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Comparing the Performance of Historical and Regular Stone Pavement Structures in Urban Trafficked Areas through the Finite Element Method (FEM) †

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Abstract: Stone pavement structures (SPS), also known as stone roads or stone-paved roads, are road pavements constructed using stones as the primary surface material. Different types of SPS exist; historically, irregular-shaped stones with downward protrusions have been often exploited since regular-shaped stones were difficult to be produced. More recently, regular cuboid stones can be also used. Accordingly, in new construction and renovations of SPS, pavement designers must take an essential decision concerning the adoption of historical or regular stones. Nonetheless, it is often confusing which of the two types of stones should be employed, considering that historical and regular SPS follow the same theory and pavement design methods. Therefore, a comparison between the performance of these two types of SPS is required to support their design and maintenance. Moreover, SPS are limitedly investigated and, to the best of our knowledge, there are no research contributions that address this specific task. Accordingly, in the present study, after conducting a laboratory characterization and in situ structural survey by Falling Weight Deflectometer (FWD) on a SPS, a comparative analysis based on the Finite Element Method (FEM) was carried out for investigating the structural performance of the historical (H-SPS) and regular SPS (R-SPS) in urban trafficked areas, where SPS must withstand heavy traffic loads. Specifically, considering both typologies of SPS, the paper aims to model and investigate: (a) the mechanical behavior under loading (displacements, stress, and strain distribution), (b) failure criteria (stone warpage and separation between the stones and the mortar joint), (c) the joint efficiency between stones, and (d) to which extent the road subgrade stiffness may influence the performance of SPS. In addition to the pavement design perspective, the research also provides a short glance at the strengths and weaknesses of R-SPS and H-SPS from other sides, such as functionality, ease of maintenance, construction techniques, and cultural and historical values.

Keywords: stone pavement structures; historical pavements; finite element method; FEM; simulation; mechanical behavior; pavement design

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1. Introduction

1.1. Definition of SPS, Construction Techniques, and Material Composition of Stones

Road SPS, also known as stone roads or stone-paved roads, are road pavements constructed using stones as the primary surface material. They have a long history and have been utilized worldwide, especially in Europe; they were widely employed before the advent of modern asphalt or concrete pavements [1]. SPS can be found in both urban and rural areas, serving different purposes such as transportation, trade routes, and historical landmarks.

SPS were developed by ancient civilizations such as the Mesopotamians, Egyptians, Greeks, and Romans [2]. The Romans, particularly, were renowned for their advanced road-building techniques. They constructed an extensive network of stone roads known as the Roman roads, which connected their vast empire (Figure 1a). Detailed design criteria and several case studies for H-SPS made by the Romans can be found in [3,4]. Especially in the latter reference, the authors provided a truly suggestive approach to understand if the Romans could follow some design criteria for designing SPS. It emerged that there is a meaningful relationship between the layer thicknesses and materials selection of the SPS used by the Romans and those deriving from calculation with current and modern analytical methods.

(**a**) (**b**) (**c**) (**d**)

Figure 1. Examples of SPS: (**a**) Roman stone-paved road; (**b**) cobblestone road; (**c**) stone-paved road with cut stones; (**d**) modern stone pavement road.

During the Middle Ages, SPS continued to be used, although the techniques and materials varied across regions. In Europe, for instance, cobblestone roads became prevalent, especially in medieval cities [5,6]. These roads include small, rounded stones tightly packed together to create a durable surface (Figure 1b). Cobblestone roads, as the name suggests, are SPS with cobblestones as the primary surface materials. Cobblestones are small, rounded stones typically found in natural riverbeds or collected from quarries. These stones are carefully selected and tightly packed together during the construction process. Cobblestones are relatively compact in size compared to larger stones commonly used in road construction. This characteristic allows for better stability and ease of installation. The exact size of cobblestones can vary, but they are typically larger than gravel or crushed stone but smaller than boulders. Cobblestones have smooth and rounded edges. This characteristic is a result of natural weathering and erosion processes that occur over time. The rounded shape of cobblestones contributes to their ability to interlock and fit closely together when placed on the road surface.

With the dawn of the Renaissance and the subsequent Industrial Revolution, advancements in road construction techniques were made. The invention of the steam engine led to an increase in the construction sector and generalized the consumption of all kinds of products, services, and natural resources [7].

The use of stones in road pavement structures continued, but the quality and consistency of their compositive materials improved. Engineers began employing larger, more precisely cut stones, creating smoother and more regular surfaces (Figure 1c). Design, executive, and functional aspects of SPS between the 19th and 20th Centuries can be found in the relevant research of Garilli and Giuliani [6].

As technology progressed, the use of SPS declined in favor of more efficient and cost-effective alternatives such as asphalt and concrete pavements. Nonetheless, certain historic sites and city centers still maintain stone roads for their cultural and aesthetic value (Figure 1d).

Indeed, as recently stated by Autelitano et al. [8], "*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*".

The construction techniques and composition of the primary surface material in SPS can vary depending on the specific design and intended use of the SPS. It is worth mentioning that, nowadays, the construction of SPS is still manual. The definition of a sort of standard or traditional structure of SPS is quite challenging since their design and construction have always been a local prerogative.

However, a structure that could be assumed to be a typical SPS is given in Figure 2 below.

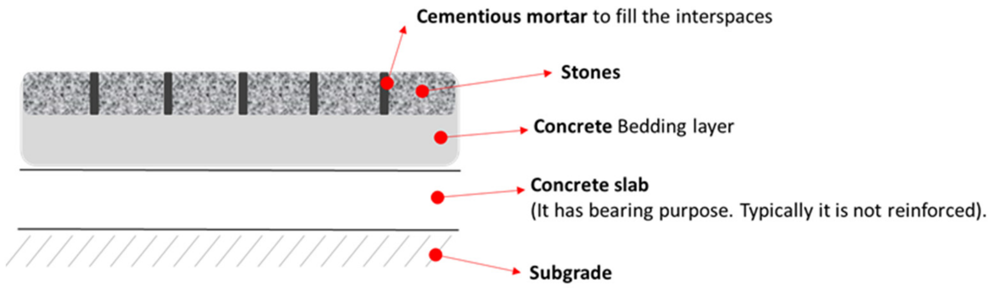

Figure 2. Cross-section of a SPS (this structure is similar to the one considered as a case study in the present research).

An explanation of their construction techniques can be recapped in the following operating steps, considering that these types of pavements are mainly a reconstruction of existing pavements:

1. Deconstruction: Labeling of each stone element and reporting the label on a plant of the pavement to reconstruct the position of each element; removing existing pavements and storing tough elements to be reused;
2. Demolition of the existing sub-base/foundation layer and compaction/stabilization of subgrade;
3. Sub-base preparation (Figure 3a): Once the deconstruction has been performed and the subgrade is ready, a sub-base layer is typically constructed to provide stability and distribute traffic loads. This layer may be a concrete slab with bearing purpose. Typically, it is not reinforced;
4. Bedding layer (Figure 3b): A bedding layer is often placed on top of the sub-base to reach the design level and create the surface for the primary surface material (i.e., the stone). This layer helps to distribute the load and promote stability;
5. Primary surface installation (Figure 3c,d): The primary surface material is installed on top of the bedding layer. The stones used in the construction of SPS can vary in size, shape, and material composition depending on the availability, regulation, desired

aesthetics, and functional requirements. Various techniques, such as hand placing, could be employed to arrange the stones in a specific pattern or design;

6. Jointing (Figure 3e,f): Once the stones are in place, joints between them are filled with sand, mortar, or other suitable materials to fill the interspace between the stones and stabilize the surface. The joints also allow for some flexibility, accommodating minor movements and preventing damage.

(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 3. Operating steps in SPS construction: (**a**) Sub-base preparation; (**b**) Bedding layer; (**c**) and (**d**) Primary surface installation; (**e**,**f**) Jointing.

As stated above, the primary surface material used in SPS is typically stone, which can be sourced locally or from specific quarries known for providing durable and aesthetically pleasing options. In road maintenance interventions, the stones that do not show a high level of degradation are reused (as specified in point 1 of the list above). The composition of the primary surface material can vary based on the desired characteristics of the pavement, such as strength, texture, and color. Common types of stones used in SPS may include granite, basalt, limestone, sandstone, and cobblestones. The specific composition of the primary surface material can also include a mix of different types of stones, depending on the desired aesthetics and functional requirements of the pavement. Based on the lithologic nature of the stone, there are different chemical interaction with the weather conditions. As a consequence, one of the criteria to select the stones to be used in SPS, when possible, is their reduced chemical susceptibility with rainfalls.

Regarding the composition of the stones used in the SPS of the present case study, as mentioned above, it depends on the local quarries. In the case of Tuscany, the identity of this region speaks the language of the so-called "*Pietra Serena*" sandstone. *Pietra Serena* sandstone was one of the main materials used by leading artists in the history of Florentine art and architecture, from ancient populations, through the Renaissance to the early twentieth century, giving rise to a real profession, that of stonecutters. In Florence, a very prestigious stone to be used in SPS is the "*Pietra Serena Extra Dura del Bucine*" (*extra-hard Pietra Serena*), a very fine-grained and dense sandstone; it is dark gray with stronger streaks of color, featuring high compression strength, wear, and frost resistance. Because of its superior strength, this material is normally used for interior and exterior floors and wall cladding, staircases, and paving. Additional information with the macroscopic and microscopic description of the stone material can be found here: https://www.pietraserena-bertisisto.com/en/prodotto/tipologia-pietra-serena/ (accessed on 21 June 2023).

1.2. Strengths, Weaknesses, and Differences between Regular and Historical SPS

The main differences between R-SPS and H-SPS lie in the following aspects:

- **Purpose**: R-SPS are typically constructed for functional purposes in modern infrastructure, such as pedestrian walkways, driveways, or decorative pathways. They are designed with contemporary construction methods and materials to meet present-day requirements in terms of bearing capacity and skid resistance. Contrarily, H-SPS were often built to serve specific historical, cultural, or architectural purposes. They may have been part of ancient road networks, significant trade routes, or iconic landmarks of a particular era;
- **Construction techniques**: R-SPS are constructed using modern methods, which involve excavating the ground, preparing an appropriate compacted subbase, and setting the stones in place using appropriate techniques such as interlocking mortar, or sand bedding. These techniques prioritize stability, durability, and ease of maintenance. H-SPS, on the other hand, were built with techniques of the respective period. These techniques may vary widely depending on the civilization, region, and historical context. Examples include ancient techniques like dry stone masonry, Roman road construction, or medieval cobblestone paving;
- **Materials**: In R-SPS, a variety of natural stones, like granite (as in the case study of the present research), limestone, or sandstone, as well as making concrete blocks are used. Natural stones are sourced from quarries and processed to meet specific design requirements. In H-SPS, the materials used are reflective of the time and place of construction. They generally include locally available stones or materials that were significant in that era, such as Roman basalt blocks or medieval cobblestones;
- **Cultural or historical significance**: R-SPS are designed to be functional and aesthetically pleasing but may not have any particular historical or cultural significance. In contrast, H-SPS hold significant cultural and historical value. They may be protected as heritage sites or landmarks, representing a specific era or an architectural style. His-

torical stone pavements are often preserved or restored to maintain their authenticity and to provide insights into the past.

Therefore, while R-SPS serve practical purposes in contemporary construction, H-SPS are desired for their unique historical, cultural, and architectural values. The strengths and weaknesses of R-SPS and H-SPS can be recapped in the following lists.

Strengths of R-SPS:

- **Durability**: R-SPS are designed and constructed using modern techniques and materials that prioritize strength and durability. They can withstand heavy loads, foot traffic, and adverse weather conditions, ensuring long-lasting performance;
- **Customization**: R-SPS offer a wide range of design options and flexibility. Various types of stones, colors, patterns, shapes, and textures can be selected to create unique and visually appealing pavements that complement the surrounding architectures;
- **Ease of maintenance**: R-SPS are relatively easy to maintain. Damaged stones can be replaced individually, minimizing the need for extensive repairs. Additionally, routine cleaning and sealing can help preserve the appearance and performance of the pavement;
- **Modern construction techniques**: R-SPS benefits from modern construction techniques. As stated before, these techniques enhance the stability, bearing capacity, and overall performance of the pavement.

Weaknesses of R-SPS:

- **Cost**: R-SPS can be more expensive compared to other contemporary paving options, especially if high-quality natural stones or complex patterns are chosen. The cost of materials, labor, and installation can be significant aspects to be considered;
- **Uniform appearance**: While R-SPS offer design customization, they may lack historical or cultural character, appearing as a fake historical pavement. They might not possess the same aesthetic charm or sense of heritage as H-SPS.

Strengths of H-SPS:

- **Cultural, historical, and architectural value**: H-SPS have significant cultural and historical significance. As previously discussed, they are often associated with specific eras, architectural styles, or important historical events. Moreover, H-SPS reflect the high skills and techniques employed during their construction. They serve as tangible links to the past, preserving heritage and providing a sense of identity;
- **Authenticity and character**: H-SPS possess a unique charm and authenticity that can enhance the atmosphere of a site. The aged appearance, irregular shapes, and weathering of the stones contribute to their distinct character and aesthetic appeal;
- **Environmental Sustainability**: Using historical stones, which may be reclaimed or recycled, can promote environmental sustainability by reducing the need for new stone extraction.

Weaknesses of H-SPS:

- **Maintenance challenges**: H-SPS may require specialized maintenance and restoration techniques. Finding matching stones for repairs or replacements can be challenging due to the rarity of certain stone types;
- **Limited functionality**: H-SPS may not always meet the functional requirements of modern infrastructure. They may lack the regularity, smoothness, or bearing capacity expected in contemporary SPS;
- **Vulnerability to damage**: Due to their age and weathering, H-SPS can be more prone to damage and wear. They may require regular monitoring, restoration, and protective measures to ensure their preservation;
- **Cost**: H-SPS can be more expensive compared to R-SPS, considering the blocks are man-made, heavier, and the installation method is more time-consuming. The cost of materials, labor, and installation are aspects to be considered.

The difference between the use of R-SPS and H-SPS depends on the manufactures. During historical eras, irregular-shaped stones were commonly used in the construction of stone pavement structures (SPS) due to various reasons. The difficulty in producing regular-shaped stones can be attributed to several factors (primarily the technological limitations); the stone cutting was handmade, and the traditional method was to leave the bottom face of the stone irregular, probably to improve its allocation in the soil. Actually, only the upper surface was left approximately flat and planar. Nowadays, the stone cutting is performed through automatic machineries that are able to provide regular stones.

It might be said that, in the design phase, there is no choice between regular and historical stones. The reason for this is that, nowadays, the reconstruction of historical SPS belongs to maintenance interventions in which the pavement surface must be preserved and, therefore, most of the existing stones need to be reused (environmental and historical law regulation). Therefore, there is no ambiguity in the selection, because actually there is no selection; if a project site includes historical stones, they will be reused except for those that need to be replaced because of damage or having a poor aspect. In this case, they are replaced with new stones.

1.3. Design of SPS

From a pavement design perspective, traditional design methods used for SPS assume that the response of the structure is equivalent to that of flexible pavements [9,10]. These methods operate under the following two assumptions: (a) the blocks and the bedding sand contribute to the bearing capacity of the SPS, and (b) these layers act as a single layer composed of an elastic, homogeneous, and isotropic material [11]. Nonetheless, even if it may be questionable, these conditions can be valid for pavements with small blocks (e.g., 200 mm-large,100 mm-wide, 65 mm-thick, as reported by [9]) or with the use of unbound material in the joint areas [12]. When larger blocks with mortar-filled joints are present, the mechanical response of the system starts resembling that of a rigid pavement rather than a flexible one [13].

For modular concrete pavements, such as SPS, empirical methods are particularly well-suited since their structural response is relatively easy to estimate. This is because the concrete is not affected by the natural and geological heterogeneity of natural stone [14,15]. Mechanistic design methods for these types of pavements consider fatigue degradation in the bounding materials and the rutting potential of subgrade and unbound granular layers. Currently, as reported by [11], three main approaches exist for calculating stresses and strains in the SPS:

- **Modified slab analysis** [16]: Stones were leaned upon a semi-infinite space, representative of all the layers of the pavement;
- **Layered elastic analysis** [17]: In the modeling of the pavement, a layered system was employed. It consists of linearly elastic, homogeneous, and isotropic materials;
- **Finite element method (FEM) analysis** [11,17]: to obtain a numerical approximation of the mechanical response of the system (i.e., the SPS), a mesh discretization technique was employed. This technique divides the continuous domain into a set of discrete subdomains, known as finite elements.

Furthermore, it is worth mentioning that apart from FEM analyses, there exist other strong numerical modeling methods that can approximate the mechanical response of the system, such as the Finite Difference Method [18], the Bezier Multi-Step Method [19], and the Differential Quadrature Method [20].

1.4. Motivation

To accurately simulate the mechanical performance of R-SPS and H-SPS, the FEM method appears to be more accurate and appropriate compared to the other two methods, which cannot consider the downward protrusion of the historical stones. Accordingly, the present paper reports a FEM comparative analysis of both R-SPS and H-SPS, to assess their performance in current SPS. Several performance criteria have been considered, namely the mechanical behavior under loading (displacements, stress, and strain distribution), the failure criteria (stone warpage and separation between the stones and the mortar joint), the joint efficiency between stones, and to what extent the road subgrade stiffness may influence the performance of SPS.

The materials of SPS and the subgrade, to be included in FEM models, have been characterized according to laboratory tests (axial compression tests for cylinder samples) and in situ surveys (FWD), investigating a real case study in the historical center of Florence.

Section 2 describes the material characterization, the FEM model setup, and the loading conditions. Section 3 reports the outcomes of the analysis and discusses the strengths and weaknesses of both R-SPS and H-SPS by comparing each of the abovementioned performance criteria. The research ends with some concluding remarks in Section 4.

2. Material Characterization and FEM Simulation

2.1. Pilot Site and Material Characterization of SPS

The following section describes the development of the FEM models for H-SPS and R-SPS. An urban SPS located in the city center of Florence, central Italy, was considered as a case study (Figure 4 below). The investigated SPS is located in a trafficked area and must withstand heavy traffic loads, since it has been designed as an urban road, with the presence of three different lanes: one lane for parking lots, one lane for traffic flow of vehicles, and one lane reserved for public transport, including the flow of buses every 15 min, from 7:00 to 18:00.

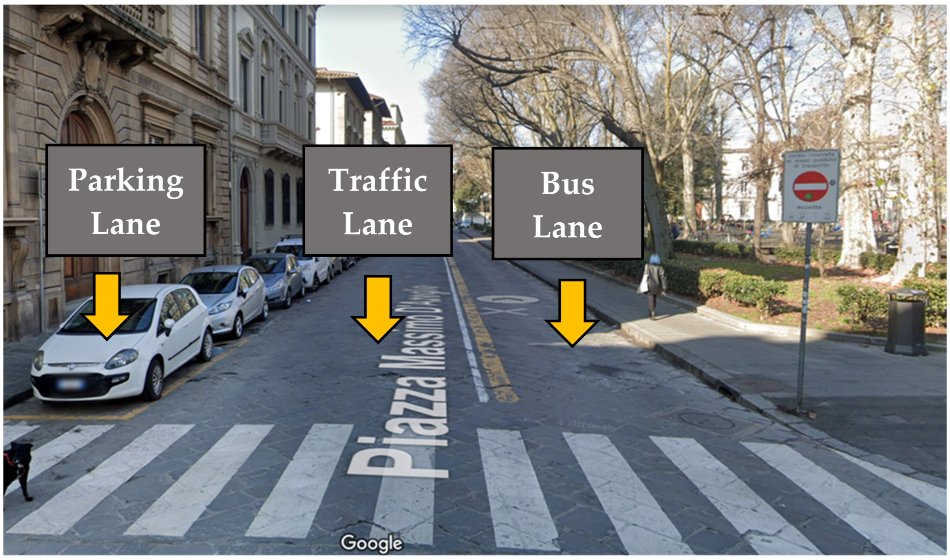

Figure 4. A case study in Florence, Italy, where a SPS was adopted in an urban trafficked area.

The material properties adopted in the FEM simulation are summarized in Table 1.

Table 1. Materials properties.

Layers and Elements of SPS	Elastic Modulus [mpa]	Poisson Ratio	Density [kg/m^3]	Reference, Laboratory Test, or In Situ Survey
Regular stones and historical stones	40,000	0.15	2400	[21]
Mortar joint Mortar bed	20,000 23,500	0.15 0.15	1750 2100	Laboratory axial compression tests for cylinder samples
Concrete base layer Subgrade	17,000 60–180	0.15 0.45	2400 1500	Back-calculated from in situ FWD survey

As emphasized in Table 1, the elastic modulus of the stones is referred to the values obtained by Villeneuve et al. [21]. Elastic moduli of the mortar joint and bed have been determined according to the laboratory axial compression tests for cylinder samples. The elastic modulus of the concrete base layer and subgrade have been back-calculated from in situ FWD tests.

In the initial configuration of the experiment, we collected also a high-definition Laser Scanner model of the irregular stone to be able to model a SPS into the software Abaqus (Figure 5 below). Unfortunately, the high complexity of the shape caused a significant reduction in the efficiency of the calculation with the consequence of excessively long processing times.

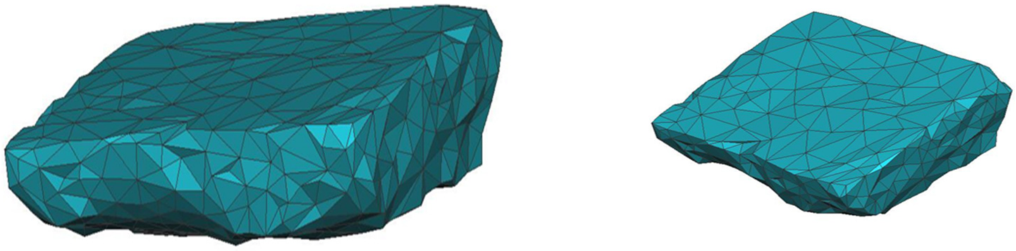

Figure 5. High-Resolution model of stones with laser scanner.

Accordingly, the geometric characteristics of both SPS exploited within the FEM simulations are shown in Figure 6, where the contact of the stone with the mortar bed is defined in two different forms. Considering the same SPS configuration of the Italian case study, the stones are buried into the mortar bed to a depth of 3 cm.

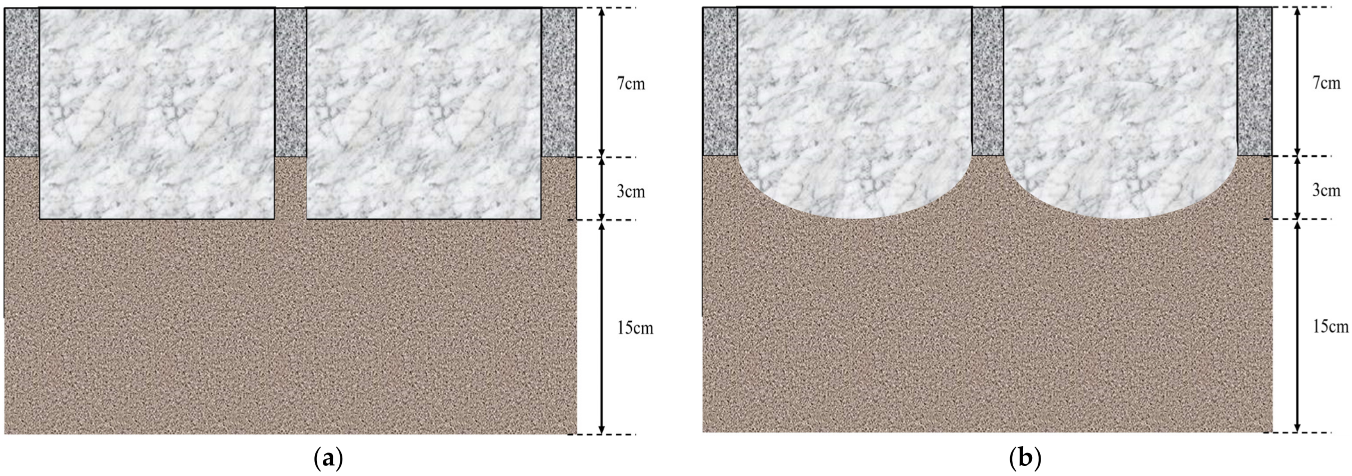

Figure 6. The geometry of SPS; (**a**) R-SPS, (**b**) H-SPS.

2.2. Geometrical Design of FEM Models

According to in situ measurements, the size of the stones was uniformly set (both R-SPS and H-SPS) to 0.4 × 0.2 × 0.1 m. The distance between two adjacent stones (i.e., the joint width) was set to 0.02 m. The thickness of the mortar joint, mortar bed, concrete base layer, and subgrade was set to 0.1 m, 0.18 m, 0.25 m, and 3 m, respectively. Figure 7 shows the specific size and shape of R-SPS and H-SPS (defined as irregular stones).

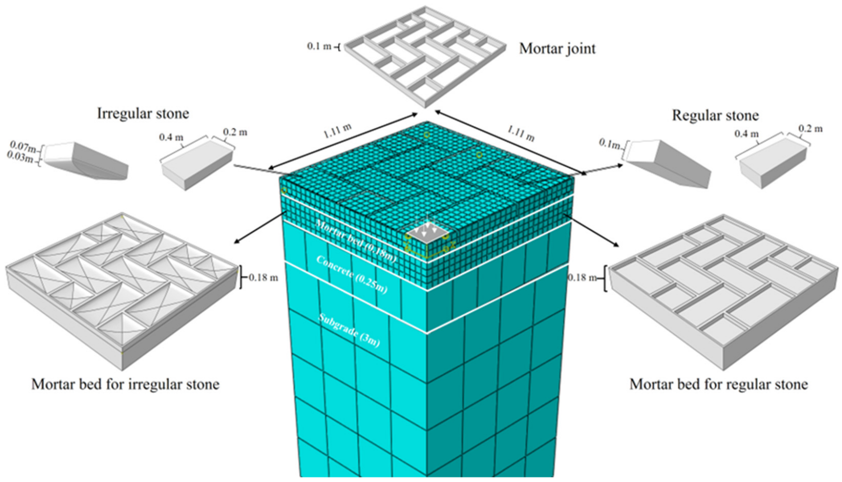

Figure 7. Physical model sizes and FEM mesh.

According to Figure 6b, it is worth mentioning that a downward protrusion with a maximum height (located at the center of gravity) of 0.03 m was set in irregular stones.

The interaction between the paving blocks and the mortar-filled joints, as well as the interaction between the paving blocks and the mortar bed, was realized by surface-based cohesive behavior and a generalized traction-separation law [22]. In the present study, the cohesive strength, the normal cohesive stiffness, and the shear cohesive stiffness were assigned the values of 7000 MPa, 18 MPa/mm, and 9 MPa/mm, respectively.

Furthermore, according to the area of the FWD loading plate (diameter = 0.3 m), an equivalent square loading surface was calculated (i.e., 707 cm^2), and a normal stress of 1.8 MPa was selected. To the whole cross-section of the left and back sides, a boundary condition was applied where $U_Y = 0$ and $U_X = 0$, respectively. In addition, the symmetry boundary conditions were applied to the front and right sides. A boundary condition of all fixed was applied to the bottom since the subgrade is simulated with a 3 m depth, which is large enough.

By simulating H-SPS and R-SPS with FEM, we can obtain reliable information concerning:

1. Vertical displacements, measured at the distance of 0 m, 0.4 m, 0.8 m, 1.2 m, and 1.6 m from the loading center;
2. Maximum principal stress distribution both in the mortar joints and mortar bed;
3. Stone warpage, i.e., the distortion of individual stones due to various factors such as traffic loads, temperature changes, moisture content, and inadequate construction practices;
4. Joint efficiency, expressed as the Load Transfer Efficiency (LTE), is evaluated according to the ratio between the displacement of two nearby geophones near the loading plate. The LTE was used to express the ability of a joint to transmit the load from the stone to the adjacent unloaded stone [23];
5. Separation behavior between the stones and mortar joints, i.e., the degree of detachment or disconnection between the individual stones and the mortar that holds them together. This behavior can vary depending on several factors, including the type of stone, the characteristics of the mortar, the construction techniques used, and environmental conditions.

3. Results and Discussion

3.1. Vertical Displacement

The vertical displacement for R-SPS and H-SPS is shown in Figure 8, with two different scales of representation in the vertical axis. The vertical displacements are measured at the distance of 0, 0.4 m, 0.8 m, 1.2 m, and 1.6 m to the loading center. To characterize the effects of road subgrade stiffness, the elastic moduli of the subgrade assume two different values, namely 60 MPa and 180 MPa.

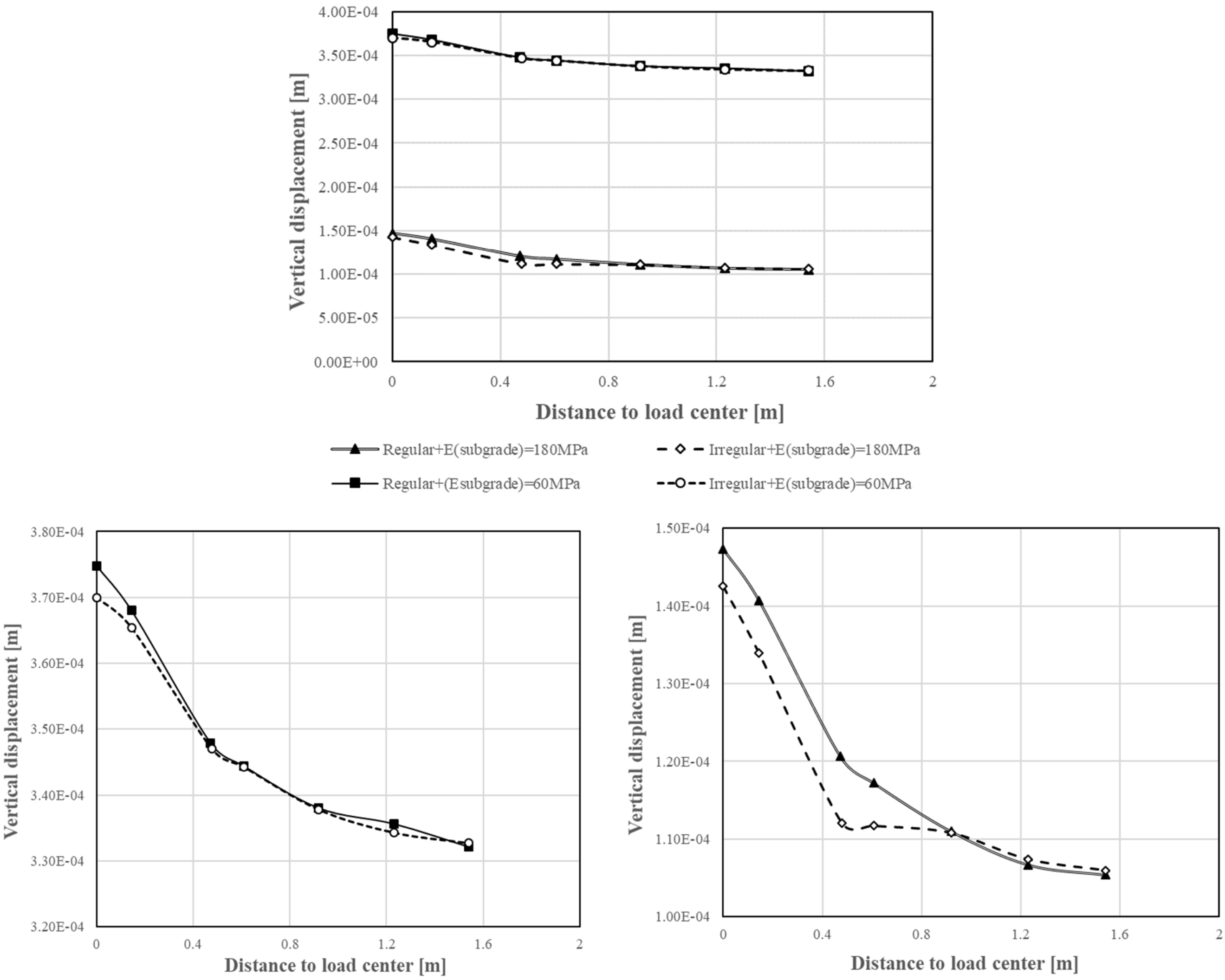

Figure 8. Vertical displacement for the R-SPS and H-SPS.

It can be observed from Figure 8 that H-SPS (irregularly shaped) shows slightly lower displacements, compared to R-SPS, closer to the loading plate and for the higher values of the subgrade stiffness (between 60 MPa and 180 MPa), demonstrating that stone types mainly influence the area closer to the load center and for stiffer subgrades.

3.2. Stress Distribution

Figure 9 presents the maximum principal stress distribution in the mortar joints. The mortar joint exhibits greater principal tensile stresses (negative values) in R-SPS, where the mortar joint is more likely to crack under the same traffic loading. This may be due to the curved surface of the historical stones, which transfers stress to the mortar bed better than the R-SPS; this letter transfers the stress almost vertically and the mortar joints are deformed with the higher shear strains.

It is worth noting that the maximum principal stress of the mortar joint in R-SPS or H-SPS is lower than the tensile strength of the material and, therefore, there are no damage issues for both types of SPS under traffic loads.

Moreover, the increase in the elastic modulus of the subgrade can reduce the maximum principal stress in the mortar joint, but the decrease is very weak.

Figure 10 shows the horizontal stress distribution in the mortar bed. Specifically, both tensile and compressive stress distributions can be observed at the top and the bottom, respectively, of the mortar bed in the SPS.

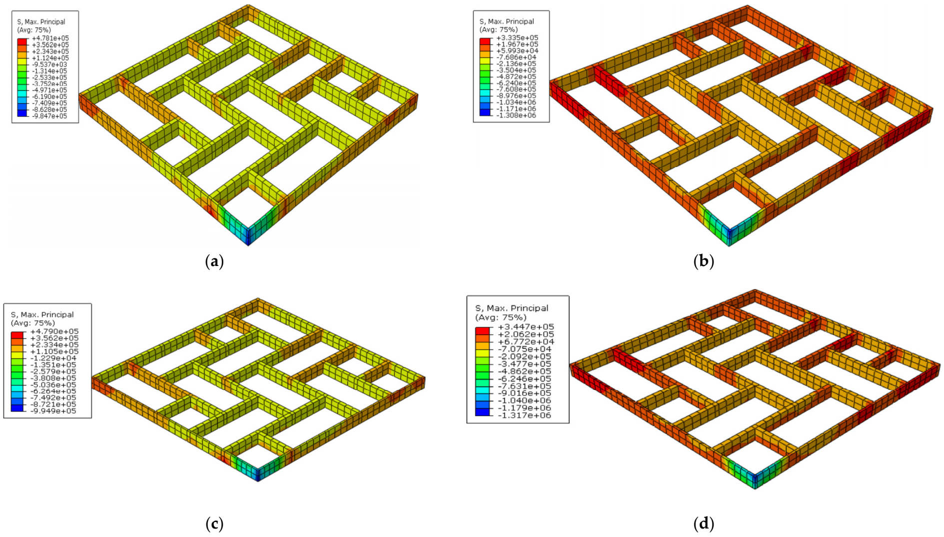

Figure 9. Maximum principal stress distribution in the mortar joints: (**a**) H-SPS + E (subgrade = 180 MPa), (**b**) R-SPS + E (subgrade = 180 MPa), (**c**) H-SPS + E (subgrade = 60 MPa), (**d**) R-SPS + E (subgrade = 60 MPa).

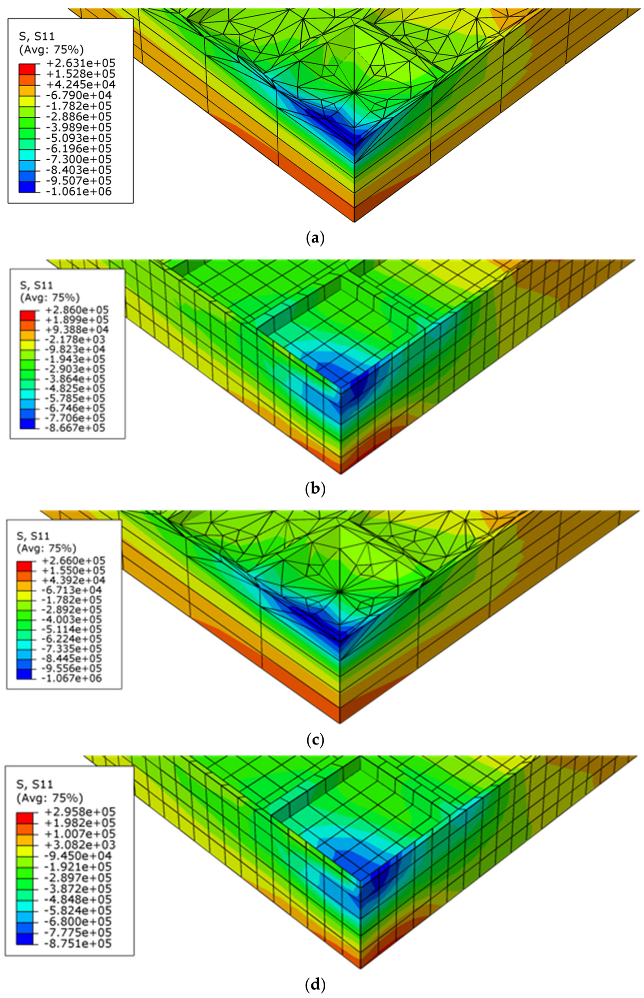

Figure 10. Horizontal stress distribution in the mortar bed: (**a**) H-SPS + E (subgrade = 180 MPa), (**b**) R-SPS + E (subgrade = 180 MPa), (**c**) H-SPS + E (subgrade = 60 MPa), (**d**) R-SPS + E (subgrade = 60 MPa).

The H-SPS shows that the tensile stress is slightly larger than the R-SPS and comparable to the compressive stress; in this case, as it is expected, the R-SPS performs better in reducing the horizontal tensile stress at the top of the mortar bed.

3.3. Failure Criteria (Stone Warpage and Separation between Stones and Mortar Joint)

As previously introduced, warpage refers to the distortion of individual stones or the entire pavement surface due to various factors such as traffic loads, temperature changes, moisture content, and inadequate construction practices. Warpage can cause road roughness, bumps, or depressions in the pavement surface, leading to discomfort for road users and potential safety hazards.

The stone warpage is defined for a single stone under traffic loading by the parameter δ in Figure 11, which is the difference between the vertical deflection of two points on the diagonal of the stone. A smaller value of δ indicates higher structural stability, demonstrating a better performance of the SPS.

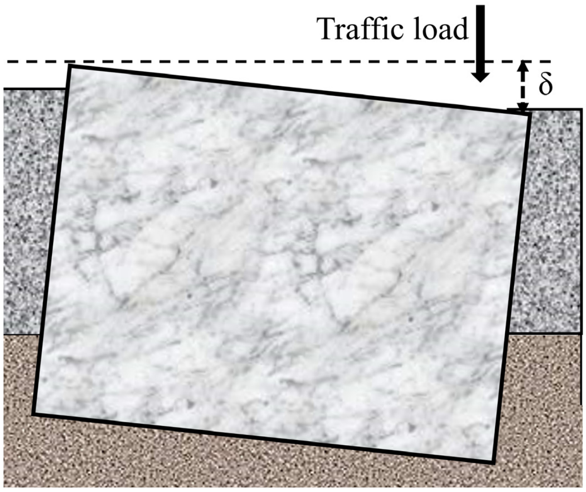

Figure 11. Definition of the stone warpage.

The simulation results of the stone warpage are shown in Figure 12. A slightly larger value of the stone warpage is observed for R-SPS, compared to an irregularly shaped one. This may be correlated to the curved bottom surface of historical stones; such a surface may generate a slip-like effect associated with limited warping issues. Moreover, regardless of the type of SPS (both R-SPS and H-SPS), the subgrade stiffness has a negligible effect on stone warpage. Therefore, the superior performance of H-SPS compared to R-SPS is not related to the subgrade stiffness.

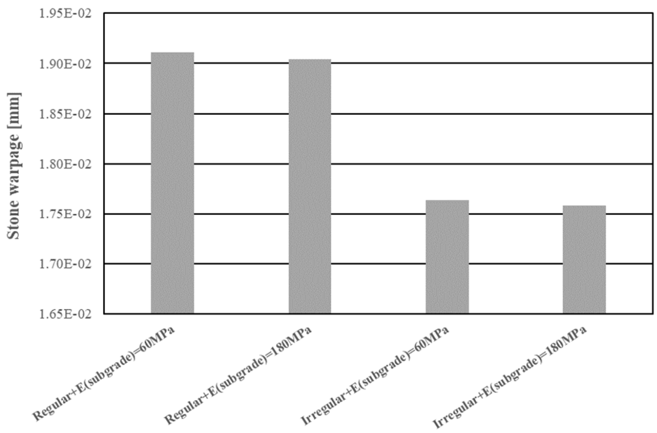

Figure 12. Stone warpage of the pavements.

The separation behavior between the stones and mortar joints is defined as the vertical difference between the top (i.e., the maximum height) of a stone and the road surface, measured by the parameter ω as in Figure 13 below.

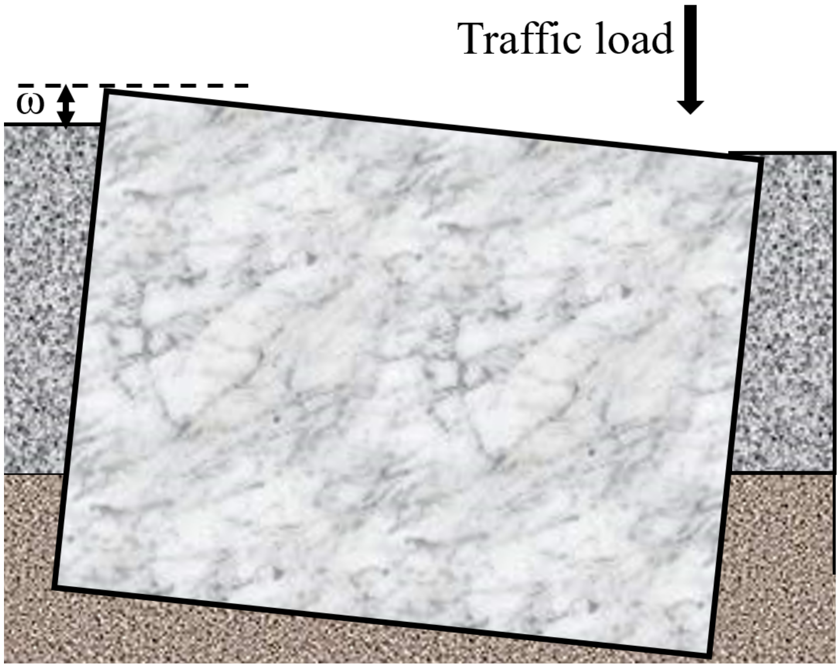

Figure 13. Separation behavior between the mortar joint and stone.

Figure 14 shows the highest separations of both R-SPS and H-SPS between the stones and mortar joints measured on SPS over a different subgrade stiffness. R-SPS are significantly more prone to reduce separation issues. Moreover, Figure 14 shows that the subgrade stiffness does not significantly influence the separation between stones and mortar joints.

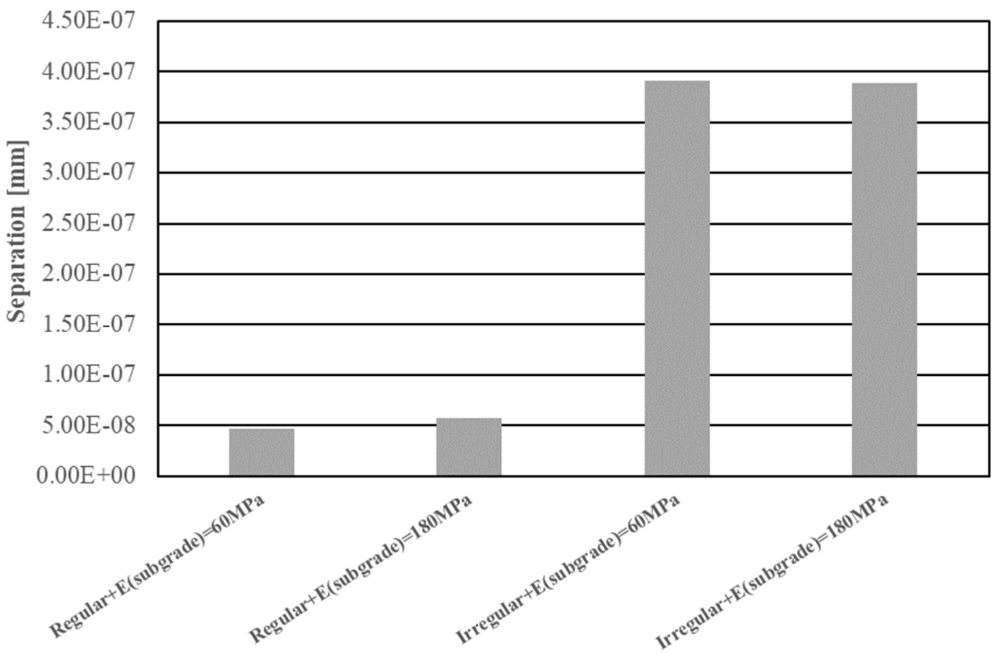

Figure 14. The separation between stone and mortar joints.

3.4. Joint Efficiency between Stones

The joint efficiency is characterized by the LTE, which is the ratio between the displacement of two points on adjacent stones; it was measured in the field as the ratio between the displacements of the two nearby geophones closer to the loading plate. The LTE was used to express the ability of a joint to transmit the load from the stone to the adjacent unloaded stone [23,24], as follows:

$$\eta = \frac{D_1}{D_0} \tag{1}$$

where D_0 and D_1 are the displacements of corners of the two adjacent stones close to the joint (Figure 15).

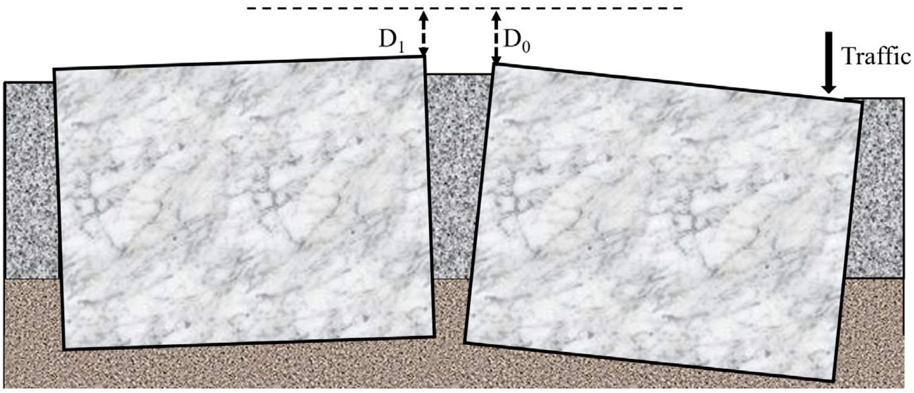

Figure 15. Joint efficiency characterized by the LTE.

Figure 16 shows the displacements at the two points (D_0 and D_1) next to the joint and Figure 17 presents the joint efficiency, expressed as a percentage derived from Equation (1). It can be observed that both types of SPS have a relatively limited influence on the joint efficiency, while an increase in the subgrade modulus can significantly impact such a characteristic.

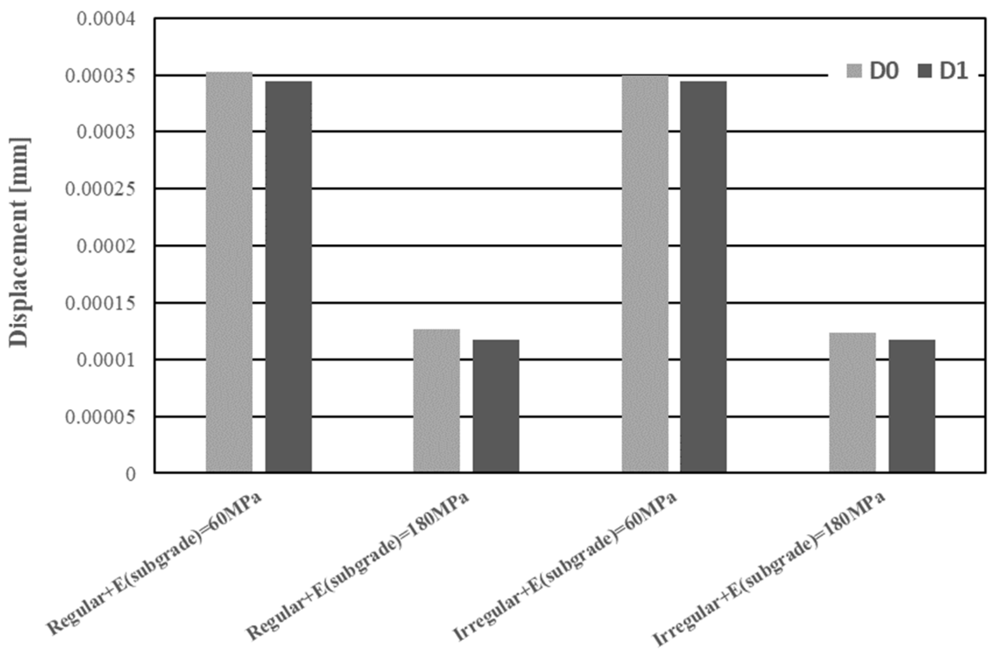

Figure 16. Displacements at the two points next to the joint.

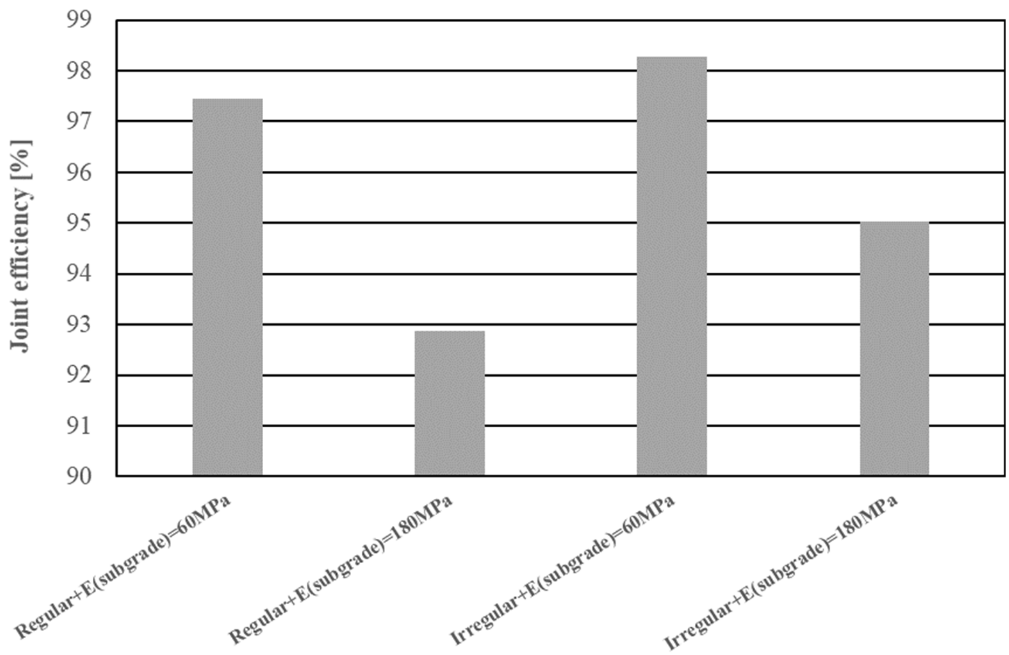

Figure 17. Joint efficiency for the pavements.

3.5. *Resume of Research Findings, Limitations, and Future Works*

To resume the outcomes of the present research, Table 2 reports a concise and direct comparison between R-SPS and H-SPS, in terms of vertical displacements, principal stress in the mortar joint, horizontal stress in the mortar bed, stone warpage, joint efficiency, and separation between the stones and mortar joint.

Table 2. Comparison between the R-SPS and H-SPS.

Investigated Aspect	SPS with Better Performance	Magnitude of the Difference in Performance
Vertical displacement	H-SPS	Minor
Principle stress in the mortar joints	H-SPS	Major
Horizontal stress in mortar bed	R-SPS	Major
Stone warpage	H-SPS	Minor
Separation between stones and mortar joints	R-SPS	Minor
Joint efficiency	H-SPS	Minor

For each of the abovementioned aspects, Table 2 indicates which typology of SPS (R-SPS or H-SPS) showed better performance. Moreover, Table 2 reports the magnitude of the difference, i.e., if the difference in performance is major (one typology of SPS is performing significantly better than the other one) or minor (the performance of R-SPS and H-SPS is comparable).

According to the outcomes recapped in Table 2, it is possible to identify four performance criteria, namely vertical displacement, principal stress in the mortar joints, stone warpage, and joint efficiency, where H-SPS outperform R-SPS. Among such aspects, solely the principal stress in the mortar joints denotes a major difference between the performance of the two typologies of SPS.

Moreover, it is possible to observe that two performance criteria, namely the horizontal stress in the mortar bed and the separation between the stones and mortar joints, where R-SPS outperforms H-SPS; among such aspects, solely the horizontal stress in the mortar bed showed major differences between the performance of the two typologies of SPS.

The research also demonstrated that subgrade stiffness has a limited influence on the SPS. This result can be somehow expected if the whole structure of the pavement is considered. Indeed, the bearing capacity is mostly provided by the concrete slab between the subgrade and the bending layer; in addition, all the materials involved are all very stiff. Therefore, it could be reasonable to expect that the stress level provided by the traffic vanishes much more in surface than in the subgrade. What occurs in the surface depends mainly on the stress concentrations between the stone and the mortar and on the modeling of their behaviors.

The present research attempts to provide some design criteria for SPS in urban trafficked areas; it should be considered as a starting point, providing insights and indicating potential areas for further investigation on SPS located in urban trafficked areas where SPS must withstand heavy traffic loads. Nonetheless, we acknowledge that there are some limitations: firstly, the H-SPS have been simplified in the FEM simulation since their actual geometry was very complex and required a huge amount of time to be processed. Secondly, elastic properties of the stones derived from literature [21] and may be different from those of the stones exploited in the SPS of the case study. Thirdly, a sensitivity analysis of input features of the FEM model should be provided, in order to provide more objective and reliable outcomes.

In our future work, we firstly aim to refine and validate the outcomes by providing readers with a sensitivity analysis focused on the properties of the stones and mortar, such as mortar thickness, stone shape, and stone thickness, since these are the main elements that can be adjusted or modified during the SPS design. Indeed, the thickness of the layer cannot be adjusted since it depends on the original level of the pavement that must be restored as it is. We aim also to exploit different types of mortar and evaluate any differences in the structural performance of SPS. The sensitivity analysis should provide several combinations of such parameters and validate the outcomes of the present research, providing additional design criteria for road authorities and pavement engineers.

We aim also to perform a quantification of the influence of such parameters with respect to the stress and strain detected through the FEM simulation by using Machine Learning Algorithms, such as the feature importance computation provided by tree-based classifiers as we performed in different research concerning road safety and road resilience against major natural events [25,26] (i.e., Classification and Regression Tree, Random Forest, Boosted Regression Tree).

Moreover, we aim also to conduct a further survey with the Falling Weight Deflectometer in order to validate the vertical deflection observed after FEM simulations.

4. Conclusions

Considering different evaluation criteria and performance metrics, the present research demonstrated the strengths and weaknesses of both regular and historical SPS. Through the characterization of the composing materials of a stone pavement structure of an Italian real case study with laboratory tests and in situ nondestructive surveys, and by performing simulations with Finite Element Method, both types of road pavements were investigated, assessing different perspectives, namely the mechanical behavior under loading, failure criteria, joint efficiency between stones, and whether the subgrade stiffness may affect the performance of these types of road pavement structures. The leading outcomes can be summarized as follows:

1. The influence of the type of SPS on performance: The research findings indicate that the type of stones used in stone pavement structures has a negligible influence on the vertical deflection, stone warpage, separation between the stones and mortar joints, and the efficiency of mortar joints. This suggests that both regular and historical stones can perform similarly in terms of these performance aspects;
2. Mitigation of stone warpage: When stone warpage is a significant failure phenomenon, historical stones demonstrate better mitigation compared to regular stones. Historical stones, with their irregular shapes, have shown a tendency to resist warping and maintain stability more effectively;

3. Preference for historical stone pavement structures: In cases where stone pavement structures are prone to cracks in the joint areas where the stone meets the mortar, historical stone pavement structures should be preferred. The irregular shapes and sizes of historical stones can help reduce the occurrence of cracks and enhance the durability of the pavement;
4. Preference for regular stone pavement structures: Regular stones have proved to be significantly more prone to reducing separation issues compared to historical stones. This implies that regular stones, with their uniform shapes and sizes, are more effective in minimizing gaps or spaces between stones, enhancing the overall integrity of the pavement;
5. Limited impact of the subgrade stiffness: The research findings suggest that the subgrade stiffness has a relatively limited impact on stone warpage, separation between the stones and mortar joints, and joint efficiency. The study did not identify a significant difference in performance between the use of regular or historical stones in relation to subgrade stiffness.

Investigating different aspects and performance criteria, the present research may support road authorities and pavement engineers needing to appropriately design or identify maintenance interventions of stone pavement structures. It is worth noting that research in the field of stone pavement structures is an ongoing process, and each study contributes incrementally to our understanding of their behavior and performance. The conclusions drawn from this research should be seen as a starting point, providing insights and indicating potential areas for further investigation on SPS located in urban trafficked areas.

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Data Availability Statement: Data are currently used for further research (please see Section 3.5). Subsequently, data will be made available to readers under reasonable requests.

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