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Deflection and friction performance of waste-wooden block pavements.

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Abstract. The use of waste wood for road light pavements is essential for environmental and economic sustainability.

The paper investigates the mechanical performance of pavements built with waste wood elements discarded from Sardinia manufacture (Italy). Without structural value, mainly Sardinian wood is used for combustion and heating due to the characteristics of dimensional irregularity, non-homogeneity, and the presence of defects. Even small urban and forest furniture comes from foreign markets. Landscape reasons, emissions reduction, and environmental integration with the local context could encourage its use if reliable techniques are available. The study first analyzed the structural response of a portion of pavement made with waste wood bricks (pine and Eucalyptus). Subsequently, a Finite Element simulation of the pavement has been validated with the tests' results. The experimental pavement was created with Interlocked Block Pavement (IBP) technique, using brick elements 13 x 6 x 10 cm. The behavior of the pavement was analyzed in situ with dynamic deflection tests using the Falling Weight Deflectometer test (FWD). Further tests performed in the laboratory investigated the friction of the wood pavement surface. The simulation results show that the wooden pavement elements do not differ substantially from the classic concrete IBP and HMA cracked pavement. The mean deflections are greater than 19%, while the vertical stress on the foundation layer is equivalent. As with the classic concrete IBP, the results largely depend on the bearing capacity of the substrate and the degree of interlocking.

Friction tests show good values with mean values of 53÷64 BPN. The most significant values were observed in the elements eucalyptus. The direction of the wood fibers also influences the results: about 3 points in the case of pine and over 7 points in the case of Eucalyptus. The study shows how the use of wood for the pavement with elements is sustainable and practicable due to the minor and low-traffic roads while also guaranteeing permeability and low-cost maintenance.

Keywords: Wood pavement; forest road; reuse of waste wood; FWD alternative application; wood element pavement

1 Introduction

The construction of road pavements has a significant impact on the environment: the removal of aggregates from nature, the energy conduction for the production of materials, and the alteration of the superficial and deep flow of water. Furthermore, road construction must follow rational criteria to gain mechanical performances, costs, and traffic [1]. In the mid-19th century, Samuel Nicolson invented the wooden block pavement, but over the centuries, the use of wood has been limited due to its mechanical characteristics and durability. Many applications remain confined to pedestrian and cycle paths and forest roads (Figure 1).

Figure 1. South Camac street (Philadelphia, USA) was paved in wood in 1917 and restored in 2017. It is an example of "Nicolson pavement" still exists in several Countries

Many previous studies of forest roads point out how the bearing capacity of the road subgrade affects the regularity and quality of the road surface [2-5]. Since waste-wood element is a by-product, almost the energy and CO_2 emissions for its manufacture have already been spent, and all the possible use in the road construction can decrease the exploitation of natural resources and limit energy consumption and CO_2 emissions. In addition, wood accumulates carbon captured by trees as CO2 from the atmosphere [6].

Many studies underline as the road subgrade bearing capacity [2-5] and the wood's resistance to biotic factors and fungi [7, 8] affect the durability. These investigations are not exhaustive why the complexity of the mechanical response of the elements pavement and the interpretation of the results are not comparable in many different approaches. For this reason, a typical approach adopted by road pavement engineers has been implemented in two-phase. First, a FE model of segmented pavement, assembled with waste wood elements, was validated with dynamic deflectometer test results. Subsequently, the model was subjected to mechanical stresses from the heavy axles.

The Falling Weight Deflectometer (FWD) is an impulsive test developed for road and airfield pavement to reproduce the wheel loads transit. The vertical applied stress has a control-shaped dropping weight on a circular load plate. At the same time, 12 geophones inline register the vertical velocity in different positions every 0.05 msec. The stress can be modified, varying the drop height (50÷390 mm) and the weight

(50÷350 kg) of the falling mass so that the impulse load can range from 40 to 120 Kn in the period of 25÷30 milliseconds [9]. The load and measures the time history for each drop is stored for 60 milliseconds. An instrumented vehicle tows the FWD, and the operator can control the test with a laptop computer (Figure 2).

Figure 2. FWD equipment

From the shape and the amplitude of the deflection basin (Figure 3), it is possible to estimate the value of the stiffness of each pavement layer throughout "*backcalculation*" post-processing, implemented by ELMOD6(c).

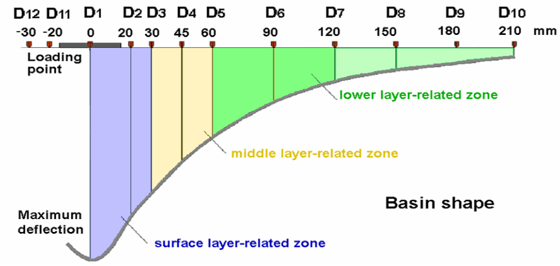


Figure 3. Basin shape profile

In addition, from the raw FWD data acquired, it is possible to obtain particular indices, called Basin Index, which are well correlated with the stiffness of the layers. Those considered relevant for the trials were:

- Base Layer Index BLI = $D_0 - D_{300}$
- Middle Layer Index MLI = $D_{300} - D_{600}$
- Lower Layer Index LLI = $D_{600} - D_{900}$

The FWD is developed to monitor flexible (asphalt), rigid (concrete), and semi-rigid pavements (asphalt and concrete). Some recent applications concern unconventional investigations such as bridges [10-12] and paving stones [13]. Some Authors use the FWD for research purposes in testing and simulating pavement structures [14-16]. The FWD became a standard to assess the performance of pavements and roads, and airport National and International authorities have integrated FWD equipment and related analysis into the regulations and technical specifications.

Brick pavements have increased considerably in Europe in the last 30 years, using stone and concrete materials for the elements. Thanks to their aesthetic characteristics and high permeability, they have been used for paving squares, parks, and residential areas. Furthermore, in Northern Europe, they have also been widely used to construct urban roads, ports, and airports.

Another practical aspect in the urban context is their ability to mitigate the thermal field, mitigating the UHI (Urban Heat Islands), and further reduction could result from the use of wood.

The pavements capable of decreasing thermal field are known as "cool pavements." The reduction can be achieved with highly reflective materials and porous layers [17]. The “cool pavements”, include conventional asphalt and concrete pavements, stone pavement [13], and nonconventional surfaces (white-colored course, resin-bonded pavements, micro-surfacing, and porous layer) [18].

Brick-pavement, under the action of traffic, tends to self-lock due to mutual action on lateral or vertical contact surfaces. The pavement is characterized by interlocking, created by the system of elements, dry-laid on a bed of sand and dry sealed with sand. Mutual interlocking ensures adequate distribution of surface loads through the support surface and the friction generated in the joints. Brick-pavement, under the action of traffic, tends to self-lock due to mutual action on lateral or vertical contact surfaces. The pavement is characterized by interlocking, created by the system of elements, dry-laid on a bed of sand and dry sealed with sand. Mutual interlocking ensures adequate distribution of surface loads through the support surface and the friction generated in the joints. Figure 4 shows typical layers that compose the block pavement: a layer of self-locking blocks, one in bedding sand, a base layer (not always present), and a foundation layer.

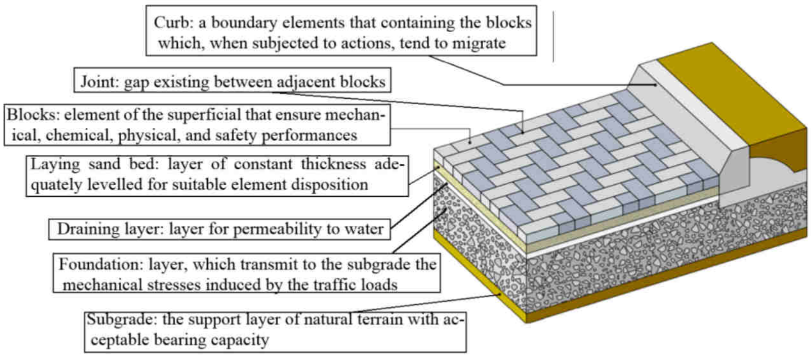


Figure 3. Typical layers of the block pavements

The presence of the joints considerably influences the regularity of block pavements. The sealing of the joints is essential for the efficiency of the structure. The interlocking effect, which is the ability to distribute the load from a block to the adjacent contact blocks, is ensured by the sand friction in the joints. The filling of the joints guarantees the mechanical function of joint-element connection and the mutual collaboration between the elements. When laying block paving, it is good practice to pre-clog the joints as soon as the installation of the elements is finished. The sand is spread and distributed over the entire surface, then vibro-compacted. Subsequently, a final clogging of the joints with further application of sand completes the pavement. A good laying is achieved mainly through the sealing of the joints. The use of unsuitable sand, incorrect clogging, or sand removal before complete clogging under load can compromise its overall stability. For block pavement, the boundary containment, suitably dimensioned, can oppose the horizontal tensions due to trafficking. The retain can be determined by the presence of fixed structures or, more frequently, by installing prefabricated containment curbs in concrete or stone, laid in place before laying the elements.

2 Data and Methodology

To find a way to use wood waste, friction tests were carried out in the laboratory, while a portion of pilot waste-wood block pavement was made in situ and subjected to bearing capacity and deflectometric tests. The wood species used were wood and Eucalyptus combined in different configurations. Subsequently, a finite element model was developed, validated by in situ tests, which allows for analyze in detail the mechanical response of the block pavement and optimize it in terms of materials, configuration and thickness.

Starting from the wooden waste planks of Eucalyptus and Maritime Pine 13.0 x 6.0 cm, through the use of a band saw, wooden bricks were obtained, each with a height of 10.0 cm

Friction tests in the laboratory

According to Standard Test [19], the surface adhesion of the pavement was investigated using the British Pendulum equipment. The test simulated the grip of the tires, in good condition, of a vehicle at a speed of 50km/h when braking on a wet road, at a temperature of 15° C. The British pendulum tester is a dynamic pendulum impact tester based on the mechanical energy loss when a rubber slider edge is propelled over the pavement surface.

The equipment consists of a pendulum with a movable arm, adjustable in height, at the end, a slide is applied, covered with a special rubber with known characteristics, preloaded with a system of springs (Figure 4).

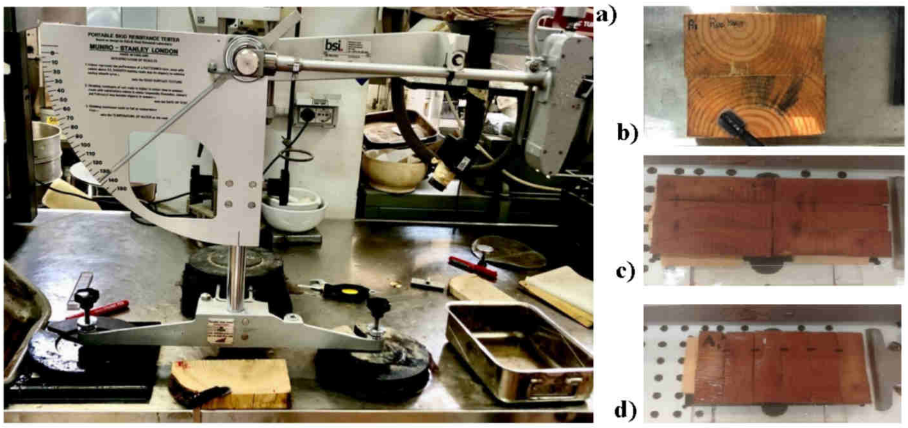


Figure 4. Laboratory adherence tests: a) British Portable Tester, b) pine sample, c) Eucalypt sample in orthogonal, and d) parallel direction.

The test is performed by manually lifting the pendulum arm and letting it fall sparsely against the surface. The ascent is detected on the appropriate scale, equipped with a maximum index.

The measured values are expressed in "BPN" units by "British Portable Tester Number." For the results to be comparable and repeatable, it was necessary to determine the value of the test temperature, as the values need adjustment factor and referred to the standard temperature of 15 ° C.

To evaluate the adherence results, the results were compared with the typical road pavement values in Table 1.

Type	BPN value	Quality
A	>65	Excellent
B	55 ÷ 65	Good
C	45 ÷ 55	Acceptable
D	<45	Slippery pavement

Table 1. Typical BPN road pavement values

Seven specimens of Maritime Pine were tested, on which the test was followed on both sides, and one specimen of Eucalyptus, obtained from 6 side-by-side and locked bricks, which were arranged to perform the test in two directions. The identification of the specimens was performed for the Maritime Pine by assigning a different letter starting from A and the two faces with the numbers 1 and 2. For the Eucalyptus, the test was carried out on the faces indicated as A1 and A2, in a direction perpendicular, A3 and A4, in a direction parallel.

Deflection tests in situ.

A prototype of the waste-wood block pavement with dimensions of 6.0 x 4.0 m was built on site. Before laying the wooden bricks, the substrate was adequately prepared, leveled, and rolled. A layer of sand was placed on this to ensure the drainage of the water. Subsequently, Maritime Pine planks have been placed on the boundaries of the pavement to retain it in place. Then have been laid the wooden bricks placed them side by side, creating a collaborative pavement structure. The joints between the brick have been filled with sand, guaranteeing mutual interaction between the wooden elements.

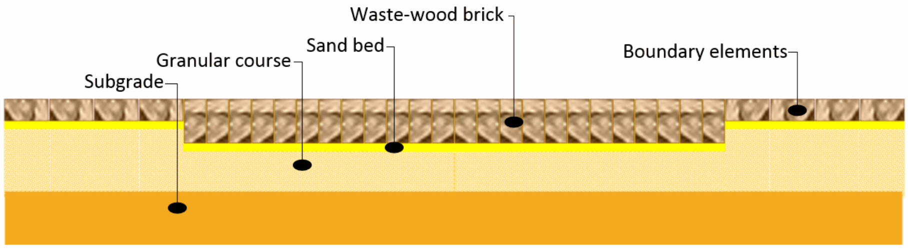


Figure 5. The layers of pavement trial section

Figure 6. Performing FWD tests on the pavement trial section

Finite element simulaiton.

Structural analysis has been implemented in ANSYS, which allows to solve complex structural engineering problems and make better and faster decisions during the the design process. In addiction, it is possible to customize and automate solutions for mechanical structural problems and parameterize them in order to analyze different design scenarios. The finite element model of the developed woodblock pavement has dimensions of 1.39 x 1.39 m and is 2.0 m high. The first 10 cm of the model represents the waste-wooden blocks. The 5 cm below the blocks is the layer of bed sand. Below is the foundation layer of 20 cm and the subgrade of 1.65 m. Each element representing the wooden brick of the pavement has dimensions in plan equal to 6.0x13.0 cm and is 10 cm high (Figure 7).

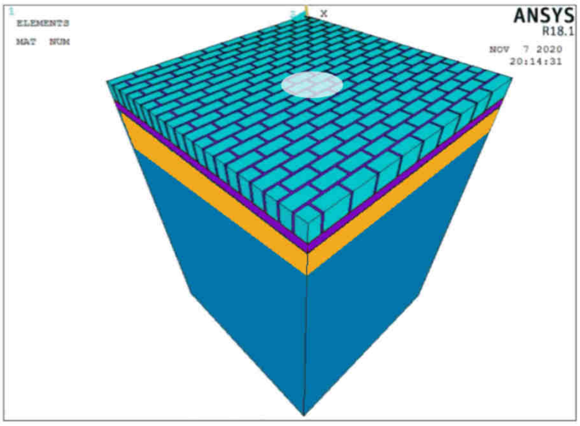


Figure 7. The finite element model implemented with ANSYS$^{(c)}$ software

The model was set on a square grid of points by arranging the rows of points alternately spaced 6 cm to identify the wooden bricks and 0.2 cm to identify the sand joints. The properties of the materials were then associated with the various elements identified by the grid. In particular, the wood material properties have been associated with bricks, while the properties of a fictitious material with a low modulus of elasticity have been associated with sand joints. This procedure has been developed in such a way as to be able to make it automatic and generate the mesh of the FEM model for all possible configurations of the arrangement of the blocks.

The load was applied to the center of the model, as shown in Figure 7. The maximum load applied is equal to 1000 kPa, equivalent to the maximum load applied with the third stress level in the FWD test.

3 Results

Friction tests in the laboratory

Table 2 shows the friction test performed with British Pendulum. By comparing the results obtained in Table 2 with the values shown in the Table 1, it can be seen that most of the Maritime Pine specimens belong to category C. Only one specimen belongs to class D. The results obtained from the tests on Eucalyptus show that 50% of the specimens can be classified in category A, while the remaining 50% in category B.

Wood	Fibber direction	Samples	Data 1	Data 2	Data 3	Data 4	Data 5	Mean (3,4,5)	Temp °C	Temp. adjustment	Adjusted values
Pine	Orthogonal	A1	56	53	55	50	51	52	20	1	53
Pine	Orthogonal	A2	57	54	52	49	50	50	20	1	51
Pine	Orthogonal	B1	50	49	48	54	46	49	20	1	50
Pine	Orthogonal	B2	55	53	51	50	50	50	20	1	51
Pine	Orthogonal	C1	61	55	55	55	50	53	20	1	54
Pine	Orthogonal	C2	56	52	51	50	50	50	20	1	51
Pine	Orthogonal	D1	60	55	55	54	52	54	20	1	55
Pine	Orthogonal	D2	55	50	50	50	50	50	20	1	51
Pine	Orthogonal	E1	60	55	54	51	50	52	20	1	53
Pine	Orthogonal	E2	56	55	52	51	52	52	20	1	53
Pine	Orthogonal	F1	60	55	54	53	51	53	20	1	54
Pine	Orthogonal	F2	60	55	54	54	51	53	20	1	54
Pine	Orthogonal	G1	60	55	54	54	50	53	20	1	54
Pine	Orthogonal	G2	60	50	50	50	48	49	20	1	50
Eucalypt	Orthogonal	A1	66	66	66	65	65	65	20	1	66
Eucalypt	Parallel	A2	69	69	69	68	68	68	20	1	69
Eucalypt	Orthogonal	A3	62	60	59	58	57	58	20	1	59
Eucalypt	Parallel	A4	63	61	60	60	60	60	20	1	61

Table 2. BPN tests data.

Deflection tests in situ.

First, the identification and analysis of the deflection basins were carried out. The 16 tests were performed in different positions, repeating the tests with increasing load levels equal to 600, 800, and 1000 kPa.

The FWD tests were performed both on the substrate without pavement, on the layer of sand, and the waste-wood block pavement. The tests on the sand layer were carried out twice on six points. Four stations have been on the wooden pavement. In Table 3, it is possible to observe the value of the displacements for each station for the maximum load value.

		Sand												Pavement			
	Distance [mm]	Station 1 [µm]	Station 2 [µm]	Station 3 [µm]	Station 4 [µm]	Station 5 [µm]	Station 6 [µm]	Station 7 [µm]	Station 8 [µm]	Station 9 [µm]	Station 10 [µm]	Station 11 [µm]	Station 12 [µm]	Station 1 [µm]	Station 2 [µm]	Station 3 [µm]	Station 4 [µm]
Drop 3	-450	-551	-914	-505	-614	-340	-556	-505	-500	-380	-374	-73	-75	-3	-75	-207	-213
	-300	-904	-679	-478	-360	-309	-462	-422	-414	-397	-431	-47	-53	0	-172	-187	-240
	0	-1390	-1425	-1350	-1398	-1558	-1537	-1175	-1309	-1600	-1592	-1616	-1652	-2106	-1794	-1857	-1643
	200	-320	-326	-281	-312	-415	-282	-298	-287	-241	-256	-254	-259	-301	-457	-277	-218
	300	-855	-610	-746	-792	-570	-283	-675	-592	-803	-244	-596	-446	-84	-181	-279	-324
	450	-413	-510	-345	-358	-375	-332	-359	-351	-505	-576	-391	-380	-198	-257	-225	-243
	600	-213	-215	-297	-295	-252	-439	-230	-230	-244	-284	-231	-261	-131	-155	-172	-178
	900	-133	-307	-161	-322	-151	-236	-167	-352	-152	-123	-233	-228	-67	-81	-73	-85
	1200	-145	-159	-92	-91	-94	-102	-97	-185	-71	-74	-160	-147	-39	-53	-53	-59
	1500	-55	-60	-59	-67	-58	-61	-146	-75	-50	-53	-118	-104	-37	-43	-45	-45
	1800	-43	-55	-47	-57	-50	-40	-43	-43	-47	-51	-45	-43	-38	-38	-37	-38
	2100	-33	-35	-45	-41	-49	-30	-71	-55	-42	-49	-30	-26	-30	-31	-40	-32

Table 3. Deflection data

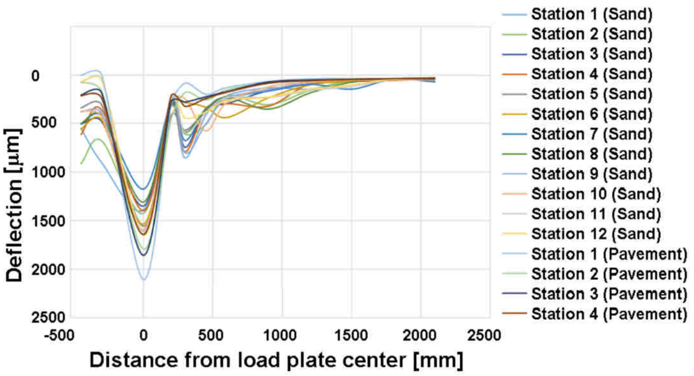


Figure 8. The deflection basin measured applying FWD drop weight with 1000 kPa pressure

In the graph (Figure 8) of the deflection basins, it is possible to observe how these have an irregular trend, typical in pavements made up of elements. The wood elements exhibit anomalous behaviors, with a rigid rotation of the wooden elements due to the action of the load. The geophones farthest from the load axis are affected by the deformation of the subgrade, with low and graduated values.

The stress-strain relationship obtained also considering the layer of the wooden pavement also has a nonlinear trend.

An analysis was then conducted on the deflection data, through which the stiffness index of the surface layers and the stiffness index of the intermediate layers were obtained. The indexes which referred to each load level and for each station, were determined (Figure 4).

	sand												pavement			
	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11	Station 12	Station 1	Station 2	Station 3	Station 4
BLI1	535	815	604	606	988	1254	500	717	797	1348	1020	1206	1932	1613	1578	1319
MLI	642	395	449	497	318	-156	445	362	559	-40	365	185	-47	26	107	146
DLI	80	-92	136	-27	101	203	63	-122	92	161	-2	33	64	74	99	93

Table 4. Basin Index

The value of the BLI, indicative of the surface stiffness, eexhibits an average value referred to the wooden pavement lower than that obtained on the sand. This denotes how the pavement is more deformable than the sand layer. The anomalousbehavior is that the wooden blocks are moving under load. However, the positive effect of the presence of wood is found in the deeper layers, distributing the load. The deep stiffness indices (DLI) are much lower than those obtained with the sand layer.

Finite element simulation.

For the validation of the FEM model, the deflection basin obtained from the FEM simulation was compared with that obtained from the trial section. In particular, mean stiffness values obtained by back-calculation of the deflectometric data have been adjusted to consider a joint efficiency factor. Therefore, these values express an "effective" value averaged over the entire pavement rather than the stiffness modulus of the single wooden element.
Figure 9 shows the two curves representing the deflection basins, the experimental one obtained using the data from the on-site test with FWD (in red) and through the FEM simulation (in blue).

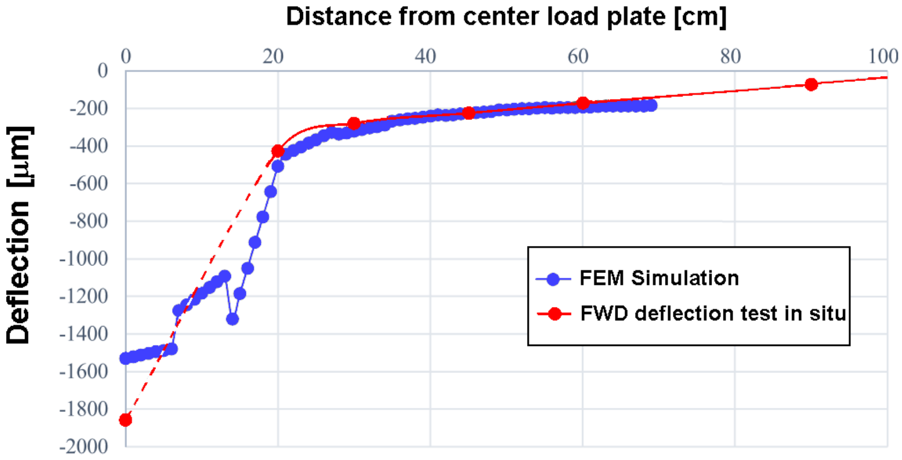
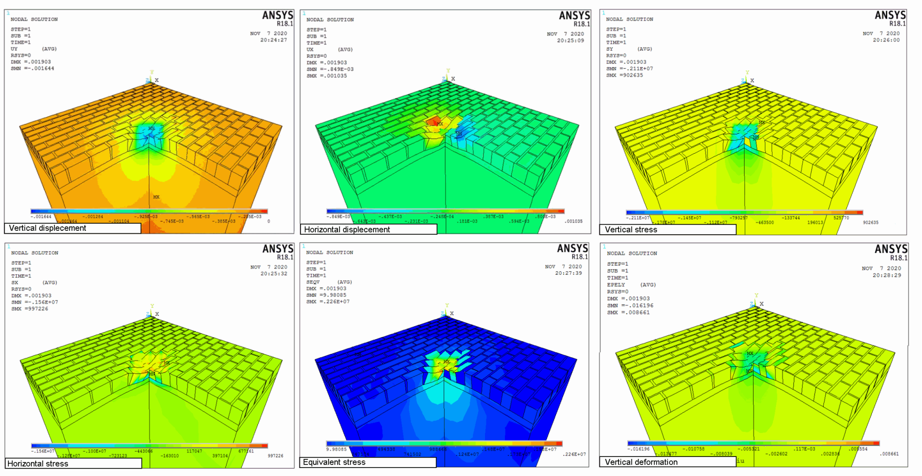


Figure 9. The deflection basin was simulated (blue line) and measured in situ (red).

In the first 20 cm, it is possible to observe the polyline profile of block pavement simulated and the red dashed line inferred by deflection measures at the first and second geophone. Overall, the red dots corresponding to the geophones position correlate well with FEM simulation, excluding the first one (D0). This is clearly explained because the woodblock dimension of 6 x 13 cm is less than the load plate diameter (30 cm) and less than the second geophone distance (20 cm from load plate center).
Structural analysis of the validated FEM model how to better understand the mechanical behavior of the block pavement. In the FEM simulation, it is possible to observe how the elements tend to rotate towards the center of application of the load, and the material associated with the joints does not contribute and does not allow the pavement to work uniformly. This causes no mutual collaboration between the blocks as there is no transmission of stresses between them. Figure 10 shows the results of the FEM simulation in terms of displacements, stresses, and deformations.



In addition, the simulations were developed considering four types of block arrangements, two load configurations, and three block thicknesses. For each analysis, the distributions of 25 stress-strain parameters were considered:

- displacements in x, y, and z-direction (δ_x, δ_y, δ_z)
- normal, tangential, and equivalent stresses (σ_x, σ_y, σ_z, τ_{xy}, τ_{xz}, τ_{yz}, σ_1, σ_2, σ_3, σ_{int}, σ_{eqv},)
- normal, tangential, and equivalent deformation (ε_x, ε_y, ε_z, ε_{xy}, ε_{xz}, ε_{yz}, ε_1, ε_2, ε_3, ε_{int}, ε_{eqv})

The study is still ongoing, but it is possible to illustrate some results. In general, it is observed that the lateral retain and the joints efficiency allow the pavement to work uniformly and therefore represent one of the crucial aspects in pavement construction. Achieving this result means that the blocks in which the loads are applied undergo a failure and the adjacent ones collaborate, transmitting the stresses.

As the thickness of the block increases, the stress distribution is uniform, and the maximum deflection decreases, thanks to the greater frictional force generated between the blocks. When there are only vertical loads, more significant differences occur between the four distributions of the blocks studied. The presence of horizontal components also determines a uniform behavior making for thicknesses more significant than 10 cm, the tension level of the four configurations almost coincident.

The maximum deflections are almost independent of the arrangement of the elements but significantly depend on the thickness. They increase by 78% for thicknesses of 8 cm and by 274% for thicknesses of 6 cm.

4 Conclusions and remarks

The investigation allowed to highlight some critical aspects of the use of waste Sardinian wood to create block pavement for light-load roads. This use would have several benefits compared to cementitious and bituminous materials: high architectural and landscape qualities, better integration with local contexts, reduced emissions, lower energy consumption, more excellent permeability, reduced thermal field, and recovery of waste materials. For this purpose, it is necessary to ensure the pavement's adequate and reliable mechanical design. The research suggests reducing waste wood into small elements (13 x 6 x 10 cm.), thus removing the effect of geometric imperfections, irregularities, and inhomogeneity.

Two main aspects are investigated: adherence and mechanical stability. The adhesion characteristics were first analyzed in the laboratory. The BPN tests have shown that the elements in Maritime Pine offer an acceptable performance while the elements in Eucalyptus exhibit high performance. Therefore, the pavement construction mixing the two species would result in suitable for transit safety. The structural response was investigated both in situ, through the construction of a trial section, and numerical simulation with the FEM model of a portion of block pavement made with waste wood bricks. The experimental pavement was investigated with dynamic deflection using the Falling Weight Deflector. The data measurements show that:

- the deflections of wood pavement are comparable to those of similar road HMA pavements cracked. The mean deflections are greater than 19%. Improving the characteristics and compaction of the subgrade would further reduce deflections. The tests also show a nonlinear response due to the lack of joints load transfer efficiency.
- The mechanical response is complex and nonlinear.
- The BLI, surface stiffness index, exhibits an average value greater on the sand surface than pavement surface. The pavement is more deformable than the sand layer, and this anomalous behavior is related to wooden block's movement under load.
- The woodblock pavement has a positive effect in the deeper layers due to its ability to distribute the load. The deep stiffness indices (DLI) are much lower than those obtained with the sand layer.

Some valuable findings can be deduced from these results:

- the coupling and the interlocking between the wooden elements is a critical issue
- The loads transmitted by the FWD assume typical road values and for DROP3 equal to 1000 kPa they correspond to an axle of a heavy vehicle of 14 tons.
- The FWD imposes excessive stresses and, by its nature of a dynamic type. Therefore, it will be necessary for future research to adapt the equipment and the stress profile to the typical ones that may affect wooden floors, in general, less than 5 tons and with low speed (< 30 km/h).
- The position of geophones is typically set for a road application, but in element block, pavement investigation needs to be modified to measure deflection every 5÷10 cm to follow block movements.

Finally, a different block configuration, thickness, and subgrade were simulated. The woodblock thickness is the main parameter that affect the pavement response, while the block configuration exhibit a low influence.

The maximum deflections are almost independent of the arrangement of the elements but significantly depend on the thickness. They increase by 78% for thicknesses of 8 cm and by 274% for thicknesses of 6 cm.

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