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Criteria for the selection and design of joints for street pavements in natural stone

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Abstract: Natural stone pavement can produce a high quality attractive streetscape with a long service life. Although the formal analogy with the interlocking concrete pavements, the peculiarities and singularities of the stone elements pose enormous challenges to the designers which have at their disposal only limited standards and guidelines. The joints represent one of the most important part of the stone paving system, performing multiple tasks: stabilize the elements, transmit and dissipate loads, control the water disposal and contribute to the aesthetic. But, the analytical study of the joints is inexplicably an understudied topic in the technical and scientific literature: many problems resulted in stone pavements from lack of understanding of joints' purposes and functions. Thus, the paper highlighted the conceptual steps necessary to the selection of the optimal jointing solution. Several aspects related to the stone elements' characteristics and laying that contribute to the joints' optimized performance have been evaluated. After a brief description of the main defects that can affect stone pavements, a state of practice regarding the jointing materials with the related application techniques have been reported.

COVER LETTER FOR SUBMISSION OF MANUSCRIPT

Parma, 14th May 2020

Dear Editor-in-Chief,

We have received your letter indicating that a revised version of our manuscript "CRITERIA FOR THE SELECTION AND DESIGN OF JOINTS FOR STREET PAVEMENTS IN NATURAL STONE" (CONBUILDMAT-D-20-02803) was requested. We strove to provide you a new better revised article following closely all the reviewers' comments, which were particularly useful for identifying aspects not well clarified and for meeting Journal standards. From that perspective, we would like to thank them for their valid opinions and time spent.

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- All authors of this research have contributed substantially to the manuscript;
- All authors of this paper have read and approved the final version submitted;

- All previously published work cited in the manuscript has been fully acknowledged
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Sincerly,

Felice Giuliani

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Title

Criteria for the selection and design of joints for street pavements in natural stone

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Criteria for the selection and design of joints for street pavements in natural stone

Abstract

Natural stone pavement can produce a high quality attractive streetscape with a long service life. Although the formal analogy with the interlocking concrete pavements, the peculiarities and singularities of the stone elements pose enormous challenges to the designers which have at their disposal only limited standards and guidelines. The joints represent one of the most important part of the stone paving system, performing multiple tasks: stabilize the elements, transmit and dissipate loads, control the water disposal and contribute to the aesthetic. But, the analytical study of the joints is inexplicably an understudied topic in the technical and scientific literature: many problems resulted in stone pavements from lack of understanding of joints' purposes and functions. Thus, the paper highlighted the conceptual steps necessary to the selection of the optimal jointing solution. Several aspects related to the stone elements' characteristics and laying that contribute to the joints' optimized performance have been evaluated. After a brief description of the main defects that can affect stone pavements, a state of practice regarding the jointing materials with the related application techniques have been reported.

Keywords: stone pavement; joint filling; restoration; polymeric sand; resin; cement mortar.

Introduction

The excellent technical-performance characteristics, together with the flexibility of the size and the inherent characteristics capable of determining colors, textures and unique aesthetic results have made the natural stone the par excellence paving material since the Roman times [1,2]. After a long period spent covering the authentic historic pavements with asphalt, we are now witnessing a renewed interest in stone pavements not only for the necessary conservation, maintenance and enhancement of this impressive artistic, archaeological and cultural heritage, but just as current reuse in a modern sense of technologies often wrongly considered obsolete and no longer meet the today's infrastructure needs (Fig.1) [3,4]. Stone pavements belong to the broader family of the elemental or segmental pavements, i.e. pavements in which the surface course is made up of individual units placed close together to each other and embedded in a bound or unbound bedding layer or laying course [5]. Although the formal analogy with the interlocking concrete pavements, whose use has been well researched and supported by an established know-how [6-8], the peculiarities and singularities of the stone elements pose enormous challenges to the designers which have at their disposal only very limited national standards and guidelines. The only international harmonized standards concern the inherent mechanical and physical-chemical performance requirements of stone units. Thus, the modern study of these pavements, according to a technical engineering perspective, for the project of a new surface or the conservation and restoration of a historic one requires a specific design of the laying conditions with maximum attention to the compatibility and the interaction between the stone elements, the bedding layer and the joints, i.e. the gaps or the distances between adjacent paving units, or units and restraints or perimeters. The joints represent one of the most important part of the composite stone paving system, performing multiple tasks:

stabilize the elements, transmit and dissipate loads, control the water disposal and contribute to the aesthetic quality of the paving [9,10]. Several jointing solutions have been traditionally used and each one responds to specific needs with its advantages and disadvantages [11,12]. However, talking about joints, it is not enough simply to consider the material that fills the gaps between units, but represent complex systems that affect with their characteristics the behavioral mechanism of the whole pavement and have a decisive influence on the selection of the stone elements' size and dressing and on the laying techniques and patterns. But, the analytical study of the joint is inexplicably an underestimated and understudied topic in the technical and scientific literature: many problems resulted in stone pavements from lack of understanding of joints' purposes and functions.

Figure 1 - Construction of a stone pavement in urban context

Thus, the paper aims to highlight the conceptual steps that can allow a rational choice of the optimal jointing solution. Several aspects related to the characteristics of the stone elements (size, shape, side-texture) and laying that contribute to an optimized performance of the joint have been analyzed in detail. After a brief description of the main types of defects that can be caused by mechanical and physical-chemical stresses but also by poor or inaccurate design, installation (workmanship) and maintenance, a state of practice regarding the current jointing materials with the related application techniques have been mentioned. Also jointing solutions which were in common use in the XIX century and have partially fallen into disuse have also been included, because in maintenance or restoration works, according to conservation principles, original materials including details and finishing and traditional skills have to be used, eventually supported by modern techniques only where traditional methods may prove inadequate.

Design criteria

The choice of the best jointing solution should come from a multi-criteria analysis, in which the designer comes up with a decision downstream of an analytical process based on functional, aesthetic and economic hierarchical requirements (Fig. 2).

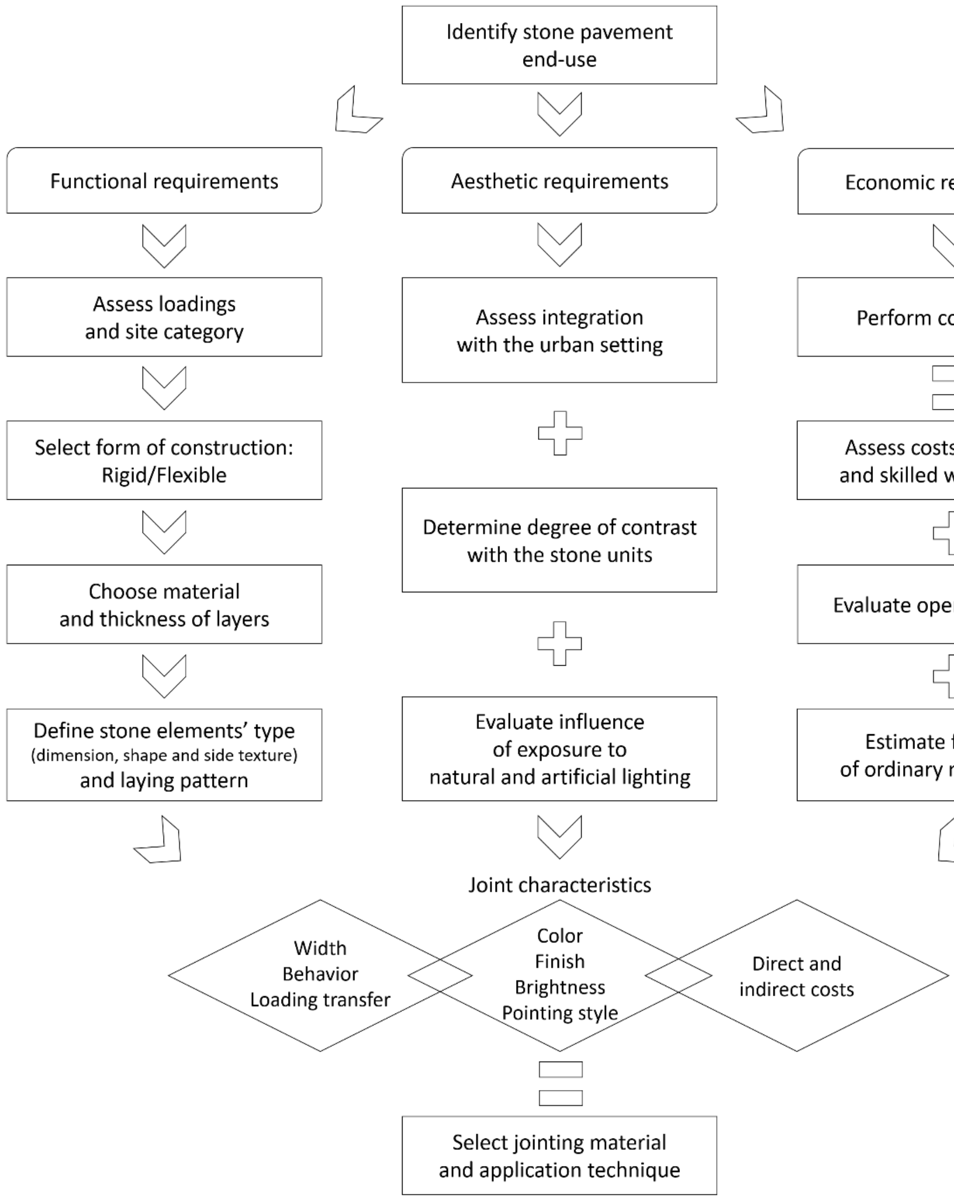


Figure 2 - Multi-criteria analytical process for selecting the best jointing solution

The definition of these requirements mainly depends on the pavement end-use, the construction technique and the stone units' material and type (dimension, shape and side texture). The broad concept of pavement end-use considers aspects related to the induced loads, the type of prevailing user (pedestrian, cyclist, vehicle) and the area in which the pavement is inserted (private, residential, historical, park). The system of stresses to which the pavement should be able to resist, and therefore have to be taken into account during the design phase, mainly concerns the presence of static or dynamic loads transmitted by pedestrian or vehicular traffic [13]. On the basis of the magnitude and frequency of this loading condition, a number of “site categories” or “operation/stress classes” can be identified. Stone surfaces are also strongly affected by secondary loadings, i.e. stresses induced by the layout and geometry of a particular site which have the effect of concentrating the loading (gradients, junctions, restricted road width, channelization, drainage channels) [9]. Besides mechanical loadings, the effects of hygral-thermal conditions, linked to climatic and seasonal variations (UV radiation, high/low temperature, frost, snow, rain), or caused by the aggression of chemical substances (air pollution, salts, lubricants or fuels) should be taken into account [14].

The designer has the possibility to select either a flexible (Fig. 3a) or rigid (Fig. 3b) pavement construction, that obviously underlies a different deformation behavior under loads, within the limitation of their bearing capacity [15].

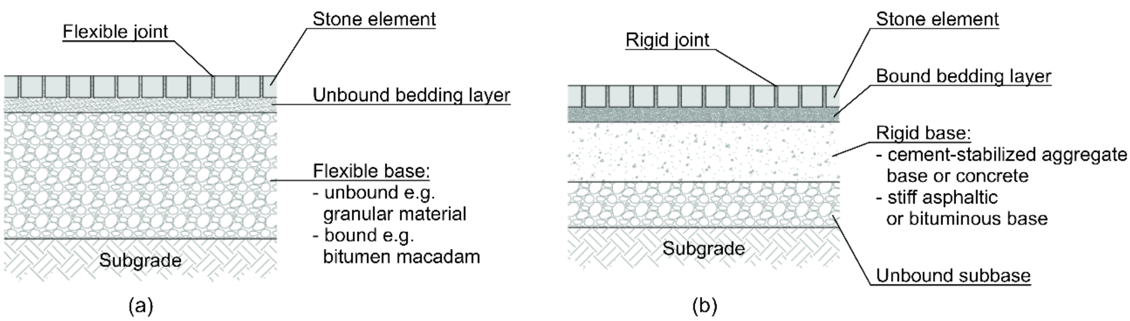


Figure 3 - Flexible (a) and rigid (b) form of construction

In addition to the type of materials that constitute the layers, also features of stone units, their laying patterns, and joint width determine the way in which the surface course responds under load, influencing the pavement structural capacity [16]. Stone elements come in a wide variety of materials, dimensions and shape, ranging from rounded cobbles, to parallelepiped shaped deep elements (cubes, setts, cut blocks) and to shallow and large slabs (flagstones and polygonal flags) [17,18]. In general terms, shallower units respond in a flexible manner to loads and are best suited to flexible construction;

as the depth of the units increases the behavior become stiffer. Typically, surfaces that react flexibly rely more on the laying course than on the joints to sustain loading, while rigid stone pavements are stabilized by the setting action of the joint material, which provide at the same time the primary resistance to load [9]. In accordance to the principle of execution consistency, the compatibility between bedding and jointing materials is required: flexible form of construction uses unbound bedding and flexible jointing (unbound or bound); whereas rigid pavement uses a rigid bound material in both the laying course and the joints [10].

In site categories subjected to regular vehicular traffic, eventually receiving heavy vehicles, the joint is required to contribute to the structural performance of the whole pavement. The joint performs its structural function in a different way when a flexible/rigid or unbound/bound material is used. Flexible joints are able to accommodate any small relative movements of the elements, induced by traffic, temperature variations or tree root growth, without failing [15,16,19]. Rigid materials are instead characterized by higher compressive and shear strengths, but are prone to local cracking even after a single stress application in excess of their capacity [20,21]. Unbound materials develop mechanical interlock, also called interlocking, and friction to "lock" the elements and transmit loads, whereas bound products perform their functions exploiting the bond adhesion strength between the stone and the joint material [22]. Interlocking, which is expressed in its three types vertical (resistance to sinking), horizontal (resistance to shifting) and rotational (resistance to tipping), represents the inability of a stone element to move independently from its neighbors (Fig. 4).

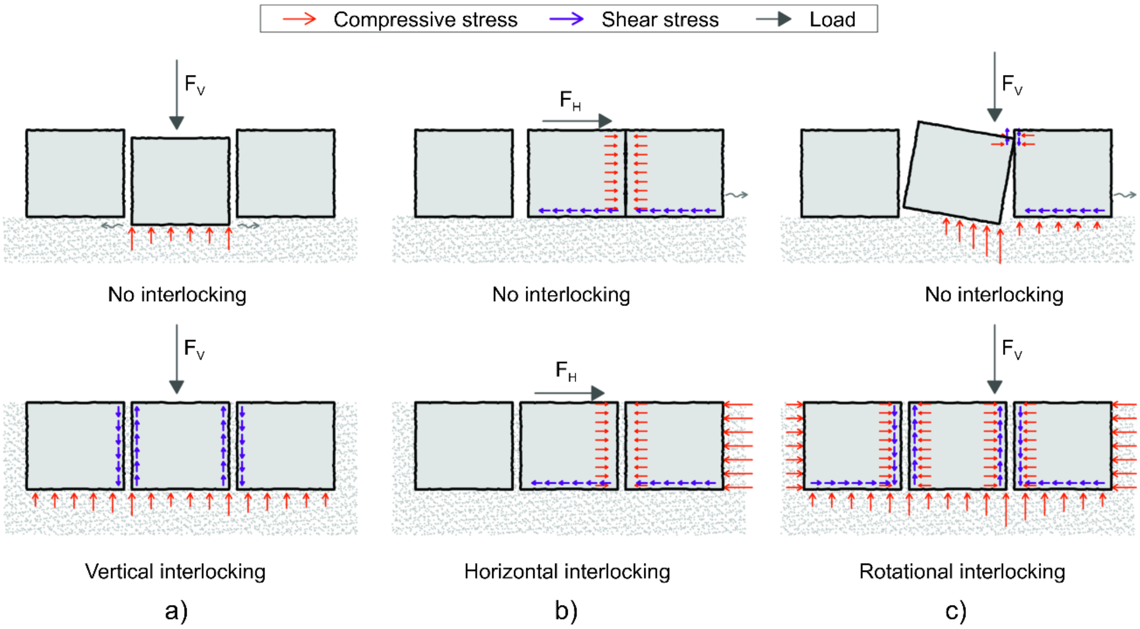


Figure 4 - Interlocking mechanisms: vertical (a), horizontal (b) and rotational (c)

Specifically, vertical interlock is primary achieved by shear transfer of loads to surrounding units through the joints (Fig. 4a), while the horizontal one through the use of laying patterns that disperse forces from braking, turning and accelerating vehicles (importance of edge restrain) (Fig. 4b). Rotational interlock is maintained by the element being of sufficient thickness, placed closely together (joint width), and restrained by a curb from lateral forces (Fig. 4c) [8]. The stone side-wall texture and the joint width play an important role in the development of interlocking. Sawn, split, cropped or sawn and re-textured units' sides produce very different adhesion and frictional bonds with the jointing material [23,24]. In terms of joint width, three main types can be defined: butt (adjacent paving units are in direct contact with one another), close or narrow (2-8 mm) and open or wide (> 8 mm) (Fig. 4).

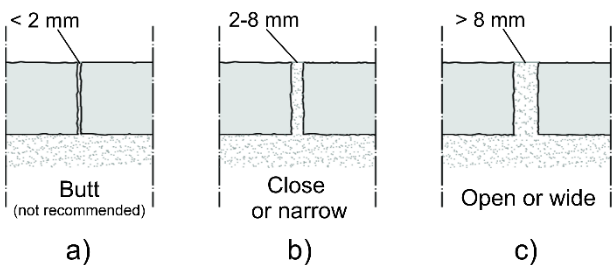


Figure 5 - Joint width types: butt (a), close or narrow (b) and open or wide (c)

In the first case the risk of damage to the edge or arris of the paving units (spalling or chipping) is extremely high (Fig. 5a). Increasing too much the width, it reduces the possibility of obtaining a satisfactory vertical and rotational interlock, especially if an unbound material is used: open joints require a bound product for best result (Fig. 5c). In wide open joints, a loss of filling makes impossible to partially transfer any stress induced by traffic loads to the adjacent elements. A consistent joint width in the surface over the whole depth and length of the joint is a fundamental design parameter to ensure a completely filling and a homogeneous compaction of the material. But, the achievement of this requirement is a very difficult practice using natural stone elements, above all with round or square but tapered units (Fig. 6).

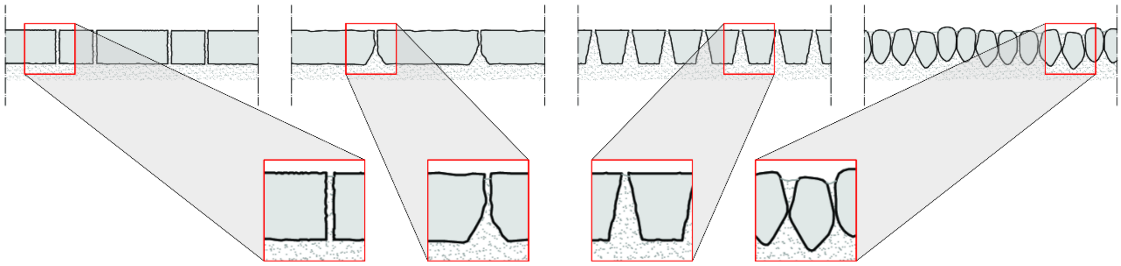


Figure 6 - Inconsistent design joint width

Obviously, the joint width is an important factor with regards to the pavement drainage. Proper and effective drainage is a fundamental design parameter to consider in order to ensure both the users' safety and the structural long term performance of the pavement. Depending on the type of support layer and the techniques and methods of drainage (surface or sub-surface), the joint may be required to be impervious or completely permeable. Where frost action is likely to occur, above all in climates with cold winters, a pervious jointing material is a preferred solution [11,25].

However, most of the stone pavements are located in historical centers and in monumental contexts, shaping the architectural and spatial character of streets or squares and redrawing the urban landscape [26,27]. Thus, the often overlooked aesthetic requirements are essential elements and very often priority with respect to the functional ones. The joint itself becomes a decorative motif that can make a decisive contribution to the overall pattern of the pavement. The material, color and detail of a jointing material can have a dramatic effect on the finished appearance of the work, completely changing its character in some cases [28] (Fig. 7).

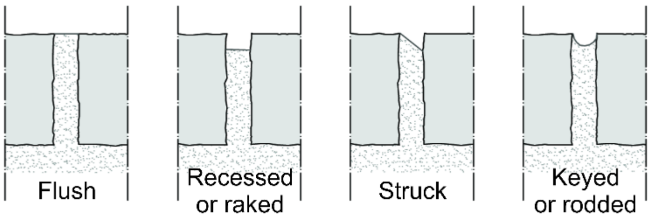


Figure 7 - Pointing styles

The chosen solution should never detract from the stone by being more visually dominant. Strap-pointing with raised bands covers the edges and causes the pointing to be too intrusive. Thus, slightly recessed joints allow the edges to be seen, but they have the disadvantage of catching dirt and allowing the accumulation of water which may make them unacceptable in some circumstances [29]. A good jointing material should complement the stone, offering a suitable degree of contrast that emphasizes the individual element: an exact match, a strong contrast, or a color that blends with units represent options to be assessed at the design stage, considering the natural (direct sunlight or shaded area) and artificial lighting (color temperature and color rendering index) conditions and exposure [30]. The chromatic effects can be obtained both by exploiting the natural color of the jointing medium both through the use of pigments, possibly characterized by enhanced properties, such as photoluminescence or thermochromism, for special and scenic applications [31-33]. Besides, the joint color is strongly affected by finishing and detail parameters (smooth vs grainy and glossy vs matte), which influence the light reflection.

But, the final decision cannot be separated from a detailed cost analysis that takes into account all the direct and indirect costs associated with the joint project, which obviously are not limited to the purchase of jointing materials. Costs also include the labor expenses for applications and repair/maintenance: this cost item can be extremely variable. Some jointing materials require advanced special-purpose tools, skilled and experienced operators and high frequency of ordinary maintenance, i.e. aspects that considerably raise the total funds needed to complete the project and correctly maintain the pavement.

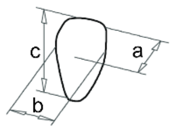
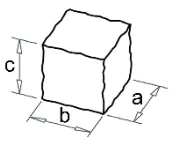
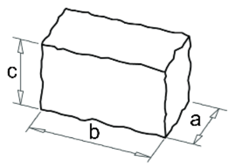
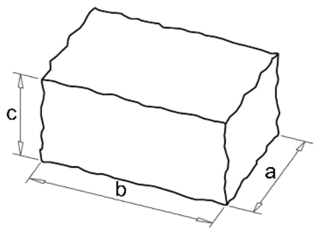
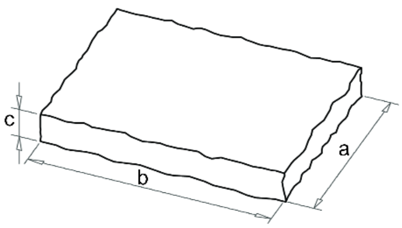
Features of elements

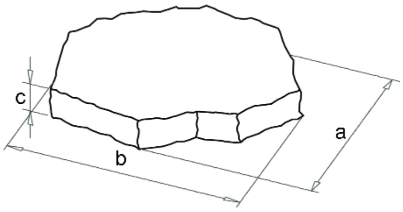
Several inherent features of stone elements (petrographic nature, mechanical and physical-chemical performances) and others resulting from quarrying, cutting and dressing process (size, shape and face texture) strongly influence the pavement design, including the selection of the joint solution and width [12,34].

The materials used for stone pavements greatly varied from place to place; the choice was dictated, especially for the pre-XIX century projects, by logistical constraints related to distance and ease of material procurement, while today due to the market globalization, designers can select different petrographic varieties characterized by peculiar properties. The most commonly used materials are porphyry, granite (and similar lithotypes), basalt, sandstone, trap and compact limestone [18,35]. Thus, jointing material must be firstly chemically compatible with the stone and with the surface finishing, particularly when sanding, brushing or bush-hammering on site is planned.

The dimensional characteristics of stone elements are an important morphological variable, conditioning the aesthetic rendering, the pavement behavior and the joint network. Stone pavements use units characterized by a multiplicity of shapes, more or less regular, and with size that vary from a few centimeters (small cubes) to over one meter in length (giant flags) (Tab. 1).

Tab.1 - Stone elements used for paving

	Dimensions [mm]	Joint width [mm]	Typical application
Cobblestone 	a = 60 ÷ 80 b = 80 ÷ 120 c = 120 ÷ 160	5 ÷ 30 (surface)	Pedestrian areas in historic settings (footpaths, squares, arcades)
Cube 	a = 40 ÷ 200 b ≈ a c ≈ a	6 ÷ 10 (40 < a < 60) 8 ÷ 12 (70 < a < 140) 10 ÷ 15 (150 < a < 200)	Pedestrian areas Pedestrian areas with occasional vehicular traffic Roads Footways overridden by vehicular traffic
Sett 	a = 70 ÷ 150 b ≈ 2a c = 100 ÷ 180	8 ÷ 12 (100 < c < 120) 10 ÷ 15 (150 < c < 180)	Roads Car parks with occasional heavy traffic Footways overridden by vehicular traffic
Block 	a = 150 ÷ 250 b ≈ 2a c = 100 ÷ 200	10 ÷ 12 (surface) Max. 22 ÷ 25 (any part)	Street and roads
Flagstone 	a = 200 ÷ 500 b = 300 ÷ 500 c = 50 ÷ 100	6 ÷ 12 Min. 4 (sawn and shallow units)	Pedestrian areas (footpaths, squares, arcades), with occasional vehicular traffic
Polygonal flagstone			

	a = 200 ÷ 500 b = 300 ÷ 500 c = 50 ÷ 100	< 30	Private drives, paths, patio and hard landscaping projects

Quadrangular elements, both rectangular and square, are the most commonly used. Unlike industrial products, which are strictly controlled in tolerances and modularity, slight deviations from the standard dimensions of stone paving elements are tolerable [17,36]. In addition to calibrate the density of the pattern in a progressive saturation of the basic shape, the size also responds to the functional needs of a pedestrian or vehicular user. However, horse-drawn carriages were the reference user in the XIX century. Thus, requirements for units' length and width were reported in specifications of that time, on the basis of horseshoes' dimension, stride length and number of longitudinal and transverse joints, which offered the animals a better foothold, preventing from dangerous slipping [25,37]. The mainly two-dimensional characteristic of the elements must not make us forget the importance of the depth (or thickness), which influences the expressive result of the surface in a lesser way, but can limit their application in certain site categories and conditions the pavement behavior under loading. Generally, deep elements ($c > 100$ mm) are predominantly stabilized by jointing and can be used also in medium-high intensity traffic applications, whereas shallow units (50 mm $< c <$ 100 mm) are stabilized by bedding and are destined to pedestrian projects subjected to occasional overrun of vehicles (Tab. 1). In addition to the size and shape, also dressing degree and side-wall texture affect the role of the joint and its width. A good dressing and secondary cutting process produces stone elements with the lateral faces perpendicular to the road surface, without marked indentations and protrusions. There is a significant difference in the regularity of paving units of different varieties of stone and also from different quarries of the same variety. Some rocks can be split up into suitable elements already after the quarrying and first cutting stage [34]. A special case is represented by cobbles; they are not dressed but naturally occurring rounded and embedded, as found in river beds or beaches, with the smaller dimension facing downwards. For blocks, slight undercut may be provided for the lower half of the sides to allow the bedding material to find an outlet during the ramming and settling. In the cubes, the taper (max. 1/8 of the upper face) can be extended to the whole depth [38]. In this case, pavers are instructed to set the cubes with the larger face up; placing the large end down, which is objectionable from a practical perspective, makes a too wide joint. But, recent guidelines suggest to lay tapered cubes ensuring that adjacent units are not in contact and the joint tolerances are maintained [9]; this recommendation is actually not ever valid and excessively conditioned by the type of jointing product. The side texture should have a suitable roughness able to optimize the adhesion and frictional bonds with the jointing material: a too fine (sawn units) or too rough (cropped) texture reduces the performance at the interface. For unbound jointing material, the grading curve is selected on whether the stone unit is sawn or cropped, i.e. finer in the first case and coarse in the second. In rigid construction, elements with split or re-textured (sandblasted) surface generally show the greatest shear capacity, whereas cropped elements present problems related to difficult in filling non-uniform joints, resulting in variable performance under loading conditions [24].

Fairly smooth cobbles are set with the smaller dimension facing downwards upon a bed of granular fine aggregate or natural soil and packed tightly together or bound with a rigid medium. Although it is possible to lay cubes, setts and blocks using any jointing material configurations, they are currently applied in rigid construction method, above all in vehicular trafficked areas [39]. Unbound jointing on an unbound bedding, although presents some maintenance and functional drawbacks in presence of vehicular traffic, represents the preferred methods for re-laying reclaimed elements from an architectural conservation viewpoint. Traditionally, small deep elements (cubes and setts) were split rather than cut, and the rough vertical faces were laid in dry-bound manner almost in contact to each other, with a recommended joint width of 5÷10 mm [40]. In general, ordinary stone-blocks pavements were laid so that any joint should show a surface width of more than 10÷12 mm and a width of more than 22÷25 mm in any part of the joint [12] (Tab. 1). In addition to be less costly, minimizing the amount of required jointing material, keep the joint tight ensured on the one hand a better vertical interlock, resulting in improved structural integrity of the pavement, and on the other producing a reduction of the surface irregularity. Specifically, the joint width in cubes and setts depends on element dimension ranging between 6 and 15 mm: 6÷10 mm for small cubes (a = 40/60 mm); 8÷12 mm for medium cubes (a = 70/140 mm) and shallower setts (c = 100/120); 10÷15 for large cubes (150/200) and deeper setts (c = 150/180) (Tab. 1), although achieving consistency in joint width is difficult in practice above all for cropped or reclaimed units [17]. Only pavement on steep grades showed comparatively wider joints to afford a good foothold for the horses [37]. But, today we are witnessing a change in the stone pavement design, in which the installation of the elements is subordinate to the types of jointing material so that it can develop its potential. The joints have therefore become progressively wider (up to 25÷30 mm), especially in cases of jointing with rigid or new generation products which require larger joints width and depth than traditional products. In this way, besides impoverishing the architectural and aesthetic quality of the pavement, is given to the joint an extreme structural role (primary source of resistance to load) that could be compromised at an early stage by local failures/fractures at the interface between the jointing material and the stone or in the material itself (Fig. 8).

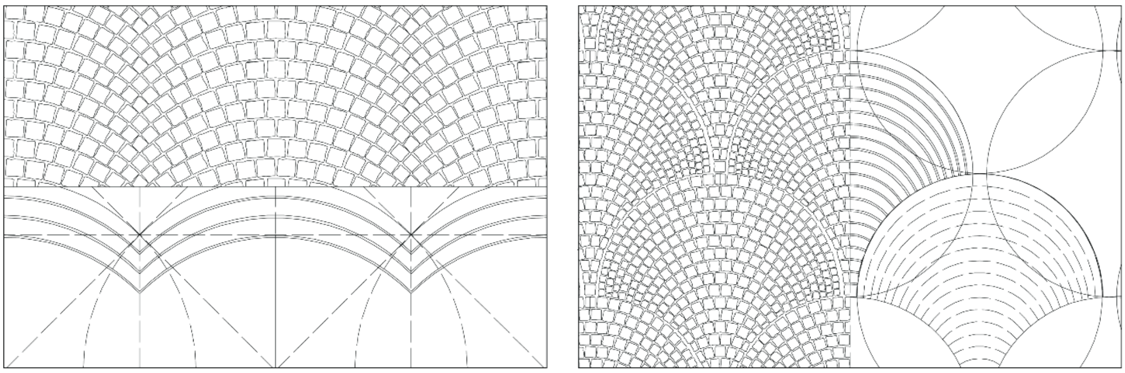
Figure 8 - Too wide joint width in a stone cube pavement

Ideally, flags should be bedded on a thoroughly compacted layer of unbound material and jointed with the same product. This is the best solution for chamfered or rounded flags. Although recommendations suggest the use of flexible construction methods for shallow units, modern applications with calibrated flagstones and polygonal slabs are realized using rigid joints, sometimes carried out as a single operation. However, this approach remains problematic from both an aesthetic and technical point of view [29]. Hard impermeable joints are not able to absorb thermal and structural movements and can cause erosion of stone edge due to the retention of moisture coupled with frost action over time. The recommended joint width for flags and slabs is 6 mm to 12 mm; but sawn stone shallow units manufactured with strict dimensional tolerances are sometimes laid considering very narrow or butt joints (≈ 4 mm) (Tab. 1). When no joint space is left between adjacent paving units, the stone is effectively “butted” together and this can cause and favor spalling or delamination, exposing the edges of the slabs to mechanical and atmospheric agents. With polygonal slabs, where it is not possible to speak of joints in a strict sense, the distance between the edges of two adjacent elements should mainly be less than 30 mm.

Laying patterns

The choice of the most suitable pavement laying pattern is determined by aesthetic requirements, but often dictated by functional ones, also in relation to the stone nature, the route type, the adopted drainage system and the loading conditions [41]. The great variability of dimension, shape and dressing of the stone elements promotes the development of a wide range of pattern solutions, in which the joints and their networks become themselves signs generating the pavement drawing [42]. The surface layout uses geometric shapes, which can constitute a modular unit repeated according to a certain rhythm in a non-directional or with prevailing orientation system [28]. This incredible flexibility allows the laying pattern to be varied, passing from a linear to a curved field, without increasing the joint width, which would be detrimental for the uniformity effect and the serviceability of the surface. Thus, the designer has the possibility to select different patterns that are able to solve, with solutions that enhance the pavement aesthetic, even critical situations. In high stressed areas where horizontal forces from braking, turning and accelerating vehicles are directly induced in the surface (stop/start lines, junctions, steep inclines or marked changes of vertical gradient) the use of specific patterns, even locally, is essential to generate horizontal interlock and ensure the elements and joints to act homogeneously [43]. Whilst not always obvious in the early life of a stone pavement, experience has shown that after a few months (time depending on traffic volume) laying patterns that are not able to develop high levels of horizontal interlocking can be disturbed by the traffic. As a rule, patterns that preclude long straight lines in either direction and thus prevent movements developing under the action of traffic are preferred [44]. Specifically, the size and the shape of the stone units influence the selection of the bond pattern.

Regular cubes are generally laid in curved patterns, in which the arc is oriented in the traffic flow direction. The arc is the most suitable construction element to horizontally transmit and dissipate towards the lateral perimeter of the roadway the forces from braking, turning and accelerating vehicles. This reduces joint compressive stress and the potential for horizontal creep of units [45]. One of the most popular curved layouts is the overlapping arc, also known as Bogen or segmental arc (Fig. 9a), in which the cubes of each row are laid in a series of inter-laced arcs of constant radius and arranged in such a way that each pair of neighbors arcs has in common the springer element [3]. In this pattern, the central angle is equal to 90° and the length edge of the cubes gradually increases from the springer to the keystone, i.e. the edge of the key element is equal to the diagonal of the springer one. Since the face of the cubes is square and not trapezoidal, the joints width grows, diverging at a certain angle, from the springer to the keystone. But, too wide or irregular joints can compromise the aesthetic result and the mechanical resistance of the paving, as well as reduce the users' comfort. Thus, each arc is composed by about 20 cubes so that the angle of divergence does not exceed a few degrees. Moreover, cubes must be placed staggered compared to those of the preceding row to offer greater structural capacity and resistance to lateral movements. However, the disadvantage of overlapping arc is that all the smaller elements (the less resistant) tend to concentrate in narrow longitudinal areas (the springing lines), which are in a parallel direction to the road axis, resulting in a potential weakness for the pavement [46]. To overcome this drawback is possible to resort to the fan pattern, in which the arcs are truncated, at points more or less distant from the springer line, to allow the insertion of neighboring truncated arcs. The smaller cubes are no longer longitudinally aligned but are arranged in a herringbone pattern along a strip of appropriate width and interspersed (spaced) with larger elements. The advantage does not just compensate for the greater difficulty of installation: this layout is mainly used in areas where the main purpose is to achieve a high decorative appearance. Another more valuable laying pattern is the European fan or peacock tail of fantail one (Fig. 9b), in which cubes are laid according to contiguous semicircles and setting the subsequent sectors on the center of the already arranged semicircles [47]. A less effective alternative, able to generate low to moderate interlock in the surface, is the coursed pattern in which the units are laid in rows at 90° to the direction of traffic (transverse), eventually flanked by longitudinal (running in same direction as traffic flow) channels or gutters at each edge, but with each row staggered by approximately half a length. This represent the most popular pattern chosen, since the XIX century, for sett work laid in streets and squares. In some situations, the arrangement of the cubes diagonally to the direction of the traffic (inclination of 45°), which represent a less effective solution, is widely used. The advantage is the possibility of reversing the flow of traffic while leaving its resistance unchanged [17].



(a) (b)

Figure 9 - Overlapping arc (a) and European fan (b) laying pattern

With regards to the elements with a rectangular plan, with different length to breadth ratios (2:1, 3:1, 3:2 and 4:3 are the most common), the most effective laying pattern is the herringbone bond, which offers greater structural capacity and resistance to lateral movements. In relation to the main direction or alignment of the pavement, stone elements are placed either along and at right-angles (90°) or at about 45°, to this direction [41]. Certain patterns assist also stone pavement realized with large flags or blocks to withstand localized horizontal forces. In the past, the most used laying pattern for vehicular traffic applications was that with courses inclined with respect to the road axis. This arrangement was necessary to avoid that the metal rims traveled in the directions of the joints, which in any case represent the weakest parts of the road surface. These permanent stresses could have determined not only direct actions on the edges but also displacements of the elements with consequent creation of tensions in their perimeter surfaces. With respect to the road axis, the most suitable and used inclination courses are those at 45° or 63° (Fig. 10). With this inclination, the edges of the elements in correspondence to the connections are better saved from transit and the number of head joints is minimized [11,40].

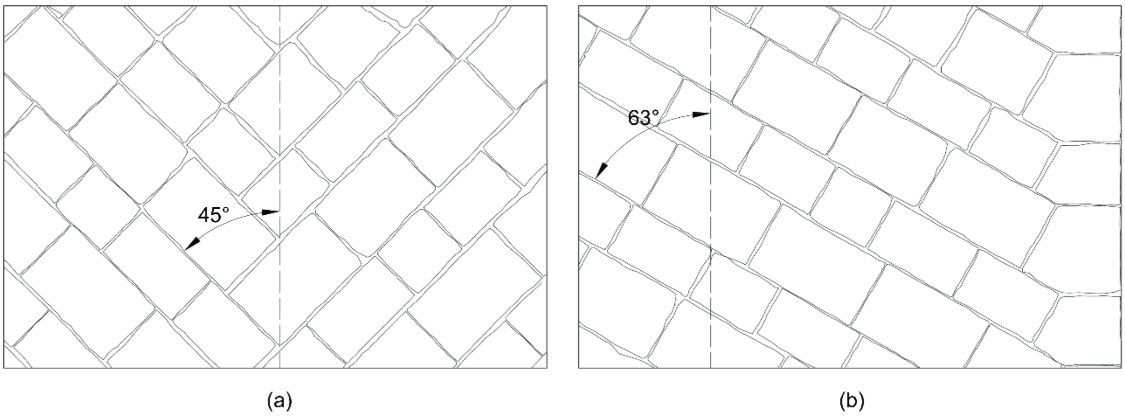


Figure 10 - Two methods of laying stone elements diagonally: 45 ° (a) and 63° (b)

Defects and pavement failure

Stone pavement defects, both in terms of performance and appearance, are caused by a number of factors often acting simultaneously, which can be broadly classified into three categories, i.e. mechanical, physical and chemical. These distresses can occur at different severity level, ranging from slight deteriorations, which require small ordinary maintenance operations, to the complete pavement failure, which imply the elements' lifting and relaying. Conceptually, flexible stone pavements typically fail under the cumulative effect of a number of load cycles, whereas the rigid ones under a single direct load, which can produce a shear failure of the joint and/or a bearing failure of the laying course under the punching action [9,39]. Also lower severity levels that do not compromise the pavement structural integrity, can reduce the serviceability, representing also a source of discomfort or safety hazard for vulnerable users, and the aesthetic rendering of the pattern [48,49]. Most of these defects are directly caused or indirectly related to the alteration of the joint system, i.e. all the modifications that may lead to the degradation of its original characteristics. Joint defects can be limited in localized of isolated areas or more widespread. The former is very often attributable to a concentration of stresses or a poor workmanship, while in the latter case is more likely to be due to inaccurate design (Fig. 11).

Figure 11 - Stone pavement defects at stop/start line

Cracking (bound joint) or loss/pumping of jointing material (unbound joint) commonly contribute to the loss of paving integrity. Two types of fractures can develop in almost all bound jointing materials, namely cracks along stone unit-filling contacts and transverse fractures across the material [20]. However, fine surface cracks can appear also in well-constructed and designed pavements and in most instances do not affect the load transfer capability of the surfacing [24]. But, when cracking is associated to the lack of punching shear resistance, a rapid deterioration induced by the vehicle tires can spread to the bedding layer [21]. In parallel, cracked joints become preferred paths for water, salt and granular debris such as freeze-thaw cycles, dissolution, salt crystallization, and abrasion will occur within the crack, leading to an ever greater severity level (progressive cracking), up to the material breakdown its removal from the joints [39]. Similarly, for unbound joints the emptying of the joint can be caused by the wear of traffic or surface cleaning operations, poor management and disposal of moisture accumulation (rainwater and runoff) and pumping under traffic loading [25]. Once the homogeneity of the surface matrix is broken, the structural benefit guaranteed by the bond adhesion strength and/or interlocking is lost and units can start to move independently of their neighbors. Inevitably, these phenomena increase inconsistently the joint width, above limit values necessary to control lateral movements and stabilize the elements which can be easily removed (small cubes or setts). Any subsequent dynamic or torsional force on the unconstrained elements lead to rototranslation mechanisms in both vertical and horizontal planes, resulting in faulting, i.e. difference or rotation of the adjacent units' elevation, punching, i.e. vertical downward movements in and around wheel paths, and horizontal creep, i.e. longitudinal displacements of the stone elements and pavement (Fig. 12) [46,50].

Figure 12 – Stone pavements affected by faulting, punching, horizontal creep and asphalt patching

Besides, the joint empting exposes the edges of the elements to traffic and weather conditions favoring stone chipping, delamination and rocking above all for large and shallow elements. Moreover, extremely wide and empty joints become receptacle of urban dirt and litter. In these case it will necessary the joint repair, through refilling operations. Great care is required above all in rigid construction, in which the joint should be raked out and cleaned before the application of the new product. Poorly matched materials following these interventions in localized areas may also be regarded as a defect at an aesthetic level [29]. In addition, the prolonged, continuous and/or frequent exposure of the pavement to atmospheric agents (moisture, temperature variation and UV radiation) or chemical pollutants can cause a chromatic alteration of the stone elements and jointing material or give rise to the formation of surface deposits due to the progressive accumulation of dirt, biological coatings (molds, weeds, mosses and lichens) and salt efflorescence [51,52].

Jointing materials' selection and application technique

Downstream of the decision-making process on the characteristics and requirements that the joint must satisfy, a synthesis is reached with the identification of the most coherent material (Tab. 2). The currently used materials and their application techniques are not very different from those of the past, even if the jointing products industry is constantly evolving to satisfy the demand for efficient and durable materials characterized by a fast, clean and simple installing method [16,45]. In general, unbound products are dry brush-in applied, while the bound materials according to their consistency (liquid, slurry, viscous or pasty) can be poured, injected or hand pointed. Each jointing medium works best when installed over a pavement characterized by proper moisture conditions (dry, slight or full wet) and may require specific equipment and tools and/or skilled workmanship (Tab. 3).

As a rule, unbound or flexible joints are realized over an unbound bedding layer (permeable system) of dry and sharp crushed aggregate of graded particle size. Traditionally, joints in pavements were filled with unbound aggregates [44]. Fine (sawn elements and narrow joins) or coarse (cropped units and wide joints) and sharp sand, capable to develop mechanical interlock and friction for stabilizing the stone elements, is uniformly spread over the completely dried surface and swept with a push broom into the joints, down to their full depth, before being compacted using a vibrating plate or a hand tamper. Inconsistent or inadequate compaction will lead to early failure of the pavement. However, vibration is most commonly employed with smaller and deeper elements and less often with larger and shallower units. Sand jointing can be carried out simultaneously with vibration, alternating compaction and filling the joints until they are completely saturated. Eventually, these operations can also be executed on a soaked pavement to aid the settle of the material. Finer dust (0/3 mm) can be finally added, especially using deeper stone element, to a thickness between 5 to 10 mm. When dust is applied, the surface can be wetted with a water spray to wash it into the joints. Unbound jointing, in addition to be cheap and easy to install, creates a permeable pavement characterized by a good flexural strength and improved aesthetic (a wide range of colors is available in naturally-occurring aggregates). The absence of curing period allows an immediate opening of road or footpath to traffic. Moreover, the pavement may be lifted and re-laid without the breakage of the stone elements [25]. This technique, although even today represents the most cost-effective jointing solution for pedestrian areas, lightly trafficked zones and perfectly draining pavements [53], did not well fit with the demands of the today's infrastructures which require high level of load carrying capacity. Sand does not protect the edge of the units from chipping and may be washed out on steep slopes or in areas subjected to frequent surface water flows or on pavements subjected to vacuum/brush street cleaning sweepers. To overcome the latter drawback, a joint stabilizing product, a paving sealant or a topping of limestone dust should be applied to protect against the loss of material. Moreover, top-up of joints with additional material may be required in pavement early life as the system 'shakes-down' and 'stiffens up' under traffic loading [23]. Among the dry brush-in type alternatives should be included the sand-cement mixtures (dry-grouting) and two different families of products, i.e. polymeric sands and the polymeric resin mortars, which are recently appeared on the market. These products have been designed to retain adequate elasticity needed to adapt to the movements of the pavement surface, preventing at the same time erosion due to weather (wind, rain and freeze thaw cycles) and light traffic. Polymeric sands and resin mortars are high-tech mixtures of graded and calibrated fine sand combined with polymer additives, which are able when activated (water and/or air oxygen) to form a strong binding agent capable of locking the sand particles together

[54,55]. These products follow the same installation procedure used for the sand, but require two additional stages to complete the catalyst process: wetting and drying. The activation of the polymeric binding agent is achieved by spraying, from 1 to 3 times, the paver surface with a very fine mist, whereas dry-grouting rely on natural moisture to cure and hydrate the cement. Most recent polymeric resin mortars work best when mixed on site with plenty of water, becoming of a slurry consistency, and spread on the pre-wetted pavement using a squeegee. Polymeric products need to dry completely (curing time: 24-72 hours) to polymerize and harden, ensuring optimal cohesion and long term stability. Air oxygen hardening polymeric resin mortar has few minutes of working life and requires 6-8 hours to complete the curing process. For both water-activated products, pedestrian and vehicle traffic should be kept off the pavement for at least 24 and 48-72 hours from the installation. Polymeric sand and mortar, like regular sand, come in a wide array of colors, representing viable options for jointing private drives, paths, patio and hard landscaping projects. But, although the market for these products is strongly growing, their properties and potential have been poorly studied by the scientific literature. The use of sand-cement mix, which unlike other products requires a dry or semi-dry bedding, is not actually recommended, as the cement does not fully hydrate and the mixture does not compact in a consistent manner the joint will ensure poor durability and adhesion properties.

In parallel, different types of bound jointing material are in common use, responding in a flexible or rigid manner. Coal tar pitch or asphalt-based products became a viable and affordable option in the late-XIX century as a flexible joint medium [36]. However, coal tar, which is considered a potentially hazardous material and is now classified as carcinogenic, has not been used by at least 30-40 years. For tight joints, asphalt cement alone is used; for wider joints a mastic (asphalt cement + fine sand + filler) is preferred.

Another option with open joints is to pour the hot (160-200 °C) asphalt cement (penetration grade depending on the latitude and the exposition) over the partially filled, by pre-heated gravel or pebbles (6/10 mm) to within 20÷25 mm of the head of the stone elements [25]. It is essential that the filling aggregates and the stone elements are completely dry because an almost unappreciated amount of water will cause the asphalt cement to foam and will prevent it from adhering and forming a solid joint. Asphalt cement is spilled in several stages until complete saturation from a pouring bucket or can and allowed to flow, making the pavement impervious as it cools. Alternatively, asphalt emulsion (asphalt cement + water), which is cold applied into the joints previously saturated with gravel, can be used [15]. A final cleaning with fine sand can be envisaged. Asphalt binder cools and solidifies within few minutes, although it will remain warm to touch and relatively soft for some hours, period after which the pavement can be opened to traffic. The success or failure of the asphalt filling depends on the product efficiency and the heating temperature. If the binder be too hard, it pulverizes in very cold weather; if it be too soft, it runs and becomes sticky in very hot weather. Any accidental spillage or overflow from the grout lines can be trimmed with a craft knife after the asphalt cement has cooled and hardened. Black traces of binder and residual staining on the surface will be removed only due to weathering and tire actions over time. Nowadays, this approach has a potential on repairs to authentic historic paving, the so-called “heritage” projects, using specifically tailored modified asphalt cements. Although freshly-poured asphalt cement could tend to have a glossy appearance, the joints become dull over few days as the surface is trafficked, retaining permanently their black deep color [51]. A technically valid alternative, effectively tested to date only as binder in asphalt wearing course or surface treatments, would be represented by clear binders (bio-binders and synthetic binders), eventually also in the form of emulsion, or products with similar mechanical, rheological and physical performance compared to the traditional asphalt cements but characterized by a pale amber color. These materials would allow to customize the joint color palettes, exploiting the chromatic properties of stone aggregates or pigment powders [31-33].

Since the early 2000s, the use of a new technology, i.e. the semi-rigid resin system, that presents application similarities to asphalt-based jointing is progressively establishing in installations for the restoration of pre-existing road pavements deteriorated by traffic realized in cubes, destined or restricted to local public transport. Although such solution is even prescribed in high demanding operation class by some very recent standards, it is premature to define its reliability, durability and maintenance of performance over time because it has not yet been tested over a prolonged period of time under different stress conditions. This system involves the use of a resin (one-component liquid amber mixtures of polyurethane or epoxy polymers) which is poured over a pre-filled aggregate joint to form a pervious and strong structure. Unlike asphalt-based product, resin requires a further filling of finer rock grit (2/4 mm) for the whole joint depth after a second vibro-compaction phase. The resin is then hand poured at ambient temperature directly into the joint using a low-pressure injector/nebulizer. The time required for the resin to completely catalyze is at least 36 hours; thus, the pavement can be opened to traffic in a short time, within 48 hours of its application, under normal temperature conditions. The joint will appear, even after the time required for complete drying, of the aggregate color with a slightly darker shade and a glossy finishing due to the amber thin film of the resin. However, resin overfilling, which can be prevented only by the operator skills and experience, leads to the complete loss of aesthetic requirements. In addition, any accidental spillage or residue that deposit on stones during joint grouting, which result in amber-colored and glossy droplets, should be removed before they become permanent and treated with a suitable cleaner or thinner.

As far as rigid jointing is concerned, hydraulically bound mortars and grouts become the most common method, as the motor traffic grew and with the development of reliable cements [20,21]. They are workable mixtures of sand, with a suitable grain size, mixed with cement and water with a variable proportion. This classification includes different forms of cementitious binders: ordinary or blast furnace Portland cement and lime. Originally, mixed on site products were prepared, while the most recent applications push towards the use of pre-mixed and modified mortars or grouts with enhanced properties (better strength, adhesion or elasticity), the so-called proprietary mixes [56]. Latex, redispersible dry and water-soluble polymers are the different types of additives used to produce polymer modified mortars [57,58]. Cement-based mixtures must achieve the right balance between strength (compressive, flexural, shear), low shrinkage and durability (resistance to frost and to de-icing salts). In general, higher performance mortars can be used with smaller setts or cubes; lower grade mortars with larger setts and slabs [24]. The application method is dependent on the jointing material consistency and the bed layer typology. Although some mortars are applied using the traditional hand-pointing methods, the two most popular techniques are joint topping (lightly loaded areas) and full depth (high loading category) applied on moist mix bed and slurry joint with a plastic bed. In hand-pointing, the mortar is firmly pressed into the joints with a trowel or a suitable rod: flush-and-struck, recessed and half-round are the most suitable pointing solutions. These mortars generally start setting within a couple of hours (high temperatures reduce and low temperatures increase the setting time) and the pavement should be pedestrian and vehicular traffic-restricted for at least 48 and 120 hours, respectively. Moist bed with topping joint require a three-stage process. Firstly, the joints are about halfway filled from the bottom by the rising of the laying course material. Additional cement mortar is put into the joint from the top and the pavement is compacted using a plate vibrator. The joints are then raked back to a depth of 30mm before re-grouting with a fine concrete slurry. In full depth applications, the moist or plastic laying course, which should not rise more than 15÷20 mm up the joint, is allowed to cure to reach initial set before the joint filling operation. After about 24 hours, flowable self-compacting grouts are spread over the thoroughly pre-wetted pavement surface and moved with a rubber squeegee towards open joints (wet-grouting or slurry method), whereas more consistent modified mortars are poured through a watering can or an injection gun into the empty joints. One traditional method, now almost abandoned because can result in a loss of durability of joint mortar, was to coat the surface with sawdust and brush this off. After completed operations, any excess of material must be scraped off using water jet and swept with a bristle brush, because the persistence of hardened cement stains and glazes significantly compromises the aesthetic result of the entire pavement and their removal is very difficult, if not impossible. The curing time determines when the pavement can be subjected to traffic loading. Traffic must be kept off until the mortar or grout sets and this is necessary not only when the pavement is first laid, but whenever plumber's cut or worn spot is repaired. Normally, cement-based products achieve the specified characteristic strength after 28 days (2/3rds after 14 days). If quicker pavement opening to traffic is required, higher strength mortar or accelerating additives might be used. The potential of ultra-rapid-hardening mortar for jointing stone small element have been recently investigated [39]. The hydraulic-cement mortar and grout make the joint impervious, holds the stone elements firmly in position, prevent the edges from chipping and the top face from wearing round and adds materially to the smoothness and durability of the pavement.

However, there are other objectionable features connected with these family of products. Firstly, a single shear stress application in excess of the material capacity cause a local failure and it wears down of breaks out from between the elements it cannot be renewed or added to with ease and success. In making repairs, which resulted to be time consuming and expensive, it is difficult to remove the stone elements without braking and to remove the hardened jointing material from the sides of the stone units. If the mortar does not penetrate to the bottom of the joints, bad defects result as the thrust from expansion then as to be carried by the upper part of the joint only, and this crushes the heads of the elements. For most site-mixed mortars the end color is determined by the color of the sand, but standard mortar can be colored by the addition of liquid or powder pigments. Alternatively, pre-packed colored mortars can be obtained.

An overall summary of the properties and performances of the above mentioned jointing materials and their related application characteristics is reported in tables 2 and 3.

Table 2 – Properties and performances of jointing materials

Type		Behavior	Load transfer	Physical state	Drainability	Appearance		
						Color	Finish	Brightness
Fine sand/Gravel		Flexible	Friction	Granular solid	Good	Aggregate color	Fairly grainy/Grainy	Matte
Polymeric sand		Flexible	Friction/Adhesion	Granular solid	Poor	Sand color + pigment	Fairly grainy	Matte
Polymeric resin mortar		Flexible	Friction/Adhesion	Granular solid	Poor	Sand color + pigment	Fairly grainy	Matte
Asphalt base compound	Cement	Flexible	Adhesion	Solid Viscous (80-160 °C) Liquid (> 180°C)	None	Black/dark grey	Smooth	Matte
	Mastic	Flexible		Solid Viscous (80-160 °C)			Smooth	Matte
	Emulsion	Flexible		Liquid			Smooth	Matte
Cement based	Mortar	Rigid	Adhesion	Pasty/self-compacting	Poor	Grey + pigment	Smooth	Matte
	Modified mortar	Rigid		Viscous		Grey + pigment	Smooth	Matte
	Grout	Rigid		Slurry		Grey + pigment	Smooth	Matte
Polyurethane resin		Semi-rigid	Friction/Adhesion	Liquid	Quite good	Gravel color + thin amber film	Grainy	Glossy

Table 3 – Application characteristics and maintenance program of jointing materials

Type		Application			Operator		Opening to traffic		Cost	Frequency ordinary maintenance
		Technique	Filling time*	Main tools	Working position	Skills	pedestrian	vehicular		
Fine Sand/Gravel		Dry brush-in	Short	Sweeping broom	Standing	Low	Immediate		Low	High
Polymeric sand		Dry brush-in	Short	Sweeping broom + Garden hose	Standing	Low	24 h	48/72 h	High	Non-documented
Polymeric resin mortar		Dry brush-in	Short		Standing	Low	24 h	48/72 h	High	Non-documented
		Wash-in	Short	Squeegee + Garden hose	Standing				High	
Asphalt base compound	Cement				Kneeling	High			Medium	Low
	Mastic	Pouring	Long	Pouring bucket	Kneeling	High	12 h	24 h	Medium	
	Emulsion				Kneeling	High			Medium	
Cement based	Mortar	Pouring	Short	Squeegee	Standing	Low			Low	
		Injection	Short/Medium	Caulking gun	Kneeling	High			Medium	
		Hand-pointing	Medium/Long	Trowel	Kneeling	Medium	48 h (min.)	7/10 days (min.)	Low	Low (early life) High (after cracking)
	Modified mortar	Pouring	Short	Squeegee	Standing	Low			Medium	
		Injection	Medium/Long	Caulking gun	Kneeling	Medium			Medium	
	Grout	Slurry	Short	Squeegee	Standing	Low			Low	
Polyurethane resin		Injection	Long	Sweeping broom+ injector/nebulizer	Kneeling	High	12/24 h	24/48 h	Very high	Non-documented

* excluding curing time

Conclusions

Natural stone paving can produce a high quality attractive streetscape with a long service life. The beauty and excellent performances of natural stone are necessary but not sufficient conditions to fully satisfy the users' needs and to enhance the aesthetic value of the pavement. Only correct design, careful installation and prompt maintenance of all components ensure the pavement the basic structural and functional requirements. However, these principles of good construction practice with reference to the joints have been and still are wrongly neglected and understudied. Thus, after having examined several tasks performed by the joints, factors affecting their performances and, at the same time, how their characteristics influence the pavement behavior and appearance have been analyzed in detail. Specifically, particular attention has been paid to the design phase. The decision-making process that leads the designer to choose the more suitable joint system represents the synthesis of a complex procedure that requires the necessary assessment of multiple criteria of aesthetic, functional and structural but also historical and cultural. This extremely complex selection mechanism is made further difficult by the stone pavement specific intended use and, above all, the environmental and architectural context in which it exists or is to be constructed. The recent renewed interest in stone pavements has often led to the implementation of restoration and conservation interventions of historical streets and squares in monumental areas of high intrinsic value. In these situations, the best theoretically technical jointing solution cannot exceed the noblest requirements regarding the preservation of the cultural significance of the road work, the recognizability of the aesthetic and the maintenance of the hygienic and functional characteristics typical of epochs prior the motorization development. The analysis of the logical path for the joint design must be based on a specific study, sometimes necessarily respectful of construction rules contained in centuries-old specifications, to achieve only at the end the identification of the most suitable material and the related laying technique. The most modern trends and state of practice tend instead to subvert the necessary process of engineering analysis and construction art, with the paradox that often the jointing material, its width and mode of filling become the starting point of the project, conditioning the type of laying pattern of the stone elements, their mutual arrangement and, finally, also the interlocking for the horizontal and vertical transmission of stresses in the pavement.

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References

[1] E. Garilli, F., Autelitano, F. Giuliani, A study for the understanding of the Roman pavement design criteria, Journal of Cultural Heritage. 25 (2017) 87-93.

[2] E.E. Poehler, The Traffic Systems of Pompeii, Oxford University Press, New York, NY, 2017.

[3] G. Blanco, Pavimentazioni in Pietra. La Nuova Italia Scientifica, Roma, 1994.

[4] CRMSF, Revêtements des Sols en Milieux Sensibles d'un Point de Vue Patrimonial, Commission royale des Monuments, Sites et Fouille, Liège, 2017.

[5] Natural Stone Institute, Dimension Stone Design Manual, Institute of America, Oberlin, OH, 2016.

[6] J. Füssl, W. Kluger-Eigl, R. Blab, Experimental identification and mechanical interpretation of the interaction behaviour between concrete paving blocks, International Journal of Pavement Engineering. 17(6) (2016) 478-488.

[7] A. Jamshidi, K. Kurumisawa, G. White, T. Nishizawa, T. Igarashi, T. Nawa, J. Mao, State-of-the-art of interlocking concrete block pavement technology in Japan as a post-modern pavement, Construction and Building Materials. 200 (2019) 713-755.

[8] W. Mampearachchi, Handbook on Concrete Block Paving, Springer Nature, Singapore, 2019.

[9] SCOTS, Natural Stone Surfacing - Good Practice Guide, 2nd Ed., Society of Chief Transportation Officers in Scotland, Dumfries, 2004.

[10] NHSS, Rigid Pavement Construction Using Pre-cast Concrete Pavers and Flags, Clay Pavers and Natural Stone Slabs and Setts Laid without Applied Vibratory Compaction, National Highways Sector Scheme 30 for Modular Paving, United Kingdom public sector, London, 2014.

[11] H. Blanchard (Ed.), American Highways Engineers’ Handbook. John Wiley & Sons, New York, NY, 1919.

[12] W.G. Harger, Rural Highway Pavements. Maintenance and Reconstruction. McGraw-Hill, New York, NY, 1924.

[13] J. Knapton, I.D. Cook, Research and development in discrete element paving systems, Proceedings of the Institution of Civil Engineers: Transport. 153(1) (2002) 13-23.

[14] F.L. González-Mesones, Guía Para el Diseño, Construcción y Mantenimiento de Pavimentos Exteriores de Piedra Natural, Ideasproprias Editorial, Vigo, 2012.

[15] CERTU, Les Pierres Naturelles en Voirie Urbaine: Dimensionnement et Mode de Pose, Territorial Éditions, Voiron Cedex, 2008.

[16] A.J. Dowson, Small element paving: design and construction, in I.D. Walsh, R.N. Hunter, L. Darrall, P. Matthews, P. Jameson, J. Thorp (Eds.), ICE Manual of Highway Design and Management, ICE Publishing, London, 2011, pp. 513-522.

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

[18] P. Tomio, F. Filippi, Il Manuale del Porfido, Publistampa, Trento, 2001.

[19] F. Giuliani, F. Autelitano, E. Degiovanni, A. Montepara, DEM modelling analysis of tree root growth in street pavements, International Journal of Pavement Engineering, 18(1) (2017) 1-10.

[20] H. Hensel, Paving design: Is rigid-fix external stone paving the way to go? Journal of ASTM International. 4(6) (2007) 1-14.

[21] P. Li, C. Fairfield, D. Fordyce, Design advice for rigid highway pavements constructed in natural stone, Construction Materials, 165(CM3) (2012) 135-144.

[22] H. Murat Algin, Interlock mechanism of concrete block pavements, Journal of Transportation Engineering. 133(5) (2007) 318-326.

[23] E.E. Bauer, Highway materials. A Textbook Covering Production, Specifications, Sampling and Testing of Highway Materials, McGraw-Hill book company, New York, NY, 1932.

[24] M.J. McHale, Stone paving for heavier traffic loads, Municipal Enginering. 159(ME2) (2006) 63-69.

[25] F.S. Besson, City Pavements, McGrow-Hill Book company, New York, NY, 1923.

[26] I. Mohora, A.A. Anghel, Urban landscape - Cubic stone streets in historical areas, advantages and disadvantages, case study Timisoara versus Rome, IOP Conf. Series: Materials Science and Engineering. 471 (2019) Article ID 082028.

[27] P. Zoccali, L. Moretti, P. Di Mascio, G., Loprencipe, A. D'Andrea, G. Bonin, B. Teltayev, S. Caro, Analysis of natural stone block pavements in urban shared areas, Case Studies in Construction Materials. 8 (2017) 498-506.

[28] L.J. Hopper, Landscape Architectural Graphic Standards, John Wiley & Sons, Inc, Hoboken, NJ, 2007.

[29] R. McLoughlin, C. Duggan, N. Matthews, O., Kelly, M. O'Neill, Paving. The Conservation of Historic Ground Surface. Department of Arts, Heritage and the Gaeltacht and Dublin City Council. Government of Ireland, Dublin, 2015.

[30] F. Autelitano, F. Giuliani, Daytime and nighttime color appearance of pigmented asphalt surface treatments, Construction and Building Materials. 207 (2019) 98-107.

[31] F. Autelitano, G. Maternini, F. Giuliani, Colorimetric and photometric characterisation of clear and coloured pavements for urban spaces, Road Materials and Pavement Design. DOI: 10.1080/14680629.2019.1662832.

[32] F. Giuliani, F. Autelitano, Photoluminescent road surface dressing: A first laboratory experimental investigation, Materiaux et Techniques. 102(6-7) (2014) 603.

[33] H. Zhang, Z. Chen, G. Xu, C. Shi, Physical, rheological and chemical characterization of aging behaviors of thermochromic asphalt binder, Fuel 211 (2018) 850-858.

[34] SWPS, Stone Paving-blocks: Quarrying, Cutting and Dressing. United Nations Development Programme (UNDP) and International Labour Office (ILO), Geneva, 1992.

[35] K.R. Hoigard, M.J. Scheffler, Dimension Stone Use in Building Construction, American Society for Testing and Materials International, West Conshohocken, PA, 2007.

[36] G. Tesoriere, Costruzione di Strade Ferrovie ed Aeroporti, Denaro, Palermo, 1963.

[37] I.O. Baker, A Treatise on Roads and Pavements. John Wiley & Sons, New York, NY, 1906.

[38] R. Ariano, Materiali e Pavimentazioni Stradali, Vol. 1, Görlich Editore, Milano, 1958.

[39] E-S. Han, J. Gong, D. Cho, S-K. Park, Experimental investigation on the application of ultra-rapid-hardening mortar for rigid small element pavement, Advances in Materials Science and Engineering. (2017) Article ID 2625437.

[40] W. Tartarini, Lezioni di Costruzioni Stradali ad Uso degli Assistenti Stradali. Ferri, Roma, 1932.

[41] DesignWorkshop, Landscape Architecture. Documentation Standards: Principles, Guidelines, and Best Practices, John Wiley & Sons, Hoboken, NJ, Inc, 2016.

[42] M. Balzani, C.F. Guerrieri, I Componenti del Paesaggio Urbano. Pavimentazioni, Maggioli Editore, Rimini, 1991.

[43] H.L. Hengl, W. Kluger-Eigl, M. Lukacevic, R. Blab, J. Füssl, Horizontal deformation resistance of paving block superstructures – Influence of paving block type, laying pattern, and joint behavior, International Journal of Pavement Research and Technology. 11 (2018) 846-860.

[44] G.W. Tillson, Street Pavements and Paving Materials. A Manual of City Pavements: The Methods and Materials of Their Construction, John Wiley & Sons. New York, NY, 1900.

[45] F.A. Santagata, F. Giuliani, et al. Strade: Teoria e Tecnica delle Costruzioni Stradali: Progettazione. Pearson Education Italia, Milano, 2016.

[46] CERTU, Dégradations des Chaussées Urbaines Revêtues de Pavés ou de Dalles, Recherche et Analyse des Causes, Entretien et Réparation. Centre d’Etudes sur les Réseaux, les Transports, l’Urbanisme et les constructions publiques, Paris, 1998.

[47] N. Davies, E. Jokiniemi, Dictionary of Architecture and Building Construction, Architectural Press, Oxford, 2008.

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

[49] S. Colagrande, R. Quaresima, Una analisi sulle cause del degrado delle pavimentazioni stradali in cubetti di pietra. Proceeding of XVI Convegno Nazionale SIIV, Cosenza, 2006, pp. 19-31

[50] P. Zoccali, G. Loprencipe, A. Galoni, Sampietrini stone pavements: Distress analysis using pavement condition index method, Applied Sciences. 7 (2017) 669.

[51] M-F. Ossola, Pierres Naturelles. Conception et Réalisation de Voiries et d'Espaces Publics. RGRA, Paris, 2010.

[52] A.B. Yavuz, Deterioration of the volcanic kerb and pavement stones in a humid environment in the city centre of Izmir, Turkey, Environmental Geology. 51(2) (2006) 211-227.

[53] F. Bullen, J. Knapton, Bedding sand permeability and segmental pavements, Road & Transport Research. 8(4) (1999) 16-27.

[54] J. Liu, Y. Bai, D. Li, Q. Wang, W. Qian, Y. Wang, D.P. Kanungo, J. Wei, An experimental study on the shear behaviors of polymer-sand composite materials after immersion, Polymers. 10(8) (2018) Article number: 924.

[55] J. Liu, Y. Bai, Q. Feng, Y. Wang, D. Zhang, J. Wei, D.P. Kanungo, Experimental study on unconfined compressive strength of organic polymer reinforced sand, International Journal of Polymer Science. (2018) Article ID: 3503415.

[56] R. Morin, G. Al Chami, R. Gagné, B. Bissonnette, Design considerations and innovative approach for restoration of historic landmarks in old Montreal, MATEC Web of Conferences. 199 (2018) Article ID 07003.

[57] N.F. Ariffin, M.W. Hussin, A.R.M. Sam, M.A.R. Bhutta, N.H.A Khalid, J. Mirza, Strength properties and molecular composition of epoxy-modified mortars, Construction and Building Materials. 94 (2015) 315-322.

[58] S. Ganesan, S.O. Mydin, N. Sani, A.I.C. Ani, Performance of polymer modified mortar with different dosage of polymeric modifier, MATEC Web of Conferences. 15 2014 01039.

DETAILED RESPONSE TO REVIEWERS

Parma, 14th May 2020

Dear Editor-in-Chief,

We have received your letter indicating that a revised version of our manuscript "CRITERIA FOR THE SELECTION AND DESIGN OF JOINTS FOR STREET PAVEMENTS IN NATURAL STONE" (CONBUILDMAT-D-20-02803) was requested. We strove to provide you a new better revised article following closely all the reviewers' comments, which were particularly useful for identifying aspects not well clarified and for meeting Journal standards. From that perspective, we would like to thank them for their valid opinions and time spent.

In the following lines we detail for each paper section the changes in accordance to all reviewer's comments, suggestions and questions. To improve reading, all the new or revised parts in the submitted revised manuscript have been identified using red characters.

GRAPHICAL ABSTRACT

In accordance to **reviewer 2** advice, a graphical abstract has been added to offer a clear and concise overview of the paper since the beginning.

DESIGN CRITERIA

As suggested by **reviewer 1** and **reviewer 2**, a flow chart has been inserted to clarify the multi-criteria analysis and the decision making process.

According to **reviewer 1** recommendations, Figure 3 (now Figure 4) has been redrawn to highlight the difference between action and reaction forces. Besides, each part of figures 2, 3 and 4 (now 3,4 and 5) was labelled and cited in the text.

FEATURES OF ELEMENTS

Upon the suggestions of **reviewer 1**, the individual characteristics and functions of each stone element have been summarized in a single table (new Table 1).

The sentence: "*relationship between progressive wider joints and cases of jointing with rigid or new generation products which are characterized by minimum joint width and depth requirements*", has been rephrased. (**reviewer 2**)

DEFECTS AND PAVEMENT FAILURE

Upon the suggestions of **reviewer 1** and **reviewer 2**, a multiple figure (new Figure 12) representing examples of stone pavements affected by several distresses (faulting, punching, horizontal creep and asphalt patching) has been added.

JOINTING MATERIALS' SELECTION AND APPLICATION TECHNIQUE

According to **reviewer 1** recommendations, the paragraph title was changed and the Table 1 (now Table 2) and Table 2 (now Table 3) are now referenced in the text also before the last paragraph.

To conclude, all the minor changes, such as typos errors or clarifications, highlighted by the **reviewer 2** have been corrected or/and inserted in the text.

We are aware of the opportunities you offered us to improve the paper, such as detailing aspects not well explained in the previous draft. Thank you again for your contribution in improving this paper and for your constructive feedback.

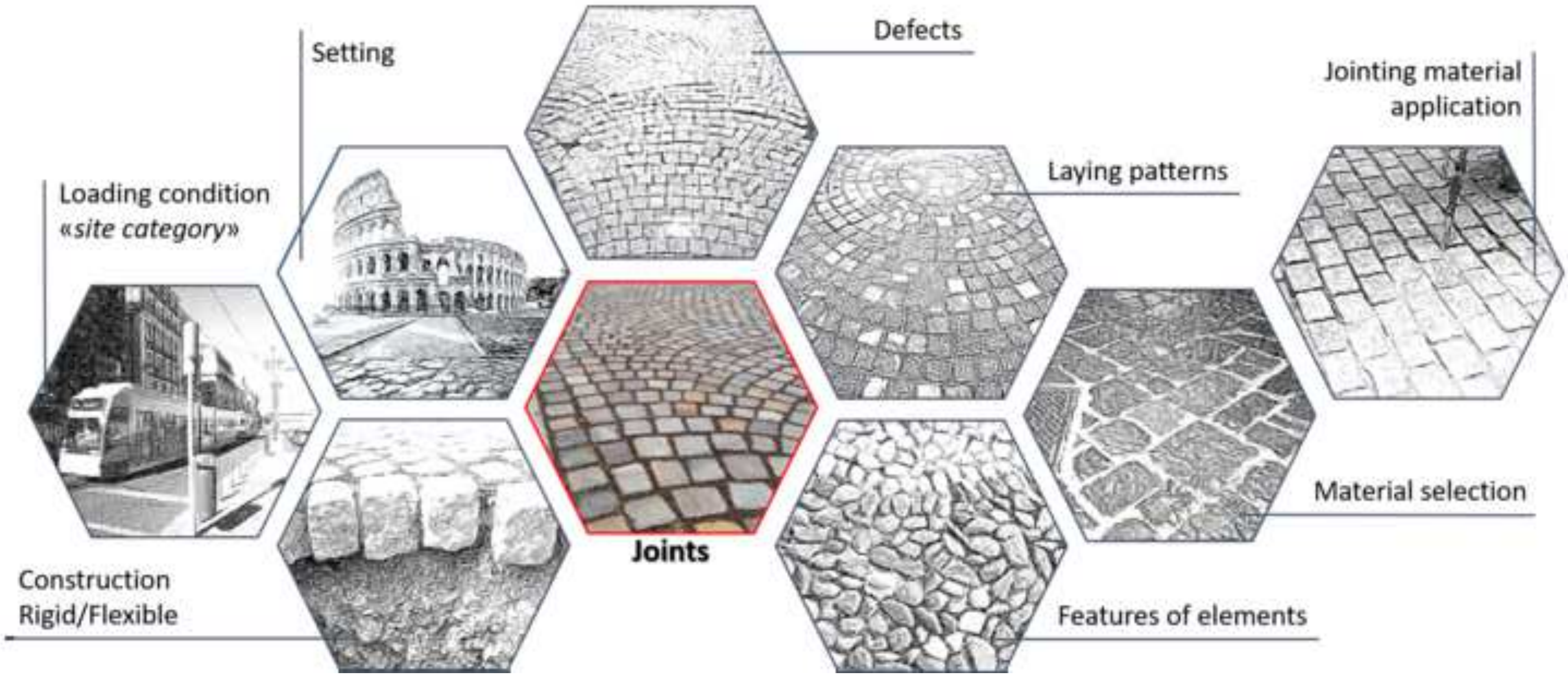
Sincerly,

Felice Giuliani

Highlights

- A multi-criteria analysis for the design of joints in natural stone pavements was proposed.
- Functional and aesthetic hierarchical requirements of joints were identified.
- Several aspects which contribute to an optimized joint performance were analyzed.
- A jointing materials' state of practice accompanied by their application techniques was reported.

Graphical Abstract



Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

*Title page

Title

Criteria for the selection and design of joints for street pavements in natural stone

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