Sponge concrete: a new cooling solution to fight the urban heat island effect

Sponge concrete : une nouvelle solution de refroidissement pour lutter contre les îlots de chaleur urbains

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RÉSUMÉ

L'accélération de l'urbanisation, combinée aux épisodes de canicule récurrents, intensifie l'effet d'Îlot de Chaleur Urbain (ICU). Ce phénomène majeur se traduit par une augmentation des températures, engendrant une hausse des consommations énergétiques, des préoccupations de santé publique et un impact sur la biodiversité. Les surfaces urbaines, en particulier les revêtements de sol imperméables qui absorbent et ré-irradient la chaleur, sont des contributeurs principaux à l'ICU. La gestion des eaux pluviales est également un enjeu crucial pour la résilience urbaine. Dans ce contexte, Holcim développe des solutions de béton perméable qui contribuent à la désimperméabilisation des sols et ouvrent la voie à des stratégies de refroidissement basées sur l'évapo(transpi)ration. Cependant, le déploiement à grande échelle de ces solutions est freiné par un manque de données expérimentales pour quantifier la performance de refroidissement. Les études menées ici visent à combler ce déficit en évaluant l'efficacité de l'évapotranspiration. L'étude se concentre sur la comparaison de deux matériaux hydrauliques : Un Béton Drainant (Hydromedia) d'une perméabilité de 5.10-2 m/s et un Béton Éponge (Sponge Concrete) d'une perméabilité de 2.10-6 m/s. Cette nouvelle technologie de béton rafraîchissant stocke l'eau de pluie dans sa porosité pour qu'elle soit évaporée lors des périodes chaudes et sèches.

ABSTRACT

The acceleration of urbanization, combined with recurrent heatwave episodes, intensifies the Urban Heat Island (UHI) effect. This major phenomenon results in a temperature increase, leading to higher energy consumption, public health concerns, and an impact on biodiversity. Urban surfaces, particularly sealing pavements that absorb and restitute heat, are primary contributors to the UHI. The management of stormwater is also a crucial issue for urban resilience. In this context, Holcim is developing permeable concrete solutions that contribute for the non sailing of soils and open the route for new cooling strategies. However, the large-scale deployment of these solutions is hampered by a lack of experimental data to quantify cooling performance. The studies undertaken here aim to fill this gap by evaluating the efficiency of evapotranspiration. The study focuses on comparing two hydraulic porous materials: A Draining Concrete (Hydromedia) with a permeability of 5.10-2 m/s and a Sponge Concrete with a permeability of 2.10-6 m/s. This new cooling concrete technology stores rainwater in its porosity so that it can be evaporated during hot and dry periods.

MOTS CLÉS

Béton drainant, Evapo(transpi)ration, Sponge city concept, Solutions rafraîchissantes

Cooling solutions, Evapo(transpi)ration, Pervious concrete, Sponge city concept

1 CONTEXT

Urban heat island (UHI) effect refers to the overall tendency of increased temperature in urban landscapes compared to surrounding rural areas. This phenomenon is linked to several causes, controllable and uncontrollable [1] higher anthropogenic heat in the cities (heat generated by vehicles, air conditioning systems, etc.), higher heat storage and release by materials in the urban landscape (dark materials, impervious pavements, higher roughness, etc.). Hence, the reduced natural landscapes, the properties of urban materials, a dense urban geometry, and weather and geography parameters are all factors contributing to reinforce the UHI phenomenon. In a context of rapid urbanization and climate change with recurrent heat wave events, it is urgent to provide solutions to build more climate resilient cities, as UHI not only causes economic and environmental concerns [2] but can also be at the origin of alerting health and safety issues for the citizens [3].

Multiple strategies are studied to act on UHI, among which one can find urban designs with optimal shading and convection, water related strategies through irrigation and blue infrastructure**,** the main principle is to consume part of the total energy received by the substrates to evaporate water. In fact, increasing the vegetation cover in urban landscapes is acknowledged as one the key levers to reduce the UHI effect [4–5]. These solutions, allowing a pervious substrate, act by two main mechanisms: evapotranspiration and shading. Evapotranspiration allows using part of the solar radiation to evaporate water, shading helps with reducing the energy received by the land cover. An additional effect of vegetation is its impact on air flow and heat exchange.

Cool materials are deployed as key levers to fight UHI. By acting on the albedo, white surfaces can be promoted but the reflection of solar radiation can be increased by the color used. Also, evaporative pavements could be an alternative solution. Evaporation of water from the pavement surface absorbs heat and cools the surrounding air. This cooling effect is like the way sweat cools our skin. Evaporative pavements promote this process, contributing to lower temperatures in urban areas. When water is present on the surface of the pavement, energy from the sun causes the water molecules to gain enough energy to transition from a liquid to a vapor (gas) state. This transition requires heat energy, which is taken from the surrounding environment, including the pavement surface and the air above it. The sponge city concept launched in China in 2013 in response to water management efforts provides benefits to fight UHI [6]. Hence authors investigated the use of permeable pavement [7] and the choice of wetting strategies [8] to optimize the Urban cooling of these materials.

2 EVAPO(TRANSPI)RATION PHENOMENOM

The knowledge of evapotranspiration of permeable (water retaining) concrete involves understanding the physics of drying of porous media. The physics of drying in saturated porous media involves interactions between water, air, and the porous structure itself. When water-saturated porous materials are subjected to drying conditions, a complex process of moisture migration and evaporation occurs. This process is governed by various physical phenomena that influence how water moves through the porous structure and eventually evaporates into the surrounding atmosphere.

In saturated porous media, capillary forces dominate. Capillary action draws water into the pores of the material against the force of gravity. As drying initiates, capillary forces cause water to move from smaller pores to larger ones, redistributing moisture within the material. This migration continues until equilibrium is reached between capillary forces, gravity, and the vapor pressure gradient between the material and the surrounding air.

As the drying process progresses, water at the surface of the porous material begins to evaporate into the air. Evaporation occurs due to the difference in vapor pressure between the water in the material and the drier air above it. This difference drives water molecules to transition from the liquid phase to the vapor phase. A drying front forms within the porous material as water is drawn toward the drying surface. This front separates the saturated region from the drying region. The rate of drying is influenced by the convective transport of water vapor away from the surface. Faster airflow enhances the vapor pressure gradient, promoting more rapid evaporation.

Vapor diffusion is another key factor. Water vapor moves from regions of higher vapor pressure to regions of lower vapor pressure. This vapor diffusion within the porous structure drives the transport of moisture towards the drying surface, allowing more water molecules to evaporate.

The drying process in porous materials can be categorized into different regimes based on the drying rate's temporal evolution.

- ✓ Constant Evaporation Rate: Initially, when the porous material is heavily saturated, the evaporation rate is comparatively high and remains relatively constant. This phase is akin to the free drainage stage in which excess water is rapidly eliminated from the material.
- ✓ Falling Rate Drying: As the drying advances and the water content decreases, the evaporation rate diminishes. This regime is often referred to as the falling rate period, where the rate of water loss becomes inversely proportional to the remaining moisture content. This stage is analogous to the matric suction-dominated phase, characterized by the gradual release of water from capillary-held pores.
- ✓ Low-Rate Drying: In the final stages of drying, when the material's water content is significantly reduced, the evaporation rate is notably low. This stage corresponds to the imbibition-controlled regime, where residual water is tightly held within micro-scale pores, necessitating an extended duration for evaporation.

3 MATERIALS & METHOD

3.1 MATERIALS

3 samples are tested and comaped with water and grass. Hydromedia is a pervious concrete with a very high permeability (5.10-2 m/s). Sponge material is a cement based material with a permeability around (2.10-6 m/s). Sponge concrete is a material combining both pervious and sponge materials. These solutions are patented.

3.2 EVAPO(TRANSPI)RATION METHOD

A specific evapotranspiration bench was developed to measure the evapo(transpi)ration of materials developed. The bench simulates chosen drying conditions (wind speed, relative humidity and temperature). The sample is prepared following a saturation protocol (pre-drying in 40°C, immersion under water and draining in 100%RH conditions). The saturation protocol allows saturating the pores which will retain water in high relative humidity conditions and disregards the water in the cavities of the samples which is drained out of the samples by gravity. This developed method measures both the mass loss through time of the sample and the temperature profile within the height of the sample (3 to 4 sensors are placed in the bottom, the middle, and the top of the sample).

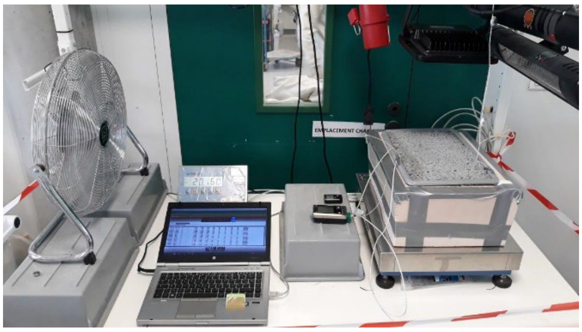


Figure 1: Bench used for evapotranspiration measurements

4 RESULTS

The results (Figure 2) show that:

- ✓ **References**: bulk **water** has a linear behavior of mass loss; **grass** had a decreasing rate
- ✓ **Hydromedia** shows a low mass loss kinetics and a low asymptotic value with time of drying
- ✓ **Sponge material** has an initial constant rate of mass loss followed by transitional decreasing rate and a final falling rate. The final mass is the highest for all the tested samples with roughly 0.5l of water evaporated per 1l sample.
- ✓ **Sponge concrete** shows intermediate features with an initial, brief, constant period rate followed by a decreasing rate of mass loss.

Figure 3 shows the results of samples expressed in evaporation rate (derivative of the mass loss) in terms of the saturation. For Hydromedia, the evaporation rate is rapidly in the falling rate with evaporation rate dropping significantly for saturation values below 80%. For Sponge material, an initial constant evaporation rate can be clearly distinguished, this regime can be maintained for saturation degrees higher than 40%, below a saturation of 40% the evaporation rate decreases. Although the evaporation rate decreases for Sponge material below this value, the evaporation rates are higher than the evaporation rates for Hydromedia or Sponge Concrete. For Sponge concrete, the evaporation rates drop linearly with decreasing saturation.

The presence of an initial constant rate period is an indication of the ability of the material to maintain a high-water flow to the surface through capillary water transfer. This feature is mainly noted for the Sponge material for saturation degree higher than 40%, whereas for Hydromedia, the drying regimes is within the falling rate period as soon as the drying starts. Sponge Concrete is an intermediate between the two materials: a brief stationary period is observed followed rapidly by the falling rate period.

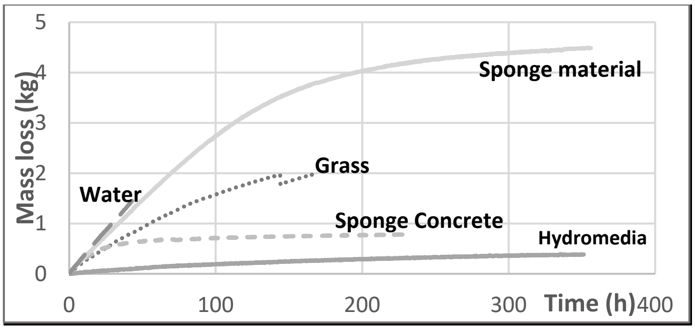
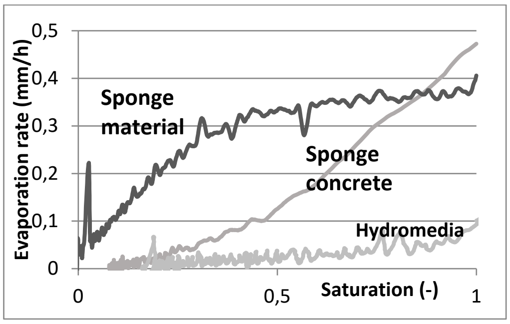


Figure 2: Mass loss of different solutions as a function of time



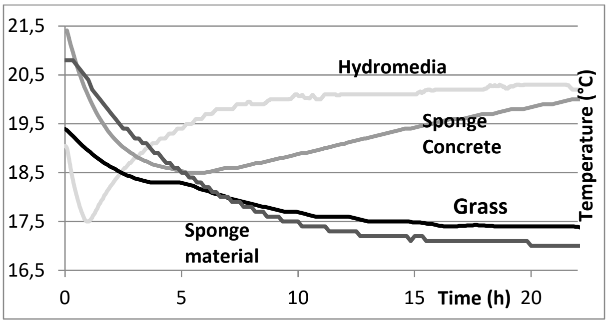


Figure 3: Mass loss of different solutions as a function of time

Figure 4: Temperature measurement in the samples

Figure 4 shows the temperature in the middle of the sample for tested materials. The observations are :

- ✓ **Hydromedia** shows a sharp decrease in temperature of 1.5 °C within the first hour.
- ✓ **Sponge material** shows a gradual decrease in temperature over time reaching a difference compared to the initial temperature of 3.5 °C, this refreshment is maintained for duration higher than 20h
- ✓ **Sponge Concrete** shows an intermediate behavior between Hydromedia and RIMS where a decrease of 3 °C is noted within the first 5 hours of drying, beyond which the temperature starts to rise gradually.
- ✓ For the sample of **grass**, a decrease in temperature of 2 °C is noted over duration of more than 20h

The developed evapotranspiration bench successfully evaluated the water management and cooling performance of porous solutions. Sponge material proved superior, maintaining a constant evaporation rate and providing the most significant, sustained cooling effect due to excellent capillary transfer. Conversely, Hydromedia exhibited rapid drying and minimal cooling. The study highlights that the inclusion of Sponge material is essential for maximizing water retention and achieving durable evaporative cooling in Sponge concrete. This new solution opens a new route for the Urban cooling.

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