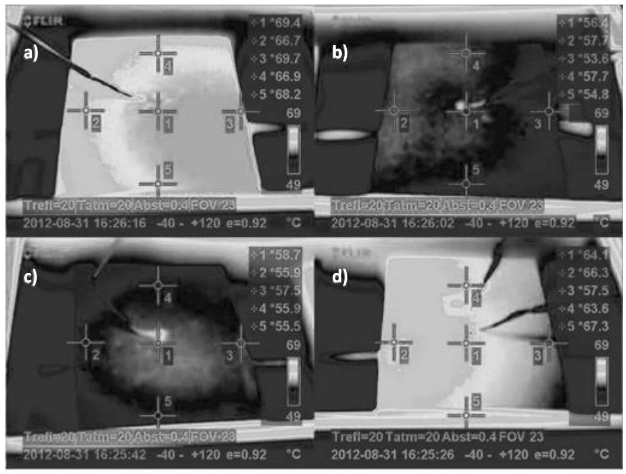

Figure 6: Thermal imaging after 4 hours radiation,
face concrete on the top,
a) V SP b) V CG c) R CG d) R RM

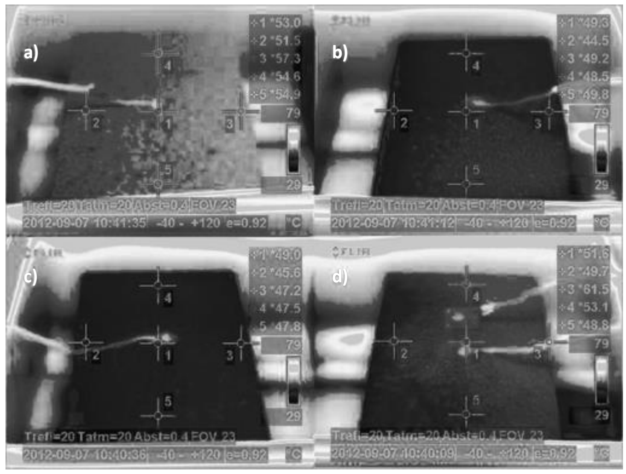

Figure 7: Thermal imaging after 40 min radiation,
mass concrete on the top,
a) SP V b) CG V c) CG R d) RM R

Temperature differences between the samples are lower than in the first case but still considerable. The expectation that the samples b) and c) show the same temperature due to the same concrete mixture was manifested. The concrete with perlite heated up the most.

The temperature rise can be related to the compaction factor. While the mixture SP1 was over-compacted, the samples with the concrete granulate only achieve a compaction factor of approx. 80%. The water absorption is increasing with decreasing compaction factor due to the higher amount of pores, which could fill with water. Hence more water evaporates and the surface is cooler for a longer time due to the better water supply.

The influence of different face layers on the temperature development is illustrated in Figure 8. For better demonstration, only the curves of the samples with concrete granulate but with different face layers are shown. While continuous lines represent the results for the setup, when the face concrete was on the top, the dotted lines represent the inverse case.

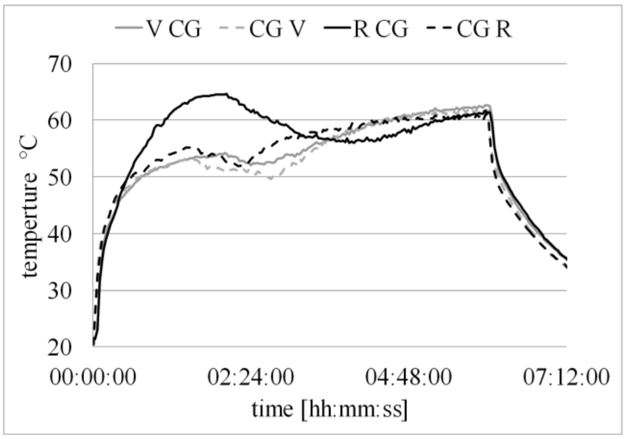

Figure 8: Time dependent temperature developing during IR-radiation

At the beginning the sample with the reference face concrete on the top is up to 10 °C warmer compared to the face concrete with viscose fibre. The reference concrete has a low ability to transport water due to the lack of viscose fibres. That causes a rapid drying. Hence the cooling effect by evaporation of water is also lost rapidly. The surface heated up until the water from the core (concrete with concrete granulate) is going up. Thus after 3.5 hours the temperature difference between the samples is marginal.

In case of the second setup, when the mass layer was on the top, both curves are very similar to the curve of the sample V CG (continuous line). Hence the cooling effect comes from the mass concrete.

5 Conclusions and Outlook

The possibilities to produce double layer concrete paving stones with an advanced performance were investigated. The aim was to develop self-cooling concrete pavers to mitigate the Urban Heat Island Effect. The compressive strength and the capillary water absorption were measured as the mandatory properties for this new paving stone. Supplementary, radiation tests to determine the influence of the surface temperature were accomplished. It was not surprising, that the mixture (V CG) with the lowest compaction have the lowest compressive strength and the highest capillary water absorption. However, it was shown, that the mass concrete is mostly responsible for the cooling effect. The results confirm the assumption that only with the substitution of granulates by material which has the ability to store water, a reduction of surface temperature is possible. The lowest surface temperature shows the sample with mass concrete with concrete granulates on the top and viscose fibre face concrete on the bottom. The conclusion would be to use only the CG mixture, but in the case of concrete pavers the compressive strength is as much essential as aesthetic issues. This applies accordingly also for self cooling concrete pavers with good water absorption. Last but not least the resistance of frost thaw is critical. With the slab-test this property will be tested in the next step of research.

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