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Article

Experimental Analysis of Natural Gravel Covering as Cool Roofing and Cool Pavement

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Abstract: Passive solutions for building energy efficiency represent an interesting research focus nowadays. In particular, natural materials are widely investigated for their potential intrinsic high thermal energy and environmental performance. In this view, natural stones represent a promising solution as building envelope covering and urban pavement. This paper concerns the experimental characterization of several low-cost and local gravel coverings for roofs and urban paving, properly selected for their natural high albedo characteristics. To this aim, the in-field albedo of gravel samples is measured with varying grain size. These in-field measurements are compared to in-lab measurements of solar reflectance and thermal emissivity. The analysis shows a significant variation of the albedo with varying grain size. Both in-lab and in-field measurements agree that the stones with the finest grain size, *i.e.*, fine sand, have the best optic-thermal performance in terms of solar reflectance (62%). This feature results in the reduction of the surface temperature when exposed to solar radiation. Moreover, a natural mixed stone is compared to the high reflectance stone, demonstrating that the chosen stone presents an intrinsic "cool" behavior. Therefore, this natural, low-cost, durable and sustainable material could be successfully considered as a natural cool roof or cool paving solution.

Keywords: cool roof; cool paving; highly reflective gravel; in-field albedo; energy efficiency in buildings; cool pavements; urban heat island; reduction of cooling demand

1. Introduction

1.1. Research Background

In the last few years, several energy savings strategies have been proposed by researchers and designers in order to improve buildings' energy efficiency, due to the relevant energy consumption, greenhouse gas emissions and pollution production attributable to the construction sector [1,2]. Passive solar design techniques for building envelopes, with the goal of enhancing the global energy performance and the indoor comfort level, have been developed [3], in addition to varying energy retrofitting measures to reduce the energy consumption of existing buildings [4]. The combination of specific passive cooling technologies, such as roof ponds, dynamic insulation and natural ventilation, could lead to a 43% reduction in building energy consumption, both in hot and humid climates [5]. In this scenario, materials with high solar reflectivity and high thermal emissivity for building envelope applications represent effective passive technologies for the reduction of the energy requirement for cooling [6]. Much international scientific research has focused on highly reflective building facades and "cool roof" solutions [7,8], with the purpose of investigating effective and financially-sustainable solutions for decreasing building energy peak demand for cooling and, additionally, mitigating the urban heat island effect. Comparative studies were performed by Doulos *et al.* [9], with the aim of investigating the suitability of materials used in outdoor urban spaces in order to lower ambient temperatures and reduce the heat island effect. Covering materials have been classified into "warm" or "cool" materials according to their thermal-physical properties, in order to select more appropriate materials for both the reduction of building energy requirements and the improvement of outdoor/indoor thermal comfort conditions. Several numerical and experimental studies have demonstrated that the adoption of cool roof technology could result in a decrease of over 70% of the energy requirement for cooling [10]. Akbari *et al.* [11], for instance, provided a detailed guide on light-colored surfaces, showing that significant energy savings are possible with a proper selection of light-colored covering materials in combination with the planting of new trees [12]. In the same scenario, Vardoulakis *et al.* [13] characterized and tested different aluminum-modified clay materials for their significant potential application as solar coolers of roof surfaces through evaporation. Therefore, cool roofs result in a lower ambient temperature that decreases the need for air conditioning and delays smog formation [14,15]. Moreover, "cool community" strategies of re-roofing or re-paving with lighter colors, which could substantially affect energy savings in terms of air conditioning, have been proposed by Rosenfeld *et al.* [16]. Additionally, Santamouris *et al.* [17] assessed that cool paving materials contribute to the reduction of peak ambient temperature, especially during summer, by consequently decreasing the intensity of the heat island effect and improving global environmental quality of the considered area.

Surface albedo plays an important role in the thermal-energy behavior of pavements and other ground surfaces and their resultant impact on humans and the environment. Bretz *et al.* [18] showed therefore that significant energy saving and increased comfort levels of urban areas can be reached through solar-reflective and high-albedo materials, by estimating the achievable increases in albedo for different surfaces. There are several existing approaches for measuring albedo, *i.e.*, laboratory, field and remotely sensed. Berdhal *et al.* [19] used the laboratory's spectral radiometer combined with a solar simulator to measure the spectral reflectivity of small samples. The same spectral radiometer technology can be flown on an aircraft or satellites to remotely sense surface albedo [20]. Portable devices for field measurement of albedo were experimented by Sailor *et al.* [21]. This method consisted of the use of a cylindrical shade ring made of opaque fabric with a known (low) albedo placed over a test surface. In this case, the measurement of albedo was accomplished by using two pyranometers situated so that the downward-facing pyranometer receives radiation only from the test surface and the shade ring. This method improved past approaches by allowing for smaller sample sizes, minimizing errors associated with the reflective properties of the surroundings, and allowing for accurate measurements, even under partially cloudy skies. Additionally, Li *et al.* [22] developed another albedo measurement system with a dual-pyranometer and automatic data acquisition system and used it to perform field measurements of the albedo of different pavements and for long-term monitoring. The albedo values were obtained for commonly used land cover materials, including asphalt, concrete and interlocking concrete paver materials with different designs.

In this scenario, the present work concerns the experimental evaluation of the in-field albedo through albedometer and in-lab solar reflectance through a spectrophotometer of a natural covering gravel for cool roofing and cool paving applications. The potentialities of such simple and low-cost, sustainable solution are discussed in terms of cool materials for energy savings in buildings and "cool" urban paving [23,24]. The comparison between both the experimental in-field and in-lab campaign is therefore carried out, and the albedo variation with different grain sizes of gravel is assessed.

1.2. Objectives of the Research

Gravel roof covering represents one of the most diffuse roof coverings for horizontal roofs in Mediterranean countries. It is mostly applied over bitumen waterproof membranes, with the purpose of preserving the membrane's integrity and to prevent the membrane from ripping off. Additionally, it contributes to the further thermal capacity of the roof and to its cooling performance, given its higher reflectance with respect to the more traditional black bitumen membranes. Nevertheless, gravel use for roofs and urban paving is still not considered as a cool paving or cool roof solution, like commercial high reflectance and high emissivity coatings. The main reason is imputable to the lack of knowledge about the reflectance and emittance properties of such a roof and urban covering, which represent the two most important parameters affecting the cooling thermal behavior of the covering. The purpose of the present work concerns the experimental characterization of a series of natural gravel coverings for horizontal roofs and urban paving. In particular, a local natural stone with a relatively high reflectance is compared to traditional materials, *i.e.*, asphalt is chosen, and different grain sizes are evaluated and compared for their inner cooling capability. Additionally, a common mixed natural gravel is characterized and compared to the naturally light gravel in terms of thermal-energy properties. Both in-field and in-lab measurements are performed, in order to identify a suitable reflective gravel for applications as building envelope covering and outdoor paving, in terms of both the passive cooling contribution and the reduction of the urban heat island effect at the inter-building level. In particular, a three-month in-field monitoring campaign of the albedo of the different gravels is carried out. These in-field measurements are therefore compared to the in-lab measurements of solar reflectance by a spectrophotometer. Finally, the thermal emissivity and surface temperature of the gravels are measured through a portable emissometer and temperature probes, respectively.

The main goals of the present work are therefore to: (i) perform in-lab and in-field measurements of the solar reflectance/albedo of the same natural gravel by comparing different grain sizes; (ii) compare the in-lab and in-field measurement results; and (iii) quantify the variation of the albedo with different grain sizes of the same natural gravel cover.

2. Methodology

The present study consists of three main sections:

- In-lab experimental campaign;
- In-field continuous monitoring;
- Comparison of the results and elaboration of the findings;

2.1. In-Lab and In-Field Measurements: Materials and Methods

The in-lab experimental campaign consisted of the measurement of the radiative properties of prototype samples (10 cm × 10 cm), namely the solar reflectance and the thermal emissivity (Figure 1).

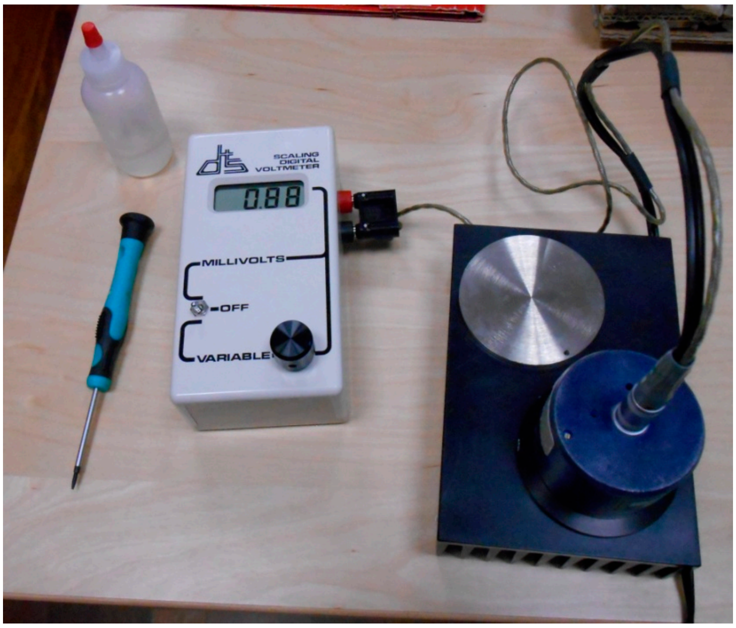
Figure 1. Five gravel samples used for the in-lab measurement, *i.e.*, “1”, “2”, “3”, “4” and “5”.

The solar reflectance of the small-square samples was measured following the ASTM E903-12 [25] Standard Test Method and the ASTM G173-03 [26] and by using a Shimadzu UV-VIS-NIR spectrophotometer equipped with an integrating sphere (Figure 2). In particular, the calculation was carried out in accordance with the regulations cited above, and the preparation of the samples was in-house made. Therefore, the surface of the samples is not perfectly homogenous, as required by the current standards, due to the different dimensions, shapes and roughness of the gravels. The output values for each measurement were post-processed according to standard procedures in order to get the results in terms of reflectance in the UV, VIS and NIR range of the solar spectrum.

The thermal emittance of each sample was therefore measured by means of a portable “Devices and Services (D&S)” emissometer model AE1 (Figure 3), according to the ASTM C1371 Standard Test Method [27]. The emissometer returns the hemispherical IR emittance as a value between 0 and 1 with a two-digit precision. Before the measurement, the instrument was calibrated using high (*i.e.*, 0.88) and low-emissivity (*i.e.*, 0.06) reference samples. Moreover, the instrument was frequently calibrated during the measuring process by using the high emissivity reference sample in order to minimize the inaccuracy caused by the instrument drift.

Figure 2. The spectrophotometer.

Figure 3. The portable "D&S" emissometer model AE1" emissometer.



Even if this measurement method is specifically developed for homogeneous and smooth surfaces, this in-lab activity is aimed at performing a comparative analysis among the tested samples, in order to investigate if the expected differences in terms of solar reflectance could be qualitatively detected by the spectrophotometer.

With the purpose of characterizing each gravel surface exposed to natural solar radiation, outdoor measurements were also carried out by means of an albedometer, according to the ASTM E1918 [28]. The in-field albedo measurements for the study were performed on 4 m × 4 m test fields situated over a flat roof of a university building in Perugia, Italy (Figure 4). The experimental field test included four different grain sizes of the same natural and high reflectance local gravel (Figure 5) typical of the local environment and an additional type of common mixed gravel, *i.e.*, "5".

Figure 4. Experimental field-test. Two images of several visible impressions with varying sunlight.

Figure 5. A natural covering gravel typical of the local environment of Perugia, Italy.

The five evaluated gravel coverings characterized with different grain sizes are listed in Table 1.

Table 1. Description of the gravel samples.

NAME	GRAIN SIZE (mm)
"1"	8–22.4
"2"	4–12.5
"3"	2–5.6
"4"	0–4
"5"	4–12.5, such as Type 2

A dual pyranometer or albedometer (Figure 6), able to measure both the incoming and reflected solar radiation on a surface, has been used to measure the albedo. Separate outputs are collected by each pyranometer every 10 min. The data are therefore automatically recorded by means of a dedicated data-logger (Figure 7).

Figure 6. The albedometer setup.

Figure 7. Data logger used for outdoor data collection.

The test procedure is weather sensitive and requires a cloudless sky and a sun angle to the normal of the field of less than 45° in order to obtain appropriate solar reflectance values, according to the ASTM E1918 [28]. Additionally, five temperature sensors were positioned over the gravels, in order to measure the surface temperature of each natural cover (Figure 8).

Figure 8. Temperature sensors located over the gravel's experimental field.

2.2. Plan for Measurements

The in-lab experimental campaign was performed in order to have at least five and two measurements with the spectrophotometer and the emissometer, respectively, for each prototype of the gravel samples.

The in-field albedo measurements and monitoring campaign were performed from September to November 2013. The albedo values were measured for each prototype in four/five days per month, continuously over time, from 9:00 a.m. to 6:00 p.m.

The external surface temperature of the in-field gravel was continuously recorded by five sensors, each one in each different gravel. Additionally, weather data concerning air temperature, relative humidity, solar radiation, rainfall, wind speed and wind direction were registered during the monitoring period, by using a continuously monitoring weather station situated over the same roof.

3. Results and Discussion

3.1. In-Lab Measurements

The trends of the samples' solar reflectance, within the range of wavelengths from 300 nm to 2500 nm, are reported in Figure 9.

Figure 9. Comparison between the solar reflectance profiles of the five gravel samples in the solar spectrum.

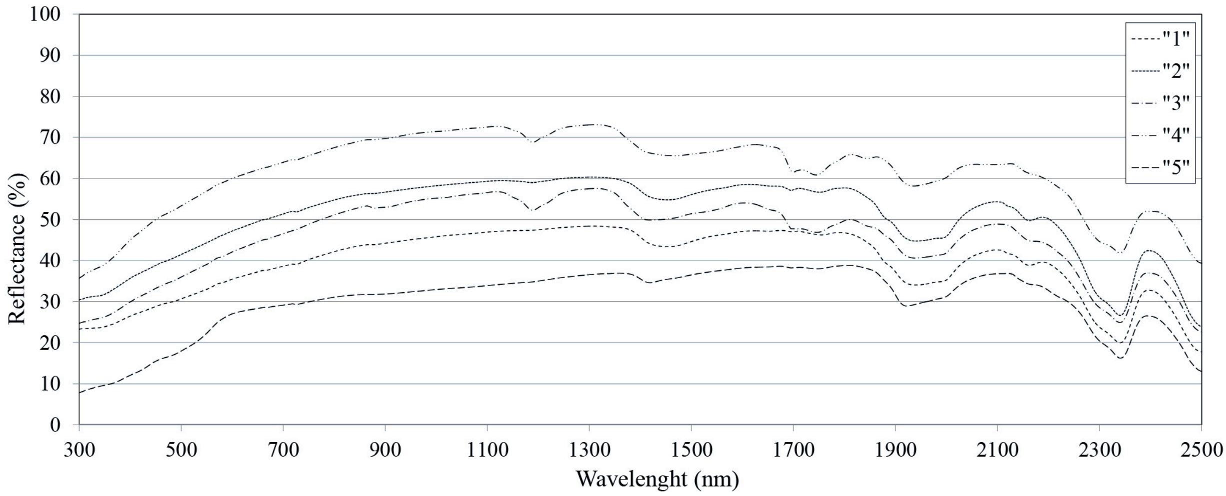


Table 2 shows the post-processed solar spectral reflectance values for each gravel sample measured by the spectrophotometer, according to the current regulations.

Table 2. Solar spectral reflectance of the five gravel samples according to the spectrophotometer.

NAME	SOLAR REFLECTANCE (%) (300–2500 nm)
"1"	38
"2"	50
"3"	45
"4"	62
"5"	27

The in-lab values show that "4", the sample characterized by the smallest dimension of grains (sand), has the highest solar reflectance (*i.e.*, 62%) compared to the other gravels. Moreover, the mixed gravel, *i.e.*, "5", which is commonly used for urban paving without paying attention to the stone finishing for "cooling" purpose, is characterized by the lowest solar reflectance (*i.e.*, 27%). Additionally, Figure 9 shows homogenous, consistent trends of the solar reflectance of the gravels, for the whole wavelength range. This is due to the fact that the material is the same for every sample, but the grain size varies, generating a change of the samples' optical surface properties. Therefore, it is evident that a different grain size of the same gravel produces differences in the solar reflectance values. In fact, by comparing "4" and "1", the samples with the smallest (*i.e.*, "4") and biggest (*i.e.*, "1") grain size, a solar reflectance decrease of 24% is measured. This is also due to the fact that "4" is the most homogeneous sample.

Moreover, by comparing "2" and "5", two gravels with the same grain size and a different stone typology-nature, it is clear that the naturally reflective gravel typical of the local area (*i.e.*, "5") is able to produce an important increase of the solar reflectance in all wavelength ranges in the solar spectrum.

In particular, the solar reflectance value of the "2" sample is higher by 23% with respect to the "5" sample, which presents the darkest color of the grains.

Concerning the thermal emittance, the values measured by the portable emissometer are all around 0.9, for both of the samples belonging to the same natural local gravel and for the mixed one, *i.e.*, "5".

3.2. In-Field Measurements

The in-field measured results are reported in Table 3 and in Figure 10. All of the albedo values refer to the monthly average of the monitored days calculated from 12:00 p.m. to 2:00 p.m., when the albedo trends are more constant.

Table 3. Monthly average in-field albedo of the five gravel samples measured with the albedometer.

Name	**Monthly Albedo Values (%) (12:00 pm–2:00 pm)**			
	September	**October**	**November**	**Total Average**
"1"	37	36	37	36
"2"	39	39	40	39
"3"	41	38	42	40
"4"	47	41	44	44
"5"	27	28	31	29

Figure 10. Monthly average in-field albedo of the five gravel samples.

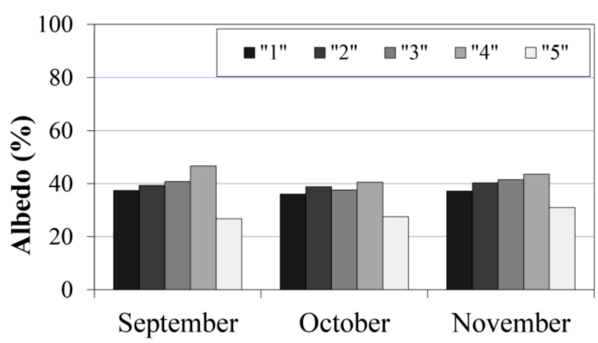


Figure 11 shows the daily maximum values of the gravels' surface temperatures measured by the sensors situated over each covering. The graphs show that the surface temperature of "4" is the lowest if compared to the other gravels', since it is the most reflective stone size. Therefore, while the incident solar radiation is constant, the absorption of the local gravel changes with the varying grain size, due to the different overall solar reflectance capability of each sample. Moreover, the surface temperature of the gravels decreases with the decrease of the grain size and with the increase of the albedo values. In detail, on 29 September 2013 and 15 November 2013, every sensor recorded similar surface temperatures for each covering, which are very close to the air temperature value, given the cloudy, windy and rainy weather.

In fact, the surface temperature variation is easier to assess when the weather is sunny and the sky is clear, such as any cool roof material. Therefore, under equal weather conditions and the same cover material, the surface temperature variation with reference to the albedo and grain size is evident in all of the gravels' behavior.

Figure 11. A comparison between the daily maximum values of the gravels' surface temperatures and the air temperature for significant days of September (**a**), October (**b**) and November (**c**).

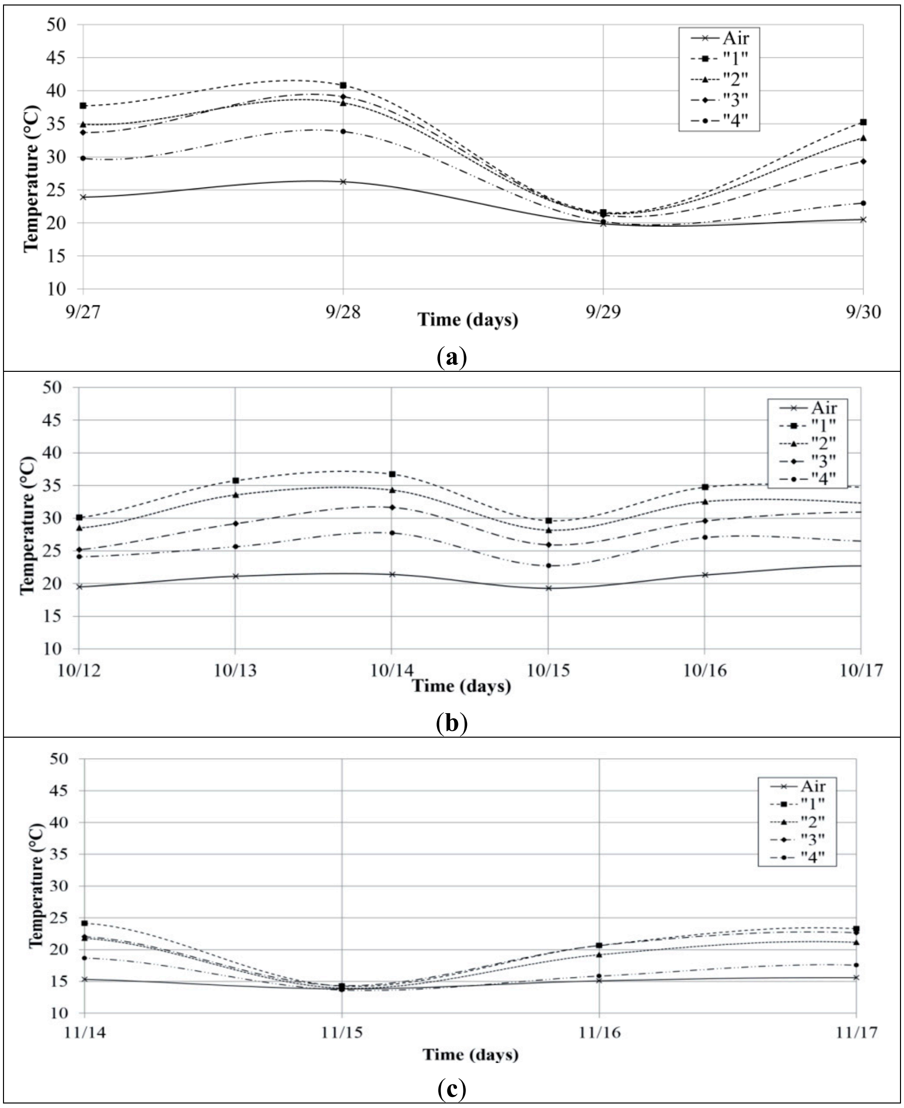
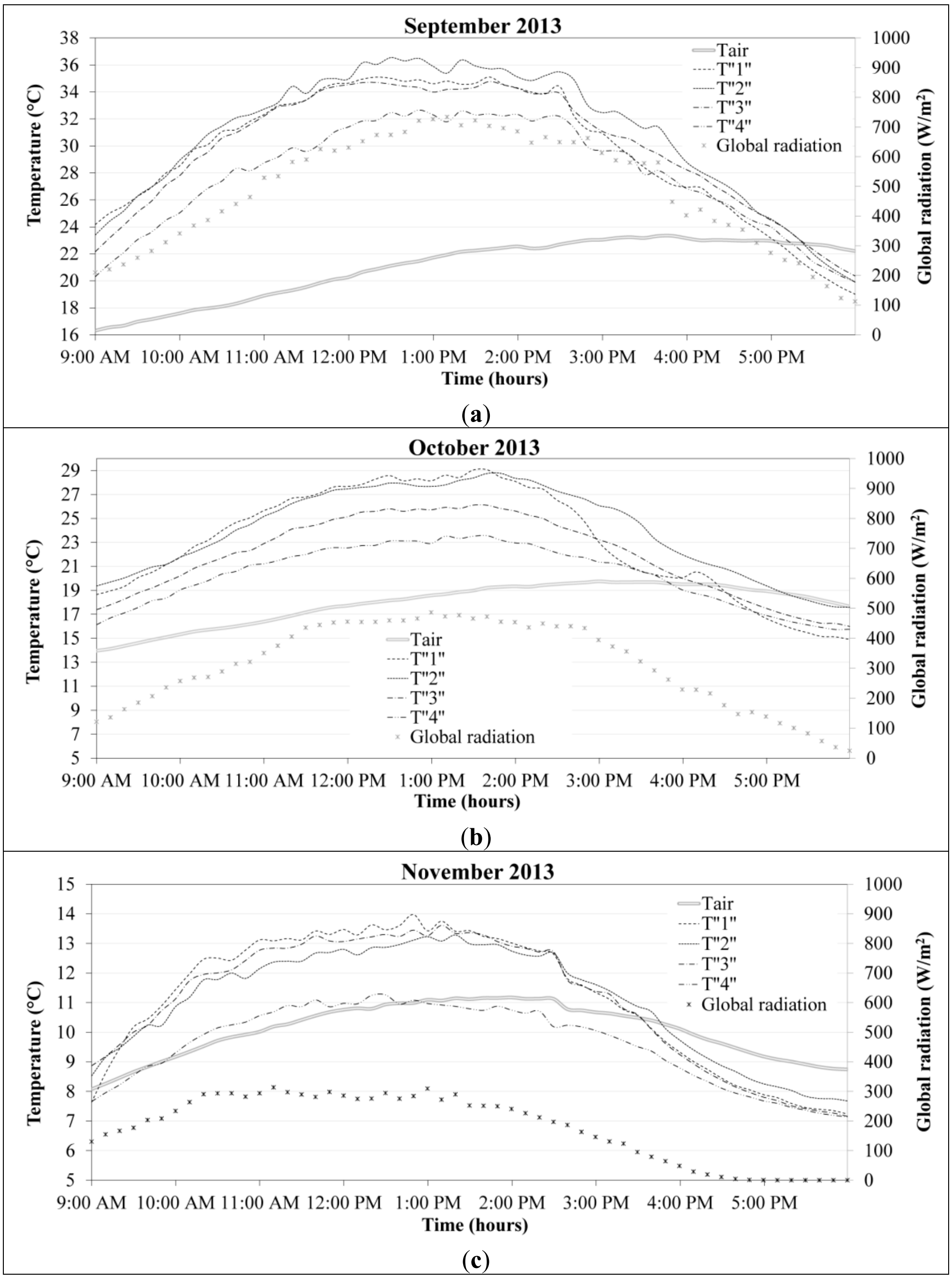


Figure 12 shows the profiles of both the air temperature and the surface temperatures of the four gravels (*i.e.*, “1”, “2”, “3” and “4”) on the monthly average day from 9:00 a.m. to 6:00 p.m., with reference to the winter thermal behavior of the gravels. The surface temperature profile of the “4” gravel is always the lowest at constant air temperature.

Figure 12. The trends of air temperature, global solar radiation and surface grain temperatures on the monthly average day for September (**a**), October (**b**) and November (**c**) from 9:00 a.m. to 6:00 p.m.

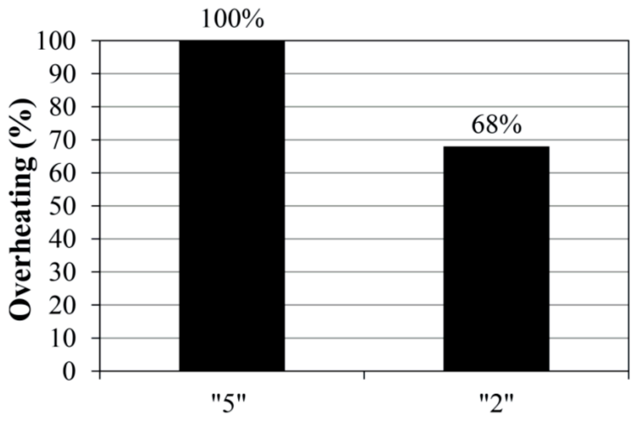


The phenomenon observed in winter is supposed to be even more evident in summer. In fact, during the winter season, the grain surface temperature profiles are very close to the air temperature, both in terms of thermal profile and values. Therefore, during warm and sunny days, a major difference between air temperature and grain surface temperature is detected, due to the different thermal-optic properties of the grain sizes. This phenomenon is observed also in the context of the monitored period, *i.e.*, from September (the warmest monitored month) to November (the coldest monitored month). By referring to the monitored data reported in Figure 12a,b,c, the maximum effect is produced by the "4" gravel, which is able to decrease the maximum thermal peaks from 12:00 p.m. to 2:00 p.m. by 5.5 °C with respect to the "1" gravel during the month of October.

Moreover, the results show that the gravel's surface temperature is significantly affected by the incoming radiation profile, as the peaks of the surface temperature and of the global radiation are coincident, *i.e.*, 12:00 p.m.–2:00 p.m. On the contrary, the peak of the air temperature is detected to be later during the day, and it tends to be within the range 12:00 p.m.–2:00 p.m. only during the colder months (*i.e.*, September–November), when the effect of the solar radiation is less significant. Additionally, during the colder months, the surface temperatures of the gravels and the air temperature profiles are closer, given less solar radiation and the minor thermal influence of the albedo.

The relation between the two parameters, *i.e.*, grain size and the different nature of the gravels, is therefore assessed. In particular, Figure 13 shows the maximum surface temperature difference between two gravels (*i.e.*, "2" and "5") characterized by equivalent grain size and their different nature, in terms of both color and origin. Gravel "2" shows a surface temperature of 32% lower compared to "5", which is similar in terms of grain size. Therefore, the influence of the gravels' nature occurs as an overheating of 32% of the "5" gravel with respect to "2".

Figure 13. Maximum surface temperature difference between gravels with a similar grain size and different natural origins, calculated in the monthly average day of November.



By considering only the effect of varying grain size, Figure 14 shows a decreased surface temperature up to 45% of the gravel "4" with respect to "1", which belongs to the same family of gravels, but is characterized by a different grain size. Therefore, the impact of the different grain sizes on the same gravel nature occurs as a 45% increase in the surface temperature of the gravel, which is characterized by the lowest cooling capability.

The monitored differences in terms of surface temperatures of the gravels with different grain sizes suggest that the same phenomenon should be more significant during the hot season, due to the higher and stronger incoming solar radiation. Therefore, more significant differences in the gravel temperature are expected to be in summer, with higher benefits in terms of indoor thermal comfort.

Figure 14. Maximum surface temperature difference between gravels with different grain sizes and the same natural origin, calculated in the monthly average day.

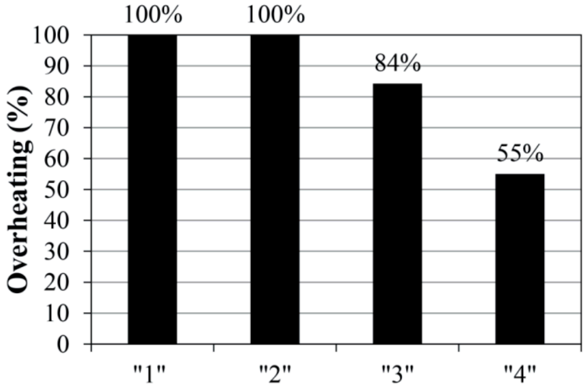
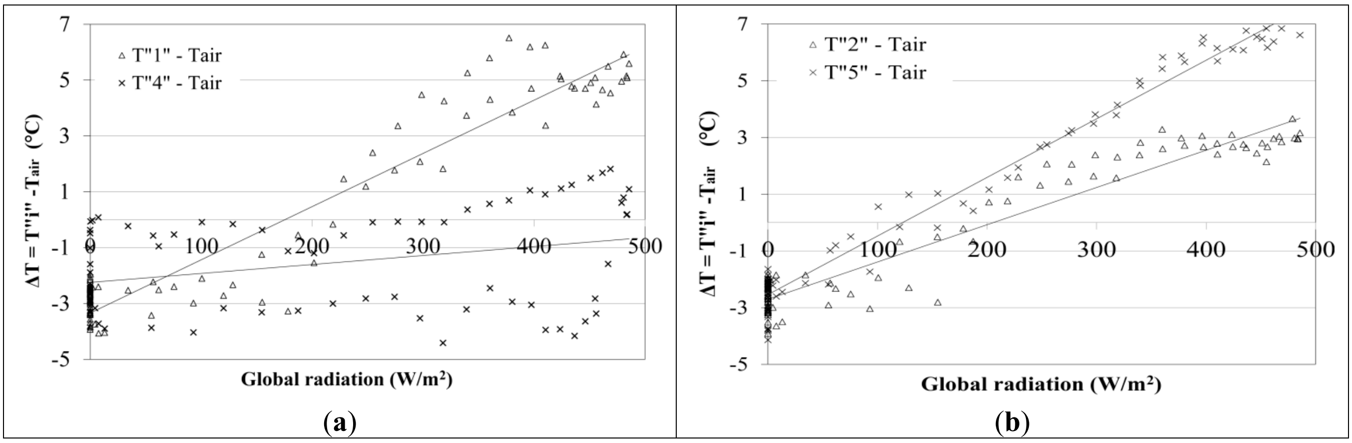


Figure 15 represents the daily trends of the overheating path with respect to the global solar radiation for "1" and "4" and for "2" and "5", respectively, with reference to a specific day in November (*i.e.*, 29 November 2013). In particular, the difference in the overheating between gravel "2" and gravel "5", related to the maximum daily value of global radiation, is more than 3.5 °C. This difference is evident from the analysis, although in winter, the global solar radiation has a low effect for determining roof overheating.

Figure 15. Comparison between the daily overheating of gravels' surface temperature ("T"i"") and air temperature ("Tair") "1" and "4" (**a**) and of "2" and "5" (**b**) in 29 November 2013, respectively.



3.3. Comparison between In-Lab and In-Field Measurements

The in-lab and in-field albedo measurements are qualitatively consistent, as they both show the same trends. In particular, the solar reflectance and albedo values are influenced by two main factors:

i. The stone typology. By comparing "5" and "2", which have the same grain size, but different colors and origins, higher values of the solar reflectance/albedo for "2" with respect to "5" are detected, given the higher darkness of the gravel.

ii. The roughness (grain size) of the surface material. The solar reflectance/albedo increases with the decrease of the grain size. The gravel "4", which is the most homogeneous material, is characterized by the highest value of solar reflectance.

Table 4 shows the comparison between the values of the gravels' solar reflectance detected by means of the spectrophotometer (in-lab) and the albedometer (in-field), respectively.

Table 4. Solar spectral reflectance of the five gravel samples according to the spectrophotometer and the albedometer, respectively.

NAME	SOLAR REFLECTANCE (%) (300–2500 nm)	MONTHLY AVERAGE ALBEDO (%) (12:00 pm–2:00 pm)
"1"	38	36
"2"	50	39
"3"	45	40
"4"	62	44
"5"	27	29

The in-lab solar radiation values are, in general, higher with respect to the in-field albedo, except for "5". This is due to the fact that the in-field measurements are subjected to a certain degree of uncertainties, *i.e.*, the instrument positioning, the changing weather conditions, which generate higher measurement variability with respect to the in-lab measurements, affected by the sample non-homogeneous surface.

4. Conclusions and Future Developments

The purpose of the present work was to: (i) characterize a natural, local, highly reflective, and durable stone in terms of its intrinsic cooling capability through solar reflectance and thermal emissivity measurements; (ii) evaluate the solar reflectance/albedo variation with the grain size of the same natural cover gravels; (iii) quantify the increase in the solar reflectance/albedo of the highly reflective stone with respect to a more commonly used gravel.

The results of this research can be useful to expand the knowledge of the optic-thermal performance of natural gravel stone commonly used as a low-cost, sustainable and simple material for paving and for flat roofs. In particular, the experimental data presented in this work can be helpful for the research community in order to evaluate and model the thermal behavior and the effects as urban paving and natural low-cost and low-impact cool roofing. To this aim, the in-field albedo was measured during three months (*i.e.*, September–November). Four different grain sizes of the same natural local and highly reflective stone were monitored and compared with another more commonly-used gravel. The relation and the impact of the variation of (i) the grain size and (ii) the nature of the gravel have been investigated.

The results demonstrated that the measured albedo of the local highly reflective stone is higher with respect to the commonly-used gravel and that the albedo values decrease with the grain dimension of the same stone typology. Additionally, it has been assessed that the homogeneity of the gravel surface has a positive effect on the albedo value. The albedo feature presented a great effect on the gravel surface temperatures in the daytime and no relevant impact in the nighttime. The cooling effect of increased solar reflectance/albedo was more evident in sunny days, consistently with other cool roof coverings. Future developments of this research will consider the outdoor measurements variation within varying weather boundary conditions, with the purpose being the analysis of the impact of external agents, *i.e.*, rain, snow and solar radiation, on the thermal properties of natural coverings for building envelopes and urban paving applications. Specific attention will be paid in order to identify the effect of aging and weathering phenomena, by taking into account the role of humidity in the thermal-energy behavior of the proposed solution.

Finally, given the promising results of this experimental work, it can be concluded that the selected reflective local gravel could represent a sustainable and low-cost alternative to traditional urban paving and roofing materials, for its intrinsic, relatively high albedo characteristics.

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Author Contributions

Anna Laura Pisello is the designer of the research work and contributed to the experimental campaign and the paper writing. Gloria Pignatta contributed to both the in-lab and in-field experimental campaigns and to the results' post-processing. She also contributed to the writing of the manuscript. Veronica Lucia Castaldo contributed to the in-field experimental campaign and to the writing of the manuscript. Franco Cotana is the coordinator of the research group and contributed to the research design.

Conflicts of Interest

The authors declare no conflict of interest.

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