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Innovative composite materials with enhanced acoustic, thermal, and optical performance for urban pavements: experimental characterization

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ABSTRACT

Over the last decades, the implementation of innovative multifunctional materials for urban surfaces has produced a variety of paving solutions characterized by self-cleaning, self-healing, electricity conductive, solar reflective, sound absorbent properties and so on. Therefore, a key challenge is nowadays represented by the need for combining multi-physics properties in a single material or system for flooring. The present work concerns the development of a new outdoor paving application with enhanced acoustic, thermal, and optical performance. To this aim, eleven concrete mix-designs were tested. The composites were characterized by different aggregate size, material and additives. The aggregates included in the composite consist of (i) natural stones with different grain sizes, (ii) expanded clay aggregates, and (iii) glass fragments. Acoustic, thermal, and optical measurements were performed for each sample. Additionally, a dedicated in-field monitoring campaign was carried out to characterize the albedo under summer boundary conditions. Finally, the thermal behaviour of the samples was tested in an environmental chamber using controlled boundary conditions in terms of temperature, humidity, and radiation. The results demonstrate that bigger grain size presents the best acoustic performance in terms of absorption capability, i.e. absorption coefficient of about 0.9 and 0.8 at 1000 Hz and 500 Hz, respectively. Moreover, the thermal-optical lab and field tests confirm previous literature results demonstrating that the mix-design with the smaller grain size has the best reflectivity potential.

KEYWORDS

Paving materials; Optimized mix-design; Thermal-optical performance; Acoustic properties.

INTRODUCTION

Urban environments are often affected by microclimate phenomena such as Urban Heat Island (UHI), a local condition that can significantly harm the health and the quality of life of citizens. In particular, the UHI consists of a significant increase in temperature in the urban area compared to the surrounding rural areas (Vardoulakis, Karamanis, Fotiadi, & Mihalakakou, 2013). Such phenomenon is generally influenced by the thermal and radiative properties of the typical urban surface materials (i.e. asphalt, cement) where the absorption of solar radiation prevails over its reflection (Taha, 2008). Moreover, the human action and the buildings operation strongly contribute to the overheating of urban areas. Such contribution is (i) direct, through traffic, industrial activities and HVAC systems, and (ii) indirect, though the alteration of the radiative properties of the atmosphere due to the high levels of associated pollution (Pisello, 2017). Over the last few decades, many techniques have been proposed for the mitigation of such phenomenon. Among the main ones there is the use of permeable surfaces in urban environment, consisting of gravels or vegetation able to generate surface cooling by means of evapotranspiration. Furthermore, "cool" materials represent another suitable solution for reducing high urban temperatures (Santamouris, Synnefa, & Karlessi, 2011). These materials are characterized by a high solar reflectance and thermal emissivity that avoids overheating of the surfaces and the air near them. The benefits achievable when installing a cool material over urban paved surfaces can be summarized as follows (Rosso et al., 2017): (i) mitigation of the urban overheating thanks to the capability to reflect most of the incoming incident solar radiation and (ii) consequent reduction of CO_2 emissions emitted in the environment. Another issue typical of urban environments relates to the high noise levels in cities and is referred to as Urban Noise Island (UNI), where depending on the road and tires characteristics and of course on the vehicles' speed, the prominent noise peak very frequently is found at 1000 Hz but it may also be shifted within the range 630-2000 Hz (Sandberg 2003). It is generated by the combination of the different and multiple sources of noise (such as traffic, industrial activities, etc.) that generate sound pollution in urbanized environments (Asdrubali et al., 2015). The study of this phenomenon, which depends on both the generation and propagation of sound, involves the environmental analysis of the external and internal sources at building level, of the control actions on the source, on the propagation path and on the receptor, as well as on the analysis of the response of the human ear to sound stress. In this case, the main mitigation techniques consist of passive type protections that act on the propagation path or on the receptor. In this sense, to reduce the problem of urban noise it is possible also to act on the shape of the buildings, i.e. mainly on the acoustic requirements of the façade (i.e. acoustic insulation). Based on the framed background, the present research work deals with the development, characterization and optimization of concrete-based materials with high-thermal and acoustic performance for urban paving applications. The aim is therefore to implement innovative materials able to mitigate both the UHI and UNI when installed over urban pavements. To this purpose, an extensive experimental laboratory and field campaign was carried out and different mix design where tested and compared in terms of their coupled thermal-acoustic behavior.

MATERIALS AND METHODS

Five different components were selected and used to produce advanced concrete mix designs with enhanced acoustic and visual performance to be used as urban pavements: sand (i.e. fine grains, 0-4 mm), pebbles (i.e. medium grains, 2-5.6 mm), chippings (i.e. large grains, 4-12.5 mm), glass fragments (4-12.5 mm) and expanded clay spheres (2-5 mm). These components were alternatively treated with titanium dioxide to maximize their capability to reflect solar radiation. The samples had a diameter of 10 cm and 2.9 cm and a thickness of 6.5 cm for the laboratory acoustic tests (i.e. for the evaluation of the acoustic absorption).

Starting from the first basic paving mix-design (i.e. traditional paving recipe chippings-based), additional samples were prepared, by varying (i) type of aggregate (sand, pebbles, chippings, expanded clay spheres, and glass fragments), (ii) TiO_2 treatment, and (iii) kind of additive (i.e. dynamon floor 20 and bt02) in the case of the pebble mix design.

Thermal-optical in-lab experimental analysis

Firstly, spectrophotometric measurements were carried out to investigate the reflectance capability of the different evaluated samples. The experimental campaign was performed by using a Shimadzu UV-VIS-NIR spectrophotometer equipped with a double-radius optical system over time and integrating sphere. Moreover, the calculation of the spectral solar reflectance in the range 300-2500 nm was carried out according to the ASTM E903-12

Standard Test Method (American Society for Testing and Materials, 2010b). Secondly, the thermal emissivity of the samples was measured by means of a portable emissometer according to the ASTM C1371 Standard Test Method (American Society for Testing and Materials, 2010a). Finally, a DM340SR (ATT) climatic chamber was used to test the thermal behavior of the samples within controlled dynamic conditions in terms of temperature, humidity and solar radiation (Fabiani & Pisello, 2017).

Acoustic in-lab experimental analysis

In order to characterize the acoustic properties of the selected materials, the impedance tube was used. To this aim, a Brüel & Kjær Kundt's tube with all the related equipment and accessories was used. The measurements were carried out according to the classic standardized procedures in materials analysis in the lab (Asdrubali et al., 2015). The test procedure involved at least three measurements for each sample to obtain an acceptable result reliability. Finally, the comparison between the absorption coefficients of the different samples was made considering the average value of the measurements carried out for each sample.

Albedo field monitoring

After the preliminary in-lab experimental campaign, the albedo of the samples was monitored in-field by means of a dedicated double pyranometer or albedometer, an instrument able to measure both the incident solar radiation and the one reflected from the surface between 300 and 2500 nm. The experimental measurement campaign was carried out according to the ASTM E1918-06 international standard (2006). The experimental campaign was performed in the period from 10 July to 10 August 2017 to characterize its reflectance potential when the climatic forcing to the boundary and the meteorological conditions vary. To this end, after the measurement of black and white reference samples (Akbari, Levinson, & Stern, 2008) the different samples were monitored on typical summer days.

RESULTS

Thermal Emissivity and Solar Reflectance

In this section, the results of the testing of the thermal-optical properties of the samples are presented. In particular, Figure 1 shows the trend of the solar reflectance of fine sand, mortar and pebbles concrete mix designs, and the obtained solar reflectance (SR), emissivity (ε) and solar reflectance index (SRI). It is clear how the solar reflectance increases as the grain size decreases. In fact, as can be seen by comparing the pure mortar with the mix designs produced by introducing the same amount of sand or pebbles, the sample with fine sand shows the greatest solar reflectance, followed by pebbles and the traditional mortar. In terms of thermal emissivity, the values are generally high, i.e. varying from to 0.91 (mortar) to 0.99 (fine sand).

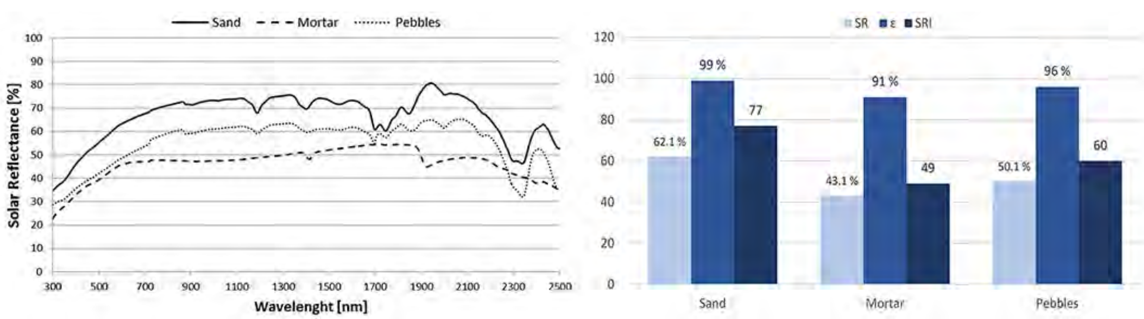

Figure 1. Solar reflectance profiles in the range 300-2500 nm, SR, ε and SRI of the samples.

Dynamic controlled environment: climatic chamber

This section summarizes the results of the tests carried out in the climatic chamber. The purpose of the tests was to investigate and compare the thermal behavior of the samples under the same controlled dynamic environmental conditions, i.e. a typical summer day in the Rome climate zone taken from the TMY (Typical Metereological Year). Therefore, the surface temperatures of the upper and lower face of the samples was measured with varying air temperature, relative humidity, and incident solar radiation.

Figure 2 shows how the samples containing fine sand present the best surface thermal behaviour, followed by the mortar and the pebbles mix design with the Dynamon 20 additive, which possess the highest thermal inertia due to their highest density and the samples with TiO_2 and glass fragments, which are capable to reflect the highest amount of the incoming radiation (an average direct radiation on the horizontal surface of 820 W/m^2 was imposed through the halogen lamp according to data from the TMY). On the other hand, expanded clay sphere and pebbles samples with bt02 or without any additive, which are characterized by a larger grain size and lower densities, show the worst performance in terms of surface temperature, reaching up to 68°C.

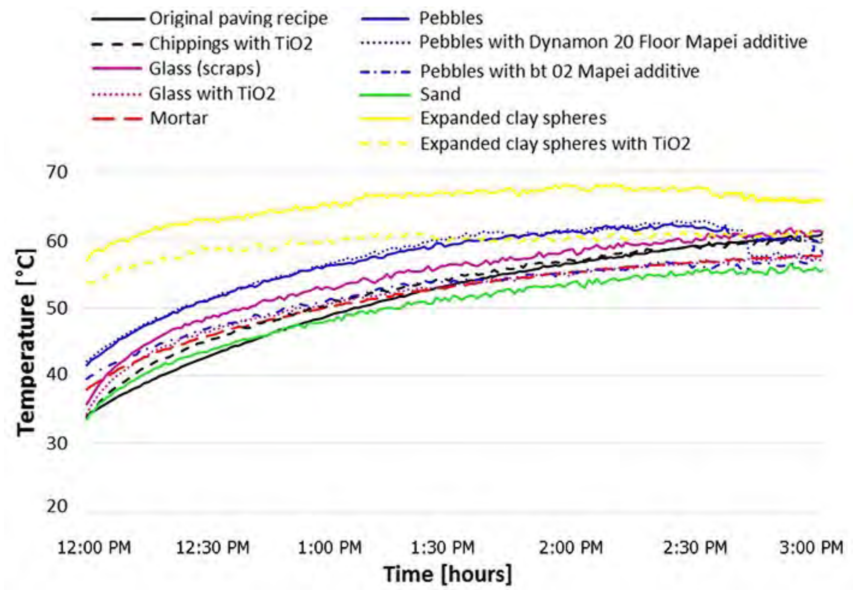

Figure 2. Average temperatures of the upper (left) and lower (right) surface of the samples.

Albedo in-field measurements

Table 2 shows the albedo values measured in the field during typical summer days (July 2017) for the different samples of paving material produced. It is evident how the paving recipe characterized by the presence of glass fragments and TiO_2 treatment present a greater albedo than all the other samples, followed by the expanded clay spheres with TiO_2 treatment. The paving samples produced using the original recipe with chippings included, and the one characterized by the presence of pebbles are those with lower potential in terms of albedo. These results are consistent with previous studies showing that albedo increases with decreasing grain size.

Table 2: Albedo test results.

Sample	Traditional asphalt	Original paving recipe	Expanded clay spheres+ TiO_2	Glass fragments + TiO_2	Pebbles
Albedo (12-3PM)	~7	37.9	40.8	44.4	36.8

Acoustic absorption coefficient

Figure 3 shows the trend of the acoustic absorption coefficient for the various samples tested with respect to the original paving recipe. The sample of the original pavement recipe is not very absorbent. In fact, the maximum absorption coefficient is equal to 0.2 at 450 Hz. As for the mortar sample, this has a maximum absorption coefficient equal to 0.2 at 600 and 1300/1400 Hz. As regarding the samples with aggregates of different grain sizes, the sand has a maximum absorption coefficient of 0.2 at 400 Hz, and then remains almost constant (<0.1) at the other frequencies. The sample with pebbles, on the other hand, presents a bell-shape absorption coefficient with a positive peak of 0.85 just before 600 Hz and a negative peak of less than 0.2 at about 1600 Hz. The clay sphere sample is characterized by a high absorption coefficient, with a peak of 0.9 at 600 Hz. As for the mix design with chippings and TiO_2, a maximum absorption of 0.3 between 500 and 600 Hz is reached. Subsequently, the absorption capacity decreases at about 0.1 between 800 and 1200 Hz, then decreasing again. By adding the bt02 additive, the aforesaid sample becomes very absorbent, with a maximum absorption coefficient of 0.9 at 500 Hz. By adding a different type of additive ("Dynamon"), the absorption coefficient reaches a value of almost 0.8 at 500 Hz. The sample produced using expanded clay spheres and TiO_2 has a very high absorption capacity, up to a maximum value of 0.8 at 500 Hz. The sample with glass fragments, on the other hand, has a low absorption capacity, with a maximum of less than 0.2 at 450 Hz. By adding the TiO_2 to the present recipe, the absorption coefficient increases slightly to 0.25 at 600 Hz and then decreases at the other frequencies.

Based on such results, the mix-design showing the highest absorption coefficient is that with pebbles, with and without additives, and the expanded clay spheres one, with and without TiO2. All the other samples examined show absorption coefficient peaks ranging from about 0.2 to 0.3. On the other hand, samples with pebbles and expanded clay spheres reach peaks of almost 0.9 with respect to the traditional paving recipe which almost does not reach 0.2. It is also possible to notice that all the tested samples have an absorption coefficient peak between 400 and 600 Hz.

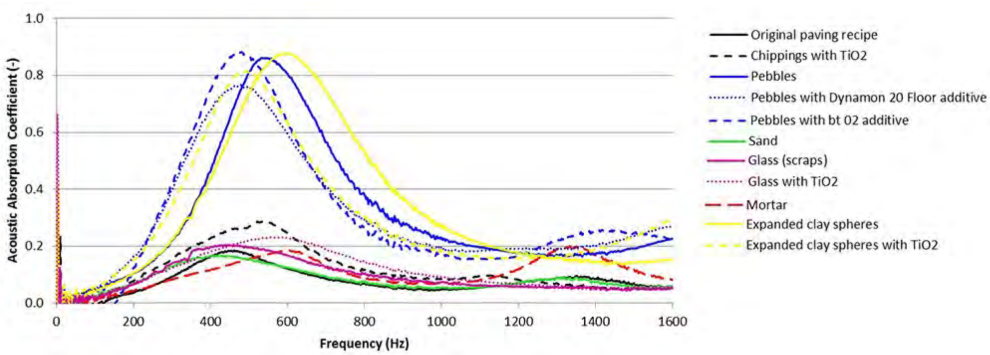

Figure 3. Comparison among the acoustic absorption coefficients of the tested samples.

CONCLUSIONS

The present work aimed at developing and experimentally characterize the thermal and acoustic performance of composite materials for external urban paving. To this purpose, samples of different materials were produced, with varying mix design, particle size, and components (i.e. natural gravel, glass fragment, expanded clay). Results from the experimental campaign allowed to identify the best recipe for urban paving application depending on the need to optimize the performance in terms of solar reflectance, thermal emissivity, albedo, surface temperature and/or absorption and sound insulation potentiality. In general, it was found that to optimize the thermo-optical performance of the paving it is necessary to reduce the grains size of the aggregates as much as possible. In fact, the solar reflectance increases as the particle size of these components decreases. As far as the albedo is concerned, the tests demonstrated that to improve the performance of the original paving mix it is appropriate to integrate glass fragments and TiO_2 (40% enhancement of the albedo compared to the traditional base-case paving recipe). As for the optimization of the acoustic behavior, it was shown that the best absorption performances are achieved by the samples in loose configuration, due to the interstitial voids that increase the amount of sound energy dissipated by the interaction between the solid matrix and the air molecules. Furthermore, it was possible to notice how the two different configurations (i.e. low density and high density mix design) work properly at different frequencies. Therefore, to maximize the acoustic performance of urban paving materials it is necessary to select materials that work well at low frequencies. In this view, the best materials in terms of acoustic absorption potential are those ones with expanded clay balls, which allow an improvement up to 0.6 (300%) compared to the original paving.

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