Urban pedestrian stone pavements: measuring functional and safety requirements

GPAV1975195 VOL 0, ISS 0

Urban pedestrian stone pavements: measuring functional and safety requirements

Erika Garilli, Federico Autelitano, Francesco Freddi, Felice Giuliani

QUERY SHEET

This page lists questions we have about your paper. The numbers displayed at left are hyperlinked to the location of the query in your paper.

The title and author names are listed on this sheet as they will be published, both on your paper and on the Table of Contents. Please review and ensure the information is correct and advise us if any changes need to be made. In addition, please review your paper as a whole for typographical and essential corrections.

Your PDF proof has been enabled so that you can comment on the proof directly using Adobe Acrobat. For further information on marking corrections using Acrobat, please visit http://journalauthors.tandf.co.uk/production/acrobat.asp; https://authorservices.taylorandfrancis.com/how-to-correct-proofs-with-adobe/

The CrossRef database (www.crossref.org/) has been used to validate the references. Changes resulting from mismatches are tracked in red font.

AUTHOR QUERIES

QUERY NO.	QUERY DETAILS
Q1	Please note that the ORCID has been created from information provided through CATS. Please correct if this is inaccurate.
Q2	Funding details (Ministry of Education, University and Research (MIUR)) have been taken from information supplied with your manuscript submission and checked against the Open Funder Registry and we found a partial match “Ministry of Education Universities and Research”. Please check and resupply the funding details.
Q3	The sense of the sentence “It is placed vertically…” is not clear. Please check that it reads correctly or supply a revised version.
Q4	If the spelling of “teethes” is incorrect, please provide a correction.
Q5	The disclosure statement has been inserted. Please correct if this is inaccurate.
Q6	Please provide missing page range for reference "Autelitano *et al.*, 2020" references list entry.
Q7	Please provide missing volume number and page range for reference "Autelitano *et al.*, 2019" references list entry.
Q8	Please provide missing volume number and page range for reference "Chu *et al.*, 2020" references list entry.
Q9	Please provide missing page range for reference "Çoşkun *et al.*, 2016" references list entry.
Q10	Please provide missing page range for reference "Garilli *et al.*, 2020" references list entry.

QUERY NO.	QUERY DETAILS
Q11	Please provide missing volume number for reference "Giuliani and Rastelli, 2007" references list entry.
Q12	Please provide missing page range for reference "Gong *et al.*, 2020" references list entry.
Q13	Please provide missing city for the reference "Griffin, 1990" references list entry.
Q14	Please provide missing city for the reference "National Association of City Transportation Officials and Global Designing Cities Initiative, 2016" references list entry.
Q15	Please provide missing page range for reference "Schnee *et al.*, 2020" references list entry.
Q16	Please provide missing page range for reference "Zoccali *et al.*, 2017" references list entry.

INTERNATIONAL JOURNAL OF PAVEMENT ENGINEERING
https://doi.org/10.1080/10298436.2021.1975195

Taylor & Francis
Taylor & Francis Group

Check for updates

Urban pedestrian stone pavements: measuring functional and safety requirements

Q1 Erika Garilli, Federico Autelitano, Francesco Freddi and Felice Giuliani

Dipartimento di Ingegneria e Architettura, Università di Parma, Parma, Italy

ABSTRACT
Urban streets have to respond to essential functions in terms of decorum, hygiene, aesthetics, communication of its architectural value and in relation to vertical constructions, with the pedestrian at the centre of the project. The quality of a pedestrian-priority space must be read according to a series of specific indicators that combine the unbeatable aesthetic requirements with those of comfort and safety. To this end, an integrated approach of experimental measurements to characterise the quality of pedestrian paths (pedestrian-only streets, sidewalks, shared areas and plazas), with specific attention to stone and segmental pavements, was introduced. The different effects, in terms of vibrations and noise, that the pavement of a pedestrian path can generate on a user pulling a suitcase trolley (telescopic handle wheeled luggage), were evaluated. These values were than associated with other parameters capable of describing the characteristics of the pavement surface, such as surface macro- and micro-roughness, skid resistance and size of the elements and joints that make up the pavements. Comfort and safety thresholds for pedestrian street pavement surfaces have been identified. They can be usefully made available to designers for the functional characterisation of urban paving solutions, with particular attention to those in natural stone.

ARTICLE HISTORY
Received 15 June 2021
Accepted 27 August 2021

Keywords
Stone pavement; vibration; comfort; safety; pedestrian path; noise

Introduction

Urban street pavements have been recognised throughout history as works of engineering, which represented the synthesis of more complex functional and aesthetic values, capable of meeting the transportation needs and demands (Garilli and Giuliani 2019, Biancardo *et al.* 2020). Their essential functions of decorum, hygiene and aesthetic were specifically tailored to offer the urban dwellers an improved public realm for movement and access and facilitate a variety of uses and activities. The street has always shaped the urban landscape, putting the person at the centre of the project. Thus, these urban paved surfaces cannot ignore an aesthetic connotation that is expressed through their architectural value in relation to the size and shape of the built environment (Garilli *et al.* 2017, Mohora and Anghel 2019). The modern street pavements design is still an expression of functional and aesthetic requirements to support environmental sustainability, public health economic activity and cultural significance (National Association of City Transportation Officials and Global Designing Cities Initiative 2016). But, some of these significant aspects are often not properly considered and are not clearly distinguished from those of pavements intended for motorised traffic (Autelitano *et al.* 2020, Garilli *et al.* 2020, Gong *et al.* 2020). The variety of the used materials, which are adopted not only for structural tasks, requires a specific analysis of the surfaces' suitability towards non-motorised and vulnerable users who travel by bicycle, wheelchair, pushchair, electric scooter and, of course, on foot (De Winne 2006, Gao *et al.* 2019, Autelitano *et al.* 2020). The quality of a pedestrian-priority space (pedestrian-only streets, sidewalks, laneways, alleys, shared areas and plazas) must therefore be read according to a series of specific indicators that balance the unbeatable aesthetic requirements with those of comfort and safety during an itinerary that may be characterised by transitions on different levels (Tanzil and Gamal 2021). This concept is more important in historic city centres, where natural stone is the most popular choice for street pavements planned for both vehicular traffic and vulnerable users, including pedestrian-priority spaces and plazas (Colagrande 2008, Zoccali *et al.* 2017, Garilli and Giuliani 2019). The change of paving material, especially for valuable stone pavements, is fundamental for the orientation in the city of visually impaired people, as well as for the identification of urban road spaces with different and specific uses. Besides, this approach translates in several technical performances regarding grip, more or less significant vertical irregularities, generation of noise or vibrations and comfort based on the people age, walking styles, type of movement and footwear. Moreover, pedestrian can have very different characteristics both from the physical point of view and for the device they use to move in an inclusive urban environment (i.e. wheelchair, elderly and disability aids, etc.) and for any items transported (luggage, stroller, shopping trolley, etc.) (Pecchini and Giuliani 2015). The disaggregated analyses of the various factors affecting the quality of a route mainly intended for pedestrians have been the subject of research by various authors (Gomes and Savionek 2014, Cepolina *et al.* 2017). However, an overall reading of the relationships among the various functional indicators, deduced from experimental measurements, has not yet been fully achieved. One of the main reasons is that several pavement serviceability parameters in the technical literature, are derived from methodologies or assumptions based and

CONTACT Erika Garilli erika.garilli@unipr.it

calibrated on the vehicle ride quality. The pavement surface features that mostly affect the users safety and comfort are evenness, texture, nighttime photometry (luminance, visibility, contrast and colour) and horizontal (Giuliani and Rastelli 2007, Giuliani *et al.* 2017, Autelitano *et al.* 2019). Therefore, an integrated approach of experimental measurements has been introduced in this study to characterise the quality of paved urban pedestrian paths, with specific attention to stone and jointed pavements. Among the planned activities, the set-up also of a smart and original procedure, named stone pavement suitcase trolley test (SPSTT), represented the main novelty and significant contribution. This test has been conceived to continuously monitor the parameters that can best describe the relationship between a pedestrian and the urban pavement surfaces. Different effects, in terms of vibrations (and therefore accelerations) that the pavement of a pedestrian path can generate on a user equipped with a pulled object, such as a suitcase trolley (telescopic handle wheeled luggage), and the relative effort that users make to perform this action due to the pulling force were evaluated. The processing of the detected acceleration intensities resulted in the definition of an index, which characterises the different pavements and that allows to associate a comfort and effort limit value on the hand-arm system (HAS) due to the pull of a wheeled luggage. In parallel, noise measurements were carried out. These values were then related with several parameters referred to the typical pavement characteristics, such as surface roughness (through the Barton comb), skid resistance and coefficient of friction (through the British pendulum test) in order to identify the most suitable pavements to be used in exterior pedestrian paths.

Typologies of analysed pavements

The experimental programme, designed to quantify the features of paving stones and other materials in city streets and squares, was developed in Parma (Italy). Parma, which is a city of about 200,000 inhabitants in the northern Italian region of Emilia-Romagna, has a recognised reputation for sustainable mobility and use of alternative transport modes to the private motor vehicle and welcomes many tourists every year, which were 375,000 (data of tourists who stayed overnight in the municipality of Parma) in 2019 (last reliable data pre-pandemic Covid-19).

Specifically, 12 pavements of different material composition and construction period were selected (Table 1): nine stone pavements and one asphalt pavement are located in the historical city centre of Parma (Figure 1(a)) and two interlocking concrete block pavements in the University Campus of Parma (Figure 1(b)). The historical city centre and the University Campus provide indeed the perfect pedestrian hubs between public transport systems, railways, hotels and tourist sites, where analyse the comfort and safety requirements of pedestrians equipped with a suitcase trolley. P01 and P02 are made of Luserna stone (metamorphic stone belonging to the gneiss group) tiles with a natural split upper face finish and placed in a stacked bond (or running bond) laying patterns. P03 and P04 are built using porphyric flagstones and Luserna flagstones with a flamed and brushed upper surface, respectively, laid down in a stretcher bond laying pattern. P05 and P06 are made of Cuasso's red porphyric stone blocks and granite blocks, respectively, placed in a stretcher bond 45° laying patterns. P07 is a covered Palladian marble pavement having smooth and polished surface, whereas P08 is a dense-graded hot mix asphalt (HMA) pavement (typical urban fine graded surface layer). P09 and P10 are constructed with small cubic elements in porphyry and Luserna stone, respectively. Specifically, the cubes are placed in P09 following an overlapping arcs laying pattern, while according to a stacked bond or running bond scheme in P10. P11 and P12 are interlocking concrete block pavements having different laying patterns, i.e. stretcher bond and herringbone. The specification of analysed pavements are summarised in Table 1.

Methodology for determining comfort and safety indices

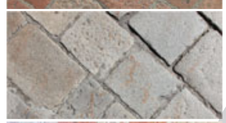
The determination and evaluation of comfort and safety perceived by a person who pull an object initially included the measurement of vibrations transmitted by the pavement to the HAS through the luggage and the noise caused by the rolling of the trolley suitcase. Specifically, the assessment of vibrations was made possible thanks to the development of an innovative and original set-up that involved the instrumentation of a trolley suitcase with a triaxial accelerometer. In parallel, the pavements' macro- and micro-texture were analysed to evaluate the safety requirement in terms of slipping potential. Finally, the acceleration and noise values were then put in relation with the pavement roughness as well as with the geometric parameters of the elements that made up the different pavements in order to determine the best solutions to be adopted in pedestrian paths with high flow.

Vibrations

Data acquisition

A kinematic analysis is presented to display the discomfort resulting from pulling a rolling luggage on a pavement. Five steps can be identified during this operation (with tilted suitcase). In the first step, the wheeled luggage is moved from the vertical to the inclined position with a specific tilted angle, the second one (start stage) concerns the start of the motion, in the third step (sustained stage) a force must be applied so that the suitcase trolley moves in the travelling direction at a given speed, in the fourth (stop stage) and fifth ones it is stopped and returned to the vertical position. The first and last stages depend on several factors (e.g. the characteristics of the suitcase and user) regardless of the pavement features. In the other steps also the pavement characteristics affect the motion. Figure 2 represents the free body diagram of tilted suitcase trolley in the start, sustained and stop stages in which F is the force to be applied to get the luggage motion, a is the suitcase height (with open telescopic rod), W is the weight, b and c are the distances between centre of mass and the side and bottom of the suitcase trolley respectively, N is the normal force at the ground, μ is the friction, α is the tilted angle, d is the distance

Table 1. Characteristics of analyzed pavements.

Pavement	Material	Dimensions of elements [mm]	Photo	Mean width of joints [mm]	Mean depth of joints [mm]	Age [years]
P01	Luserna stone	150 × 900		10	3	1
P02	Luserna stone	100 × 750		10	3	1
P03	Porphyry	200÷400 × 400÷1200		10	6	20
P04	Luserna stone	500 × 1000		4	3	<1
P05	Cuasso's red porphyry	250÷400 × 250÷400		30	5	>50
P06	Granite	250÷400 × 250÷900		25	10	>50
P07	Marble	Irregular		Thin and irregular	0.2	>50
P08	Asphalt concrete	Continuous pavement		No joints	No joints	<1
P09	Porphyry	80÷120 × 80÷120		20	5	1
P10	Luserna stone	60÷90 × 60÷90		25	9	3
P11	Concrete	96 × 194		2	1	10
P12	Concrete	102 × 206		2	1	6

between the handle and the ground and F_a is the force due to the vibration received by the suitcase during the motion on a specific pavement.

Only the sustained stage has been considered in this study. In this configuration, the force (F) which must be applied so that the suitcase trolley moves in the travelling direction at a given speed depends on the distance between the handle and the ground and on the tilted angle. These parameters in turn vary not only in function of the users' anthropometry but also with time: for example, during the walk, there is also the swing of the arm holding the suitcase trolley handle. The force F is time-dependent since also the vibration simultaneously changes as a function of the pavement surface. Only the vibrations transmitted to HAS by the wheeled luggage pulled on different pavements have been considered to reduce the above-mentioned variables and to analyse in a direct way the comfort. Hand-arm vibrations (HAVs) are the vibrations which are transmitted through a handle to the HAS and, from this, are transferred to the rest of the body. Transmitted vibrations can cause injury, hurt or discomfort, depending on many aspects: axes, amplitude, frequency and duration as well as the gripping force, contact area and posture are the main influencing factors (Griffin 1990, Alphin *et al.* 2013).

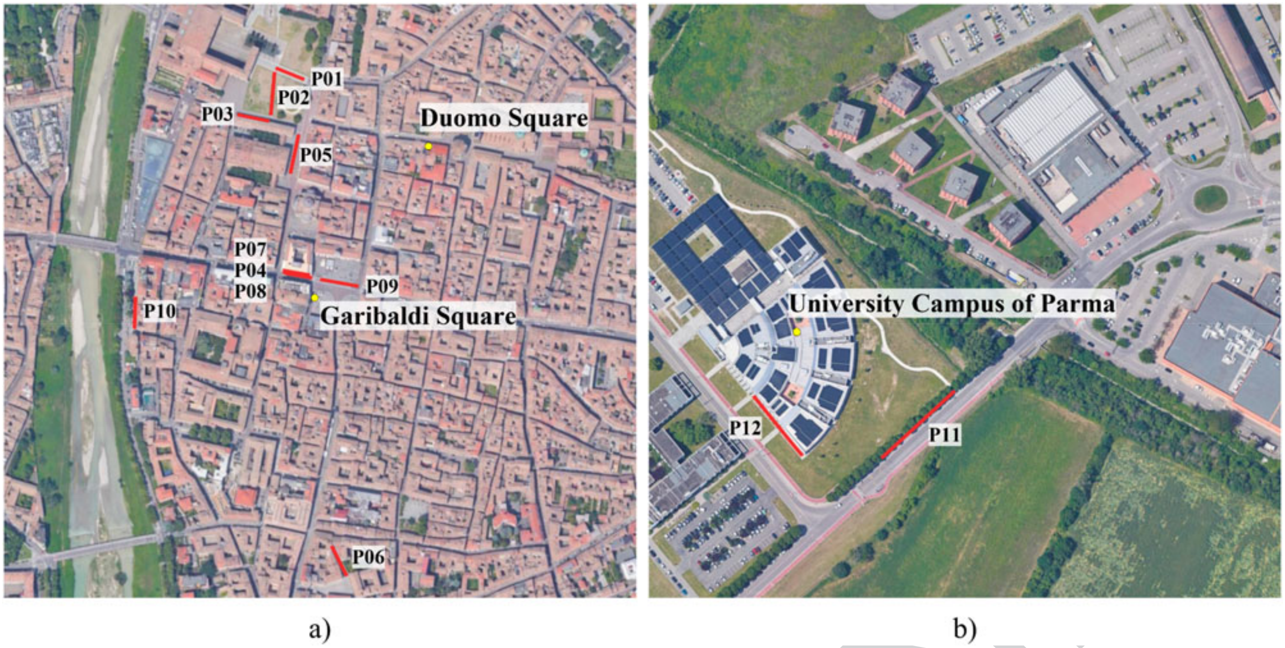


Figure 1. Location of the analyzed pavements.

A low-cost system for the data acquisition of pavement vibration has been implemented to determine and evaluate the degree of comfort perceived by a pedestrian user pulling an object. The experimental apparatus of the SPTT shown in Figure 3 consists of a rolling luggage equipped with a triaxial accelerometer for registering vibrations. The best location of the measuring device is at or close to the surface of the hand, where the vibration penetrates into the body (ISO 5349-1:2004). Ideally, the accelerometer should be placed in the centre of the handle area; however, it is impossible to place an accelerometer in that position because it would interfere with the operator's normal hand grip. Besides, special adapters could be used, but they are only suitable for positions with a fixed hand on the handle (portable adapter) or make it very difficult to use for triaxial measurements (individually shaped adapter). In our case, the hand is not fixed on the handle because the relative position between the trolley suitcase and the HAS varied over time. Thus, the triaxial accelerometer was fixed close to operator's hand at the end of the telescopic rods near to the towing handle. The suitcase used

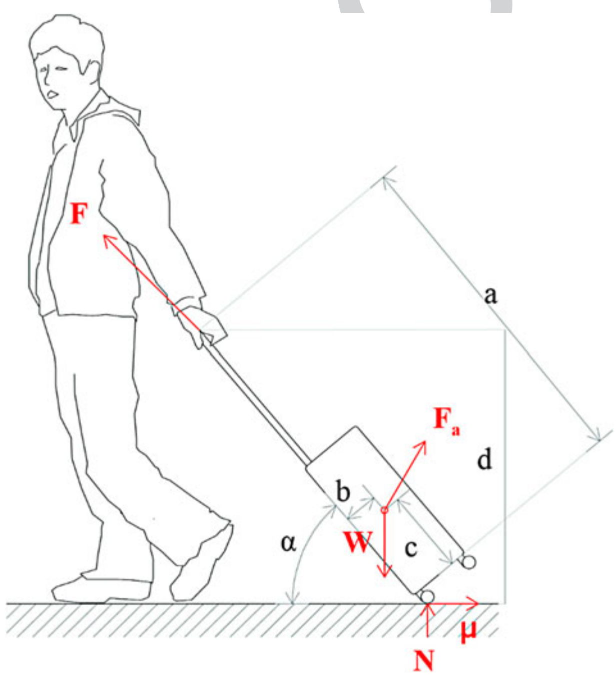


Figure 2. Free body diagram of pulled trolley suitcase.

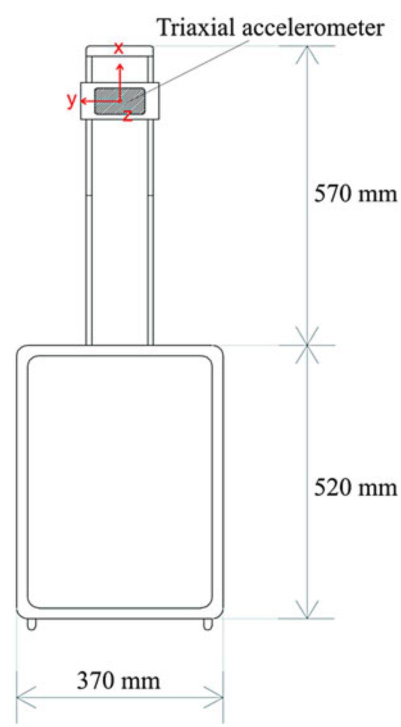


Figure 3. Frontal view of the stone pavement suitcase trolley test (SPSTT) device.

in the detection system is a 520 mm high, 370 mm wide and 250 mm thick two-wheeled (non-swivel wheels) carry-on trolley suitcase, having 570 mm telescopic rods. The choice felt on this kind of luggage, since it is the most used by millions of peoples who travel by train, plane or car. The accelerometer used for the surveys is a triaxial type. The specific test needs the use of a stand-alone device that permits to measure and save acceleration data. In particular, the adopted device produced by FIAMA s.r.l. is equipped with a motion-activated triaxial accelerometer ADXL 355 manufactured by Analog Device. ADXL355 is low noise density, low 0 g offset drift, low power, 3-axis and 20-bit digital accelerometer with selectable measurement range (Analog.com 2016). The device is configured and controlled via an Android mobile operating system with a BLE communication app. Thanks to this application, it is possible to define all the acquisition parameters, i.e. frequency and full scale, as well as the activation and deactivation parameters, i.e. the intensity of the initial impulse necessary for the activation and the minimum time for which the intensity must remain above this value, the intensity of the acceleration below which the accelerometers must deactivate and the minimum time in which this condition must occur, and the recording time after the sensors are deactivated. This software enables to download and share data very quickly and the data collected are available in.txt and.csv formats. The flexibility of the device permits to distinguish the different phases during the tests.

Twelve different pavements were analysed and one pavement was tested at once. For analysis purposes, the duration of the test is significant, since in its first and final part, there are disturbing factors, such as the walking that is not yet regular and uniform and the arm oscillation to set the inclination of the suitcase trolley. For this reason, straight paths with an extension between 40 and 50 m have been chosen to allow the operator to walk a sufficiently long section following an homogeneous pace. Another important parameter to consider is the luggage weight, which was kept constant and equal to 6 kg. The accelerometer parameters adopted for the tests are listed in Table 2. Specifically, the sampling frequency was set at 256 Hz in accordance with several studies which have analysed vibrations in different transport modes (Zoccali *et al.* 2017, Schnee *et al.* 2020). For each pavement, the tests were carried out by 10 operators. Each operator repeated the route five times, in order to obtain more data to compare and on which to base the analysis.

Data processing

Acceleration values along the three sensing axes (x, y, z), expressed in relation to time, were obtained. Since the accelerometer was attached to the luggage and the relative position between the trolley suitcase and the HAS varied over time, the three acceleration components on the operator's hand and arm were not possible to be determined. Thus, the resultant acceleration was calculated and considered. As already mentioned, the duration of the test is significant: after some preliminary attempts, the analysis of the 15 central seconds of the test resulted to be an ideal interval time to delete the disturbing factors (walking that is not yet regular and uniform and the arm oscillation to set the inclination of suitcase trolley). Once the part of the signal to be analysed was selected, it was filtered between 0.5 and 100 Hz in order to study all the components involved, including those due to arm swing, operator step, etc. The spectral power densities (PSD) were calculated from the acceleration data to describe the energy distribution over the frequency band from 0.5–100 Hz to compare in detail the different pavements. PSD decomposes a vibration signal into frequency components and represents the amount of energy present in the analysed signals at each point in the frequency domain. The sum activity of hand vibration was determined as the integral of the frequency spectrum in the analysed range, i.e. the area under the PSD curve (APSD). The evaluation of vibration includes measurements of the weighted acceleration mean square (a_{rms}), which is expressed in m/s^2 and is calculated for translational vibrations from Equation (1):

$$a_{hw} = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt} \qquad (1)$$

where a_w is the weighted average acceleration, $a_w(t)$ is the time-weighted acceleration and T is the duration of the measurement (s). The term under the radical sign is equivalent to the APSD and for this reason $a_{rms} = a_{hw} = \sqrt{APSD}$.

Table 2. Accelerometer parameters.

Parameter	Set value
Full scale	8 [g]
Acquisition frequency	256 [Hz]
Activation acceleration	100 [mg]
Activation time	15 [ms]
Deactivation acceleration	50 [mg]
Deactivation time	1000 [ms]
Deactivation delay	0 [ms]

Noise

In parallel with the vibration analyses, noise tests were performed. For this purpose, the NIOSH sound level meter app, a free-to-download iOS app produced by the National Institute for Occupational Safety and Health (Washington, DC), was used. The choice has fallen on this application because previous studies have shown that it is the most effective among the available free apps with a coefficient of determinations of 0.97 with an accuracy within 0.7 dB in the 40–85 dB range and the measurements were found to be comparable with dosimeter results (Speaks and Beamer 2020, Crossley *et al.* 2021). Noise tests were conducted at night, so that they were not disturbed by background noise (vehicular traffic, speaking people, working activities, etc.) by a single operator who made five 10-seconds measurements. An iPhone 11, which was held at the ear (microphone at 1.5 m from the ground level), was used for collecting data. For the purpose of the analysis, the LAeq value, which is the equivalent (averaged every second) continuous sound level in A-weighted decibels, was registered for each analysed pavement and compared. The sound level value attributed to each pavement is given by the average of the five measurements carried out.

Surface roughness, skid resistance and coefficient of friction

The main subject of this study is stone pavements: the choice of the type of rock as well as of the surface characteristics (roughness) of the individual element greatly influence the pedestrian safety and comfort. This selection is done upstream, in the design phase, balancing the needs of the designer, the stone characteristics in the quarrying phase (some stone paving blocks are not further processed) and, eventually, in the subsequent cutting and dressing steps. The pavement macro-roughness is generally determined in the road sector using the volumetric patch technique (EN 13036-1). It consists in spreading, with a special pad, a known volume of sand, with pre-established granulometric characteristics, on the surface to be analysed. This operation allows the measurement of the area of the circular surface that can be covered, because of depressions and gaps between the roughness of the road surface, with the volume of provided sand. From the volume and the area, the average height of these roughness, called Mean Texture Depth (MTD), is calculated. MTD classification is represented in Table 3. However, this technique cannot be used directly in the quarry as well as on elements of small dimensions on site. For these reasons, the use of a tool borrowed from the field of geology rather than those generally used in the road sector was considered more suitable. A profilometer, specifically the Barton comb (Barton and Choubey 1977), was selected to analyse the surface macro-roughness and evenness. This profilometer is designed to identify the roughness of rock discontinuities. Barton comb consists of 0.9 mm wide and 80 mm long teeth to cover a length of 150 mm. It is placed vertically on the surface to be measured and starting from the vertical displacement of the teethes the surface's profile is defined. In order to compare the different pavements, which have elements of different sizes, a profile's trend over a length of 100 mm was considered. The profile of each pavement was established by analysing the Barton comb pictures (Figure 4). On the basis of this image processing, the average macro-roughness height (ARH) of the pavement was determined as $ARH = A/L$, where A the area above the profile obtained with the Barton comb (black area in Figure 4) and L is the measurement length, i.e. 100 mm. These measurements were made in 5 positions 5 m apart and the pavement ARH value was calculated as the average of that of the 5 positions. The standard volumetric patch method was performed on the asphalt pavement (P08) to determine also the MTD. A classification of macro-roughness is included in the Italian standard C.N.R. 94/1983: it is described as a function of the "altezza media di sabbia" (HS), which is equivalent to MTD of the European

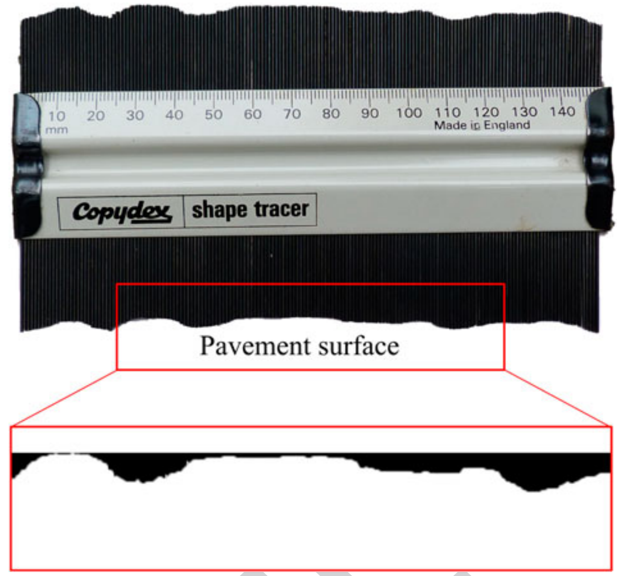


Figure 4. Pavement profile obtained from the Barton comb.

Colour online, B/W in print

standard. According to this classification, P08 was found to have a medium HS. Thus, this pavement was taken as a reference and the ARHs were arbitrarily classified using the HS limits and descriptions reported in Table 3.

The skid resistance was determined by using the Munro Stanley portable British Pendulum Tester (BPT) to analyse safety and the comfort of the tested pavements (EN 13036-4). BPT is a dynamic pendulum impact tester used to measure energy loss when a rubber slider edge is propelled over a test surface; the individual measurement is expressed as the Pendulum Test Value (PTV). Since the slip rate of BPT is very low, PTV is mainly dependent on micro-texture. Measurements were carried out at five different locations, 5 m apart, in dry and wet conditions. The average of the five results was taken as a representative result of the skid resistance of the analysed pavement. A large TRL(55) rubber slider (76 mm × 25.4 mm × 6.35 mm) was adopted to test pavements except P09 and P10 pavements on which the small TRL(55) rubber slider (31.75 mm × 25.4 mm × 6.35 mm) was used because there was insufficient space on the test surface for a larger one. The calculated pendulum values have been then classified according to slip resistance (Table 4) and slip potential (Table 5) reference ranges (Çoşkun et al. 2016).

On the basis of the PTV values, the friction coefficient (μ) was calculated starting from Equation (2) (Sabey and Lupton 1964, Chu et al. 2020):

$$PTV = \frac{330\mu}{3 + \mu} \qquad (2)$$

Table 3. Macro-roughness classification according to C.N.R. 94/1983.

HS [mm]	Macro-roughness classification
<0.2	Very fine
0.2–0.4	Fine
0.4–0.8	Medium
0.8–1.2	Coarse
>1.2	Very coarse

Table 4. Classification of slip resistance (Çoşkun et al. 2016).

Slip resistance	PTV [–]
Dangerous	0–24
Limited	25–34
Adequate	35–64
Very good	>65

Table 5. Classification of slip potential (Çoşkun *et al.* 2016).

Slip potential	PTV [–]	Typical uses
Very low	>55	Exterior areas, ramp area
Low	45–54	Exterior walking pathways, surroundings of swimming pools exterior areas, stairs
Medium	35–44	Shopping center food courts, hotel entrance saloons, public changing rooms, interior area stairs
High	24–34	Bathroom, storage, laundry room
Very high	<24	Shopping centers

Results and discussions

The a_{rms} values were determined by analysing the data obtained from the SPTT to describe and evaluate the degree of comfort perceived by a pedestrian user equipped with a pulled object. Once the signal was selected and the filter was applied in the range 0.5–100 Hz, the a_{rms} was determined for each signal, for the 12 pavements and for the 10 operators. The results appeared to be significantly dispersed, and sometimes doubled, across different operators for the same pavement. For this reason, the single values were examined by relating them to the respective average speed during the single test. By way of example, Figure 5 displays the acceleration magnitude for P02, P03, P07 and P11 pavements as a function of operator speed. It can be seen that a_{rms} increases as the speed increases independently of the analysed pavement. Then, the a_{rms} values have been linearly interpolated as a function of speed: the results for the different pavements tested are shown in Figure 6.

The graph clearly shows the presence of two classes of pavements, characterised by two different a_{rms} ranges, i.e. a first group (P03, P04, P07, P08, P011, P012) registered an average value of about 4 m/s^2 whereas a second one reported a_{rms} levels near to 6 m/s^2 (P01, P02, P05, P06, P09, P010). However, regardless of these numerical data, the trend of accelerations with the walking speed always follows a linear tendency defined by the same slope, with the exception of P10 and P06 for which the increase in speed leads to a greater growth in acceleration. This behaviour is presumably due to the presence in these two surfaces of significant vertical misalignments of the single stone elements. The accelerations obtained at an average speed of 1.6 m/s were considered and extracted to better compare the pavements (Figure 7).

In parallel with the vibration analyses, noise tests were performed. The obtained results are represented in Table 6, which highlights how the LAeq trend is very similar to the accelerations one.

ARH values are reported in Table 7 and Figure 8. Comparing the results shown in Figure 6 and Figure 7 and Table 6 with the ARH values (Figure 8) and joint size (Table 1) three distinct groups of pavements can be identified. The first set is represented by the P07 and P08 pavements. P07 is a Palladian marble pavement with very fine ARH having honed and polished surface with irregular joint widths but very small joint depths (0.2 mm). P08 has a medium ARH but is a continuous pavement, and therefore without joints. The second class is composed of the P03, P04, P11 and P12 pavements, which are made of stone and concrete elements with regular shape and dimensions and, for this reason, with regular joints having small width and depth (Table 1). As regards the macrotexture, P03 and P04 show a medium ARH, while for P11 and P12 a low value is found. The third group counts P01, P02, P05, P06, P09 and P10 pavements. Two subcategories can be

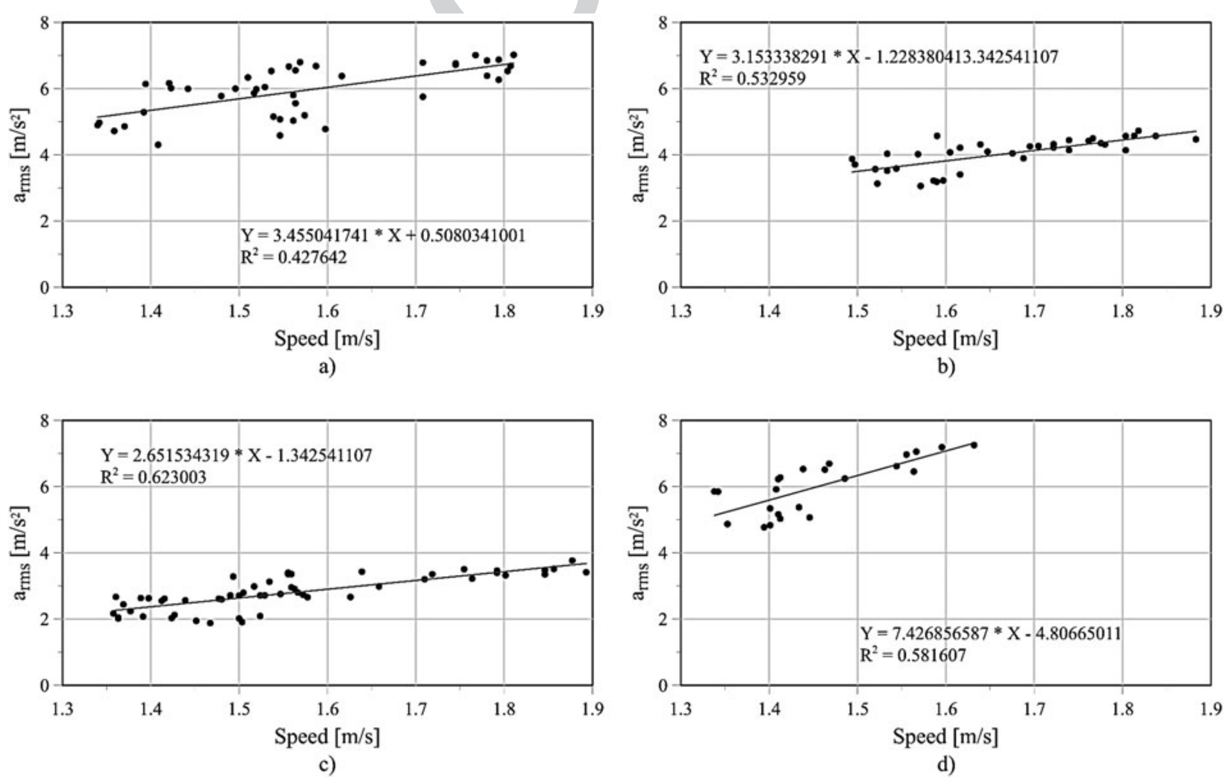


Figure 5. a_{rms} magnitude as a function of operators speed for (a) P02, (b) P03, (c) P07 and (d) P10 pavements.

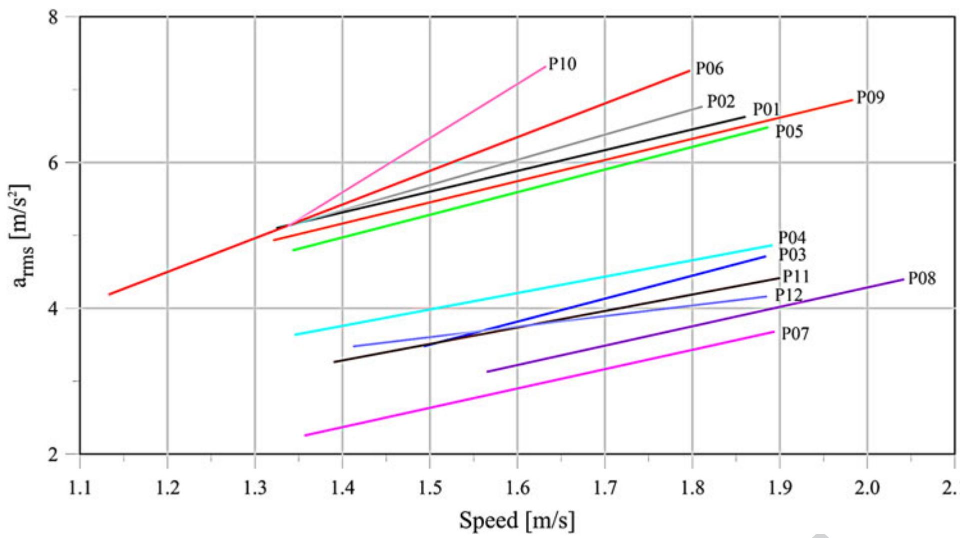


Figure 6. a_{rms} trend of analyzed pavements as a function of speed.

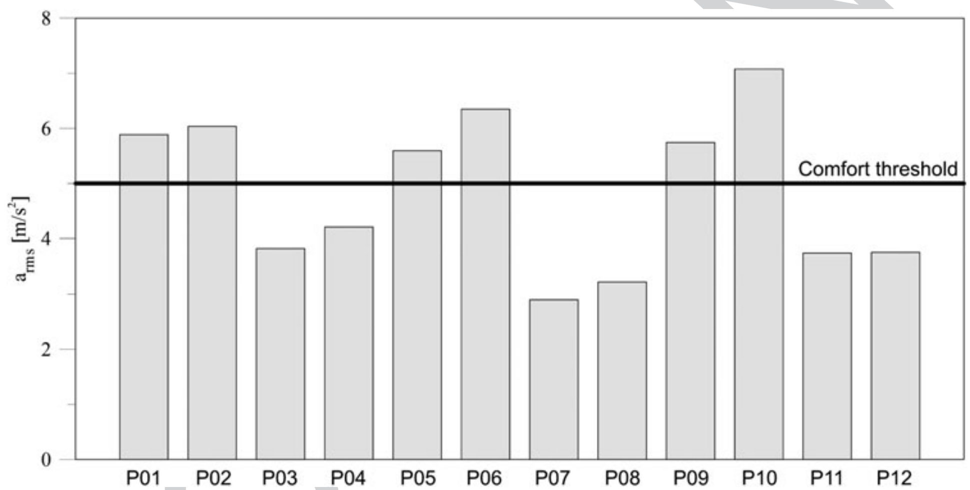


Figure 7. a_{rms} at 1.6 m/s of analyzed pavements.

distinguished in this set: the first one is represented by pavements made with split elements (both on the upper and on the lateral surface) having an irregular shape and therefore irregular joint width; they also exhibit medium and coarse ARH. P05, P06, P09 and P10 pavements belong to this subcategory. The second subcategory includes pavements with stone elements of regular shape and size. These pavements also have regular joints of small width and depth and are saturated with filler material. The individual elements that constitute the pavement have a rough and irregular

Table 6. LAeq of analyzed pavement.

Pavement	LAeq [dBA]	
	Mean	SD
P01	70.4	0.5
P02	70.2	0.5
P03	66.3	0.7
P04	67.2	0.5
P05	68.4	0.3
P06	69.4	0.4
P07	58.9	1.0
P08	66.1	2.3
P09	69.6	0.9
P10	71.3	0.4
P11	64.9	0.7
P12	65.0	0.3

Table 7. AHR values of the analyzed pavements.

Pavement	ARH [mm]		RHmax [mm]	Macro-roughness classification
	Mean	SD		
P01	0.82	0.12	2.12	Coarse
P02	0.97	0.15	2.14	Coarse
P03	0.44	0.07	0.79	Medium
P04	0.74	0.06	1.31	Medium
P05	0.52	0.14	8.39	Medium
P06	0.93	0.16	3.66	Coarse
P07	0.19	0.04	0.46	Very fine
P08	0.65	0.12	1.29	Medium
P09	0.84	0.09	1.66	Coarse
P10	0.95	0.17	3.05	Coarse
P11	0.31	0.07	1.00	Fine
P12	0.33	0.06	0.65	Fine

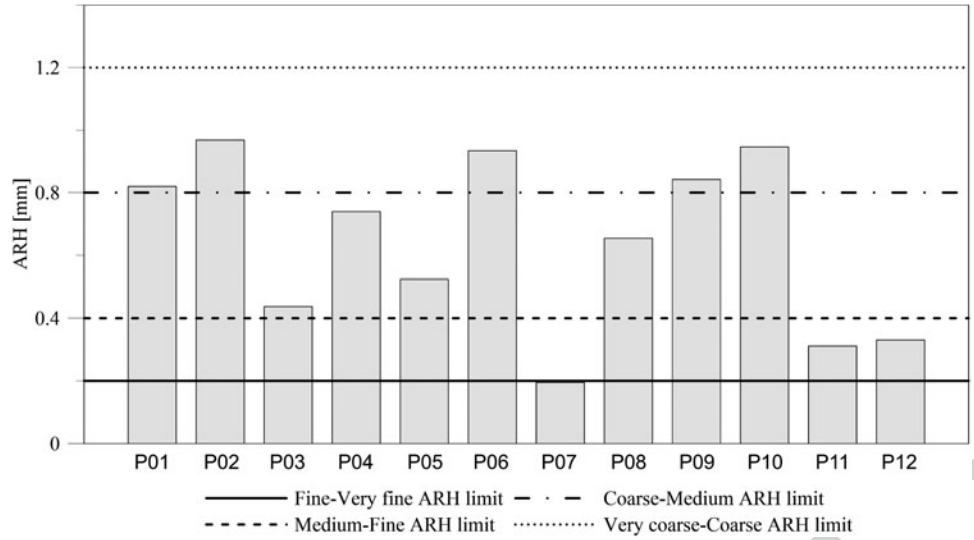


Figure 8. ARH values for the analyzed pavements.

Table 8. PTV and μ values of the analyzed pavements R^2.

	PTV [–]		μ [–]		Slip potential	
Pavement	Dry	Wet	Dry	Wet	Dry	Wet
P01	85	52	1.04	0.56	Very low	Low
P02	83	52	1.01	0.56	Very low	Low
P03	57	30	0.62	0.30	Very low	High
P04	87	53	1.07	0.58	Very low	Low
P05	59	37	0.65	0.37	Very low	Medium
P06	63	39	0.71	0.40	Very low	Medium
P07	47	16	0.49	0.15	Low	Very high
P08	85	55	1.05	0.61	Very low	Very low
P09	67	36	0.76	0.36	Very low	Medium
P10	84	52	1.02	0.56	Very low	Low
P11	90	60	1.13	0.67	Very low	Very low
P12	90	62	1.13	0.69	Very low	Very low

upper surface with coarse ARH. P01 and P02 pavements belong to this subset. All operators evaluated the pavements in the third group as uncomfortable when passing with a suitcase trolley: for this reason, a pavement comfortable-uncomfortable acceleration threshold of 5 m/s^2 (at a speed of 1.6 m/s) has been established and considered (Figure 7).

The skid resistance was determined by using the British Pendulum Tester (BPT) for all pavements in dry and wet conditions to analyse the safety parameter. The obtained results are presented in Table 8. As can be seen from Figures 9 and 10, all pavements reported a reduction in slip resistance, with a consequent increase in slip potential, in the wet condition compared to the dry one. All the analysed pavements registered a reduction in PTV between 30% and 40%, with the exception of the P03 and P09, i.e. pavements made with porphyric elements, which showed a reduction of 47% and P07 pavement, i.e. Palladian marble pavement, which highlighted a decrease of 65%. All pavements showed a slip resistance ranging from very good to adequate with a slip potential ranging from very low to low in the dry condition. The situation significantly changed considering such pavements in wet condition: only P08, P11 and P12, i.e. asphalt concrete

Colour online, B/W in print

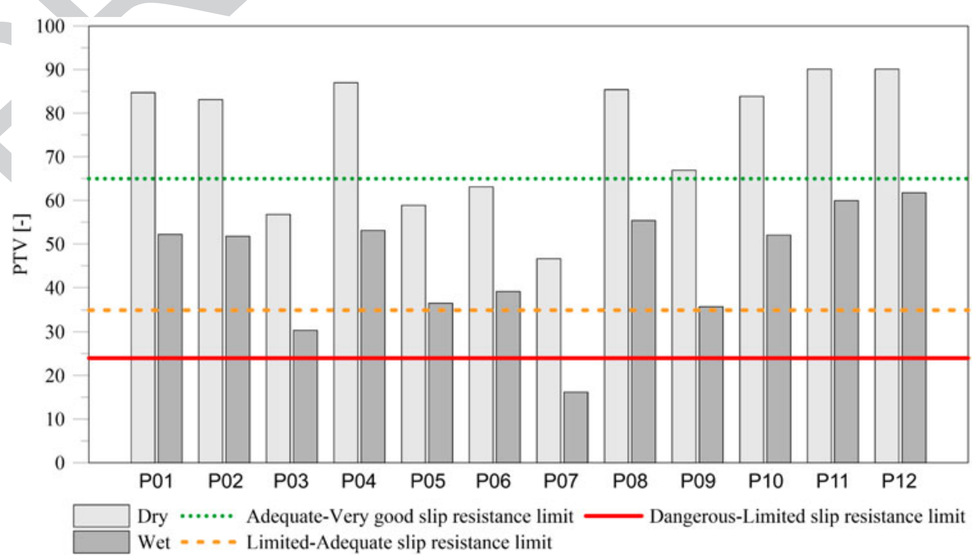
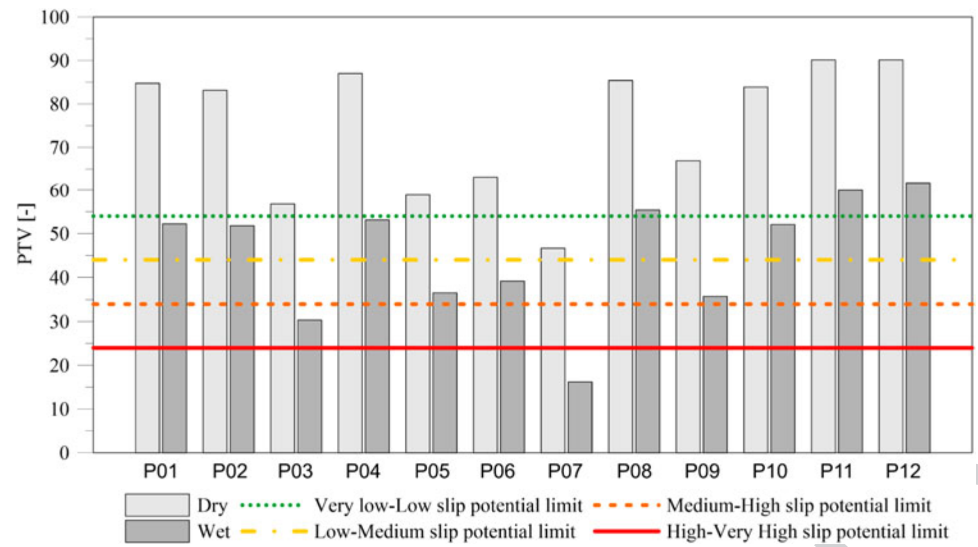


Figure 9. Slip resistance of the analyzed pavements in dry and wet conditions.



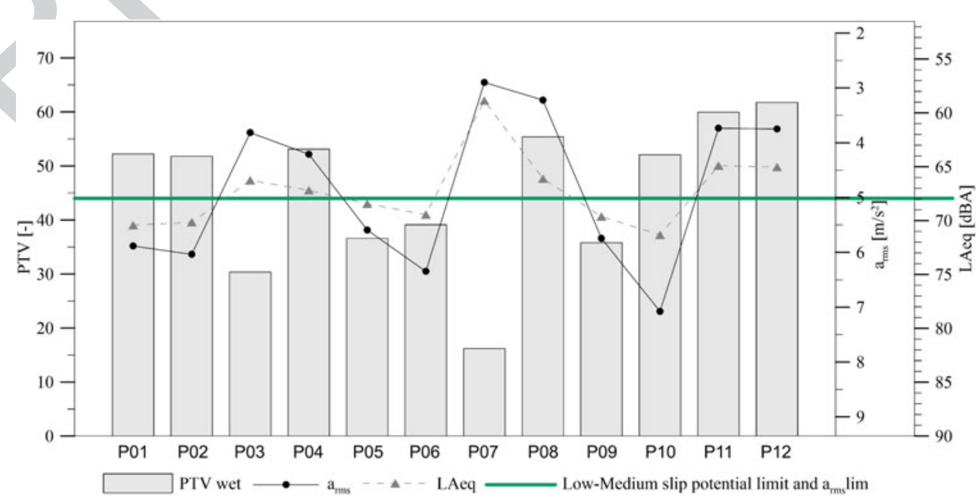
Colour online, B/W in print

Figure 10. Slip potential of the analyzed pavements in dry and wet conditions.

and interlocking concrete block pavements, have a very low slip potential which makes them suitable for being used in external and ramp areas. Moreover, P01, P02, P04 and P10, i.e. pavements made with Luserna stone elements, have a low slip potential, resulting a proper solution for exterior walking pathways. On the contrary, P05, P06 and P09, i.e. pavements made with porphyry and granite split elements, have a medium slip potential and P03 and P07 pavements, i.e. pavements made with flamed porphyric flagstones and marble with honed and polished surface, have a high and very high slip potential respectively. These findings suggest that these kinds of pavement are not recommended in external pedestrian areas. So, in summary, pavements having a PTV less than 45 in wet condition should not be used in exterior walking pathways.

Finally, the acceleration and noise values were compared with the slip potential values to identify the most suitable pavements for pedestrian-priority spaces. The obtained results are presented in Figure 11. The bars represent the PTV of different pavements in wet condition; values greater than or equal to 45 (above of the horizontal line) define a suitable pavement. The black dots depict the a_{rms} at the speed of 1.6 m/s; pavements have proven to be comfortable if a_{rms} is less than 5 m/s^2 (above of the horizontal line). Finally, the grey triangles symbolise the LAeq values; the users' opinion on noise was the same as that given for vibrations and for this reason, a limit value of 68 dBA was considered. In light of these considerations, taking into account safety and comfort, P04, P08, P11 and P12 pavements resulted to be the better alternatives.

As far as the material is concerning, the PTV values suggest that Luserna stone, asphalt concrete and interlocking concrete blocks, offering a low and a very low slip potential, are eligible solutions. Marble, granite, and porphyry instead would seem to be unadvisable, even if the presence and frequency of joints, which represent a discontinuity element, could limit the actual slipping of users. Analysing the dimensions, small stone elements having a regular shape can be used, since consequently also joints have consistent size and shape, as long as they have a fine ARH. But, if the elements have a medium ARH, it is advisable to use larger pavers. Small elements,



Colour online, B/W in print

Figure 11. a_{rms} at 1.6 m/s and PTV in wet conditions of the analyzed pavements.

even with a regular shape and consequently regular joints, but with a high ARH generate too large vibrations and noise that are considered uncomfortable by users. In the same way, elements of large size but with irregular shape lead to wide and irregular joints (even more than 30 mm): also these pavements produce excessive vibrations and noise.

Conclusion

The urban streets have to respond to several essential functions, which have to simultaneously meet the needs of people of all ages and abilities to offer high-quality public spaces. Thus, the quality of a pedestrian-priority space must be read according to a series of specific indicators that combine the unbeatable aesthetic requirements with those of comfort and safety. To this end, the authors have introduced an integrated approach of experimental measurements, which were carried out in the historical city center of Parma, to characterise the quality of pedestrian paths, with specific attention to stone and segmental pavements, also through a smart original test set-up. The authors evaluated the different effects, in terms of vibrations and noise, that the pavement of a pedestrian path can generate on a user pulling a suitcase trolley. These values were than associated with other parameters capable of describing the characteristics of the pavement surface, such as macro- and micro-roughness, skid resistance and size of the elements and joints that make up the pavements.

Based on these investigations, the following conclusions can be made:

- The acceleration values, measured at the luggage handle, obtained on a single pavement by different operators appear to be significantly dispersed. However, analysing these values as a function of the operator's speed, a linear increase with increasing speed was noted regardless of the pavement type.
- Considering the acceleration values at an average speed of 1.6 m/s, it was seen that the arms and LAeq values followed the same trend. Therefore, such pavements had the same vibrational and acoustic comfort, on the basis of which pavement comfortable-uncomfortable acceleration and noise thresholds of 5 m/s^2 and 68 dBA were set.
- The skid resistance was determined by using BPT in dry and wet conditions. All pavements showed a reduction in slip resistance, with a consequent increase of slip potential, in wet condition compared to the dry one. All the analysed pavement showed a PTV reduction between 30% and 40% with the exception of pavements made with porphyric elements (47%) and the Palladian marble pavement (65%). Thus, among the selected materials Luserna stone, asphalt concrete and interlocking concrete blocks resulted to be suitable for pavements mainly intended for pedestrian since they offer a low and very low slip potential. Contrary for the same reason, marble granite and porphyry should not be used in pedestrian-priority spaces.
- Analysing the dimensions, small stone elements having a regular shape can be used, since consequently also joints have consistent size and shape, as long as they have a fine ARH. But, if the elements have a medium ARH, it is advisable to use larger pavers. Small elements, even with a regular shape and consequently regular joints, but with a high ARH generate too large vibrations and noise that are considered uncomfortable by users. In the same way, elements of large size but with irregular shape lead to wide and irregular joints (even more than 30 mm): also these pavements produce excessive vibrations and noise.

Finally, the whole experimental plan permitted to identified comfort and safety thresholds for different pedestrian street pavement surfaces. These values can be usefully made available to designers for the functional characterisation of urban paving solutions, with particular attention to those in natural stone.

Disclosure statement

No potential conflict of interest was reported by the author(s). Q5

Funding

This research was developed within the PRIN 2017 "Stone pavements. History, conservation, valorisation and design" (20174JW7ZL) financed by the Ministry of Education, University and Research (MIUR) of the Italian Government. Q2

ORCID

Felice Giuliani http://orcid.org/0000-0002-8842-5083

References

Alphin, M.S., Sankaranarayanasamy, K., and Sivapirakasam, S.P, 2013. Experimental investigation to study the influence of handle diameter on low-frequency, hand-arm vertical vibration. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 23 (2), 140–148.

Analog.com, 2016. ADXL355 Data Sheet [online]. Available from: https://www.analog.com/media/en/technical-documentation/data-sheets/adxl354_adxl355.pdf [Accessed 7 June 2021].

Autelitano, F., Garilli, E., and Giuliani, F, 2020. Criteria for the selection and design of joints for street pavements in natural stone. *Construction and Building Materials*, 259. Q6

Autelitano, F., Maternini, G., and Giuliani, F., 2019. Colorimetric and photometric characterisation of clear and coloured pavements for urban spaces. *Road Materials and Pavement Design*. Q7

Barton, N., and Choubey, V, 1977. The shear strength of rock joints in theory and practice. *Rock Mechanics Felsmechanik Mécanique des Roches*, 10 (1–2), 1–54.

Biancardo, S.A., *et al.*, 2020. Modeling Roman pavements using heritage-BIM: a case study in Pompeii. *Baltic Journal of Road and Bridge Engineering*, 15 (3), 34–46.

Cepolina, E., Marradi, A., and Ulivieri, D, 2017. Functional aspects of modern and ancient pedestrian mobility on historic stone pavements. *International Journal of Sustainable Development and Planning*, 12 (3), 589–598.

Chu, L., Guo, W., and Fwa, T.F, 2020. Theoretical and practical engineering significance of British pendulum test. *International Journal of Pavement Engineering*. Q8

Colagrande, S., 2008. Pavimentazioni stradali in masselli di pietra. *Strade & Autostrade* (70).

Çoşkun, G., Sarıışık, G., and Sarıışık, A, 2016. Classification of parameters affecting slip safety of limestones. *Cogent Engineering*, 3 (1). Q9

Crossley, E., *et al.*, 2021. The accuracy of iPhone applications to monitor environmental noise levels. *The Laryngoscope*, 131 (1), E59–E62.

Gao, J., *et al.*, 2019. Cycling comfort on asphalt pavement: influence of the pavement-tyre interface on vibration. *Journal of Cleaner Production*, 223, 323–341.

Garilli, E., Autelitano, F., and Giuliani, F, 2017. A study for the understanding of the Roman pavement design criteria. *Journal of Cultural Heritage*, 25, 87–93.

Garilli, E., *et al.*, 2020. The influence of laying patterns on the behaviour of historic stone pavements subjected to horizontal loads. *Construction and Building Materials*, 258.

Garilli, E., and Giuliani, F, 2019. Stone pavement materials and construction methods in Europe and North America between the 19th and 20th century. *International Journal of Architectural Heritage*, 13 (5), 742–768.

Giuliani, F., *et al.*, 2017. DEM modelling analysis of tree root growth in street pavements. *International Journal of Pavement Engineering*, 18 (1), 1–10.

Giuliani, F. and Rastelli, S., 2007. Color and retroreflection measurements of urban road surfacing materials | Mesures de couleurs et de rétroréflexion des matériaux pour revêtements routiers en milieu urbain. *Bulletin des Laboratoires des Ponts et Chaussees*, (266), 53–69.

Gomes, H.M., and Savionek, D, 2014. Measurement and evaluation of human exposure to vibration transmitted to hand-arm system during leisure cyclist activity. *Revista Brasileira de Engenharia Biomedica*, 30 (4), 291–300.

Gong, J., *et al.*, 2020. Evaluation of long-term performance for bonded natural stone pavement using accelerated pavement test [part II: skid resistance, response of deflection and FEM analysis]. *Applied Sciences (Switzerland)*, 10 (3).

Griffin, M.J., 1990. *Handbook of human vibration*. Elsevier.

Mohora, I., and Anghel, A.A., 2019. Urban landscape-cubic stone streets in historical areas, advantages and disadvantages, case study Timisoara versus Rome. *In: IOP Conference Series: Materials Science and Engineering*.

National Association of City Transportation Officials and Global Designing Cities Initiative, 2016. *Global street design guide*. Island Press.

Pecchini, D., and Giuliani, F, 2015. Street-crossing behavior of people with disabilities. *Journal of Transportation Engineering*, 141, 10.

Sabey, B.E., and Lupton, G.N, 1964. Friction on wet surfaces of tire-tread-type vulcanizates. *Rubber Chemistry and Technology*, 37 (4), 878–893.

Schnee, J., *et al.*, 2020. Auto-correction of 3d-orientation of IMUs on electric bicycles. *Sensors (Switzerland)*, 20 (3).

Speaks, H., and Beamer, B., 2020. Developing a simple tool noise comparison procedure for use in a Buy Quiet program. *In: Proceedings of 2020 International Congress on Noise Control Engineering, INTER-NOISE 2020*.

Tanzil, Y.T., and Gamal, A., 2021. Elements identification for pedestrian comfort. *In: IOP Conference Series: Earth and Environmental Science*.

De Winne, E., 2006. Towards an integral accessible public area in the city. *WIT Transactions on Ecology and the Environment*, 93, 807–815.

Zoccali, P., Loprencipe, G., and Galoni, A, 2017. Sampietrini stone pavements: distress analysis using pavement condition index method. *Applied Sciences*, 7 (12).