

Replacing Granular Layers Beneath Slabs with Plastic Dome-Shaped Forms

Influence of soil properties on the behavior of concrete pavements cast on Plastic Dome-Shaped Forms

A. Comisini P.Eng, *Pontarolo Engineering*

S. Secchi PHD, *CNR-ISIB, Padova, Italy*

P. Simonini P.Eng, *Department IMAGE, University of Padova, Italy*

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ABSTRACT: Plastic dome-shaped forms posed between ground and concrete slabs may be an interesting method to realize industrial pavements, thus avoiding the use of classical and customarily utilized granular interface layer. To evaluate the effectiveness of this construction technique, a full-scale experimental investigation has been carried out. Its results have been used to calibrate a finite element model to describe the overall slab behavior as a function of relevant geometrical and soil parameters. The paper outlines some interesting outcome of the tests carried out so far, showing also the applicability of the numerical model to suitably describe this soil-structure interaction problem.

1. Introduction

Plastic dome-shaped forms (PDSF) interposed between ground and concrete slabs may be an interesting alternative method to realize industrial pavements, avoiding therefore the use of the classical and customarily utilized granular layer between natural soil and concrete slab. The typical PDSE is shown in Figure 1a. Each PDSF is interlinked with other PDSF to create a formwork for successive complete casting of the concrete slab (Figure 1b). An additional advantage of PDSF system is to provide an internal orthogonal duct mesh allowing for free air-circulation, thus reducing possible humidity rise through the pavement.

To evaluate the effectiveness of this technique as a function of different PDSF types and sub-grade conditions, an experimental research has been recently undertaken and partially carried out. To this end, a new reinforced-concrete test tank, in which typical sub-grades supporting the dome-shaped concrete slabs, has been recently constructed. On these sub-grades, several tests have been performed out by using different combinations of PDSF and slabs, forcing them to failure by increasing vertical load and monitoring, along with the load increase, the vertical displacements for a careful reconstruction of the system deformed geometry. The results of the experimental tests have been back-analyzed using the finite element method, in order to calibrate and

validate a finite element model to describe the overall behavior of the slabs as a function of soil conditions, type of dome-shaped plastic element and Thickness/reinforcement of concrete slabs.

The paper outlines the most interesting results of some experimental tests carried out so far, as far as the effectiveness of the numerical analysis that incorporates linear and non-linear models for sub-grade response, to reproduce the interaction between ground and the pavement structure.

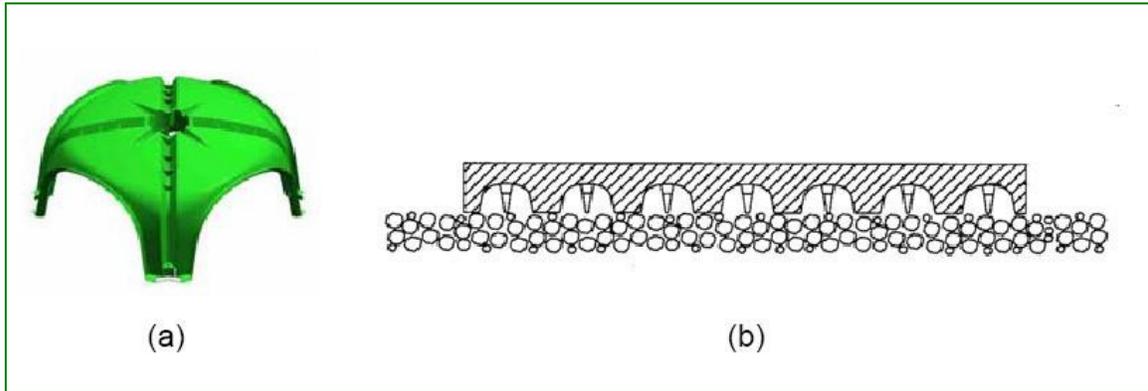


Figure 1. Typical dome-shaped Forms (a)

detail of the dome-shaped slab (b).

2. Experimental Program

In order to carry out the experimental program, the reinforced-concrete test tank shown in *figure 2a* has been designed and constructed. The dimensions in plan of the test tank are 6m x 6m with the tank depth was selected to allow the preparation of foundation beds up to a maximum thickness of 1.5 m. The tank dimensions ensure that, during the stress-failure tests, the soil would be not affected by the restraints provided by the containment walls and by the concrete floor at the bottom.

The loading device comprises an arch with a hydraulic jack that transmits the load to the dome-shaped slab through a square rigid steel plate with dimensions 56cm x 56cm. The loading system is provided with a load cell whilst six displacement transducers monitored the vertical displacements of the slab throughout all the tests. A view of the location of the vertical displacements transducers is provided in *Figure 2b*.

1.1 Sub-grade preparation

Two different sub-grades have been selected, to reproduce various ground stiffness conditions, namely:

- i) A unique homogeneous layer of medium-fine silty sand (S1), with $D_{50}=0.052$ mm and $U = 10$ was used to reproduce a typical natural ground condition. This layer was compacted by moist tamping at 10% water content to reach a final dry unit weight = 15.7 kN/m³.

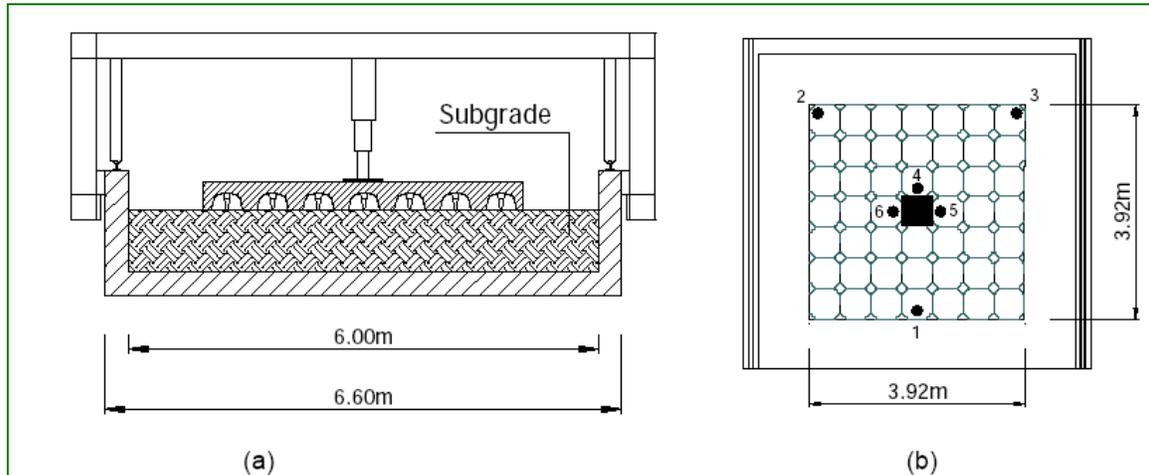


Figure 2. Lay-out of the testing system (a) and location of the six displacement transducers (b).

- ii) A double layer system (S2) composed of a gravel layer with thickness = 30cm compacted above the medium-fine silty sand S1. This second sub-grade condition, used to evaluate possible improvement effect provided by the gravel onto the natural ground, was prepared by dynamically compacting a sandy gravel characterized by $D_{50}=2.8$ mm and $U =20$. The average final dry unit weight of the sandy gravel after compaction was $\gamma_d= 20.4$ kN/m³.

Non-repetitive static plate load tests (ASTM D1196-93 - plate diameter = 30cm) were carried out to characterize the stiffness of each sub-grade. In addition some special plate tests were performed by using a 12cm x 12cm steel plate to reproduce as closely as possible the behavior of the feet of the PDSF, when posed onto the ground.

Figure 3 shows the plate vertical stress-settlement response measured on sub-grade S1 and S2. Note the effect of plate size: as clearly expected, the plate with a size close to the PDSF breadth shows a much stiffer response when subjected to the same load

increase. The presence of a poor concrete layer S3 above S1 increases at very high level the sub-grade stiffness.

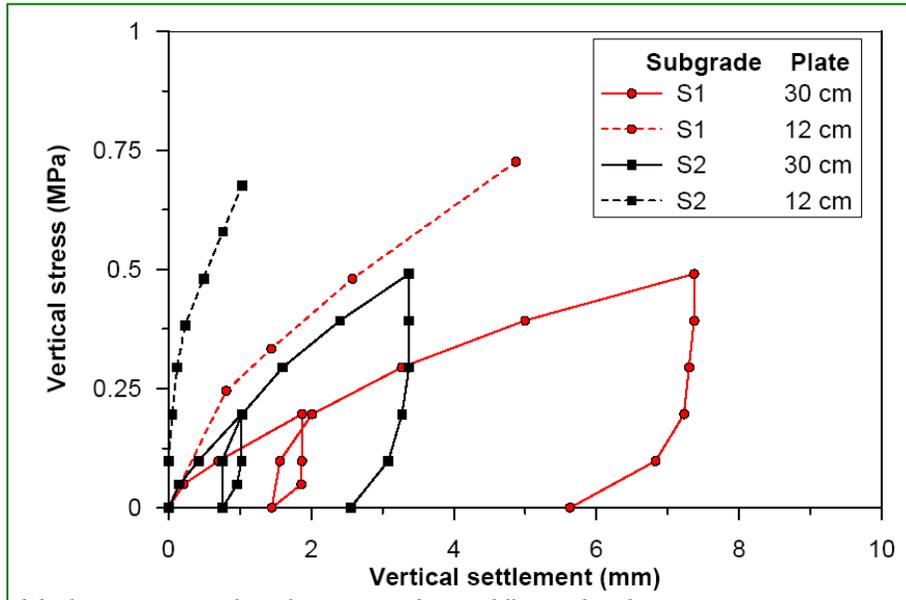


Figure 3. Load-displacement response from plate test carried out on different subgrades.

To interpret the stress-displacement response the classical Winkler elastic coefficient k was used. The interpretation of the vertical stress – settlement curve was performed by using a hyperbolic relationship (e.g. Duncan and Chang, 1970) evaluating the initial tangent stiffness, whose values are reported in Table 1. The hyperbolic curve was also used to model the non-linear stress-strain response in the finite element analysis.

Table 1. Values of stiffness coefficient from plate tests.

Plate [cm]	k_{S1} [N/cm ³]	k_{S2} [N/cm ³]
30	80	200
12	260	940

1.2 Test program

23 loading tests formed the preliminary test program considering various combinations of different type of PDSF, slab thickness and reinforcement, formed by welded wire fabrics

were considered. A typical test configuration includes 7×7 modules installed side-by-side and covered by in-situ casted concrete. The load was then applied via the hydraulic jack up to the breakage of concrete slab, due to the typical mechanism of shear- bending rupture. As a matter of fact, the most significant load distribution, during the pavement life under service condition, is that maximizing the bending moments, the break generally occurring by exceeding the flexural strength. The test was devised so that, after an initial loss of stiffness due to the initial flexural rupture, the load may be increased again, up to the triggering of a punching failure mechanism.

An additional test (N. 24) was carried out by casting a traditional concrete slab on to the gravelly layer S2, without interposing the PDSF. This test was performed in order to compare the PDSF solution on a typical ground with the classical and customarily used three layer system composed by natural soil / gravel layer / slab.

The readings of vertical displacement were performed by the 6 transducers, whose arrangement was shown in *figure 2b*. Transducers 1,2,3, and 4 are in contact with the concrete slab measuring total vertical displacements DZ1, DZ2, DZ3 and DZ4, whereas transducers 5 and 6 measure the relative displacements DZ5 and DZ6, as depicted in *Figure 4*.

The pictures of Figures 5a and b show a typical view of the PDSF pavement before load application and at the end of the test, characterized by a clear punching failure of the PDSF slab.

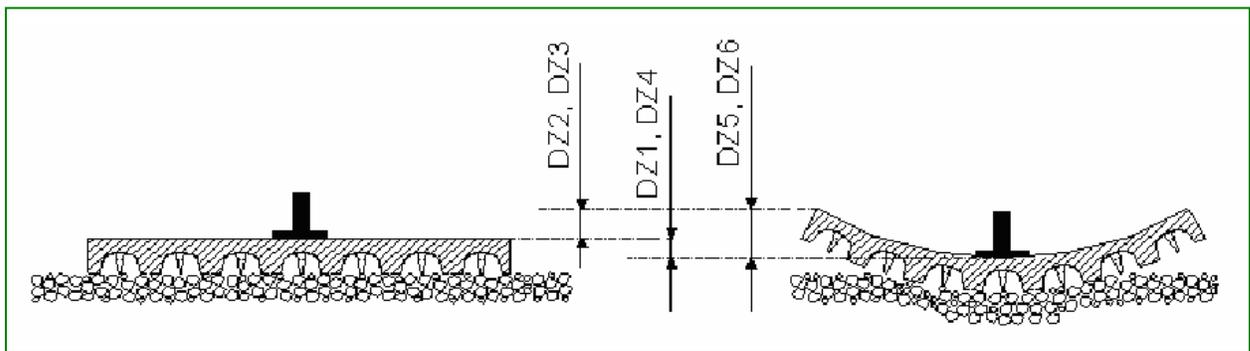


Figure 4. Relevant vertical displacements of the pavement under load increase.

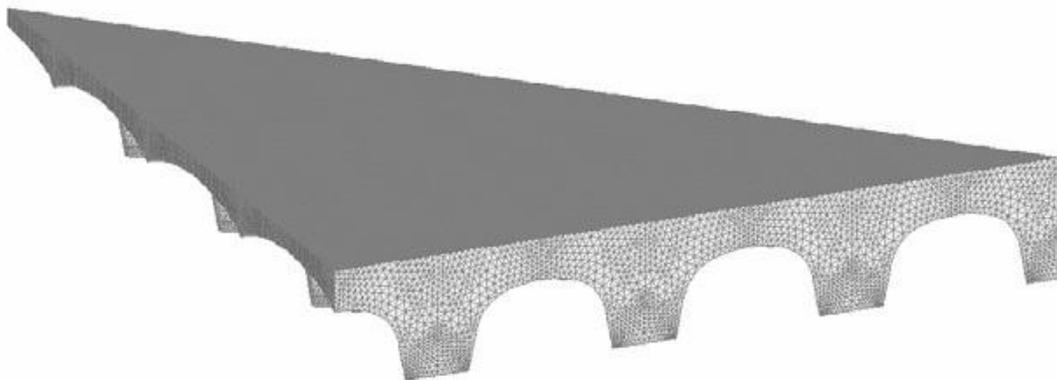


Figure 5. General view of the test tank with a) a typical pavement on PDSEs before load application and b) at the end of the test.

Among the various tests carried out so far, only a few of them are described here and modeled by the finite element method, to show mostly the effect of different ground stiffness on the overall response.

2. Numerical modeling and Comparison with experimental data

To model the overall behavior of the pavement both 2D and 3D FE Model were used (e.g. Bathe, K.J., 1996). 3-D option seemed however an almost obvious choice, in order to correctly represent the complex geometry of the pavement and the inelastic mechanical behavior of the slab. In addition, 3D analysis was preliminarily used to



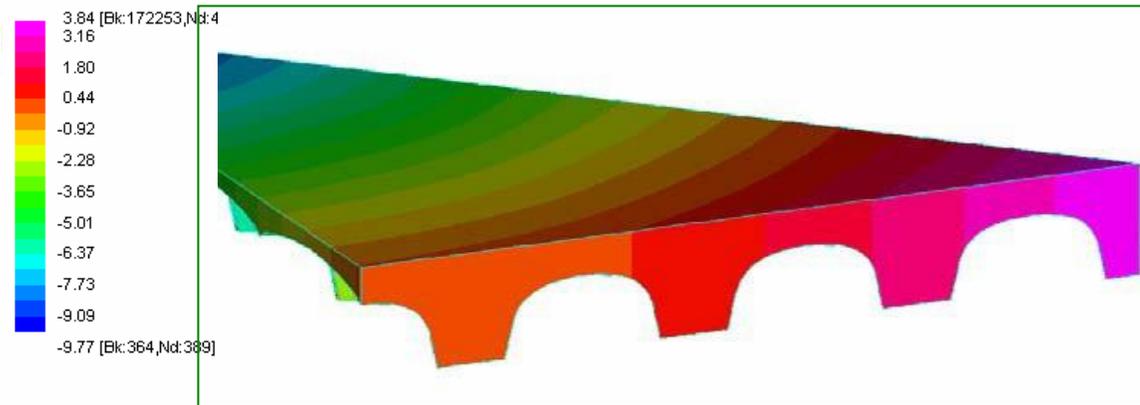
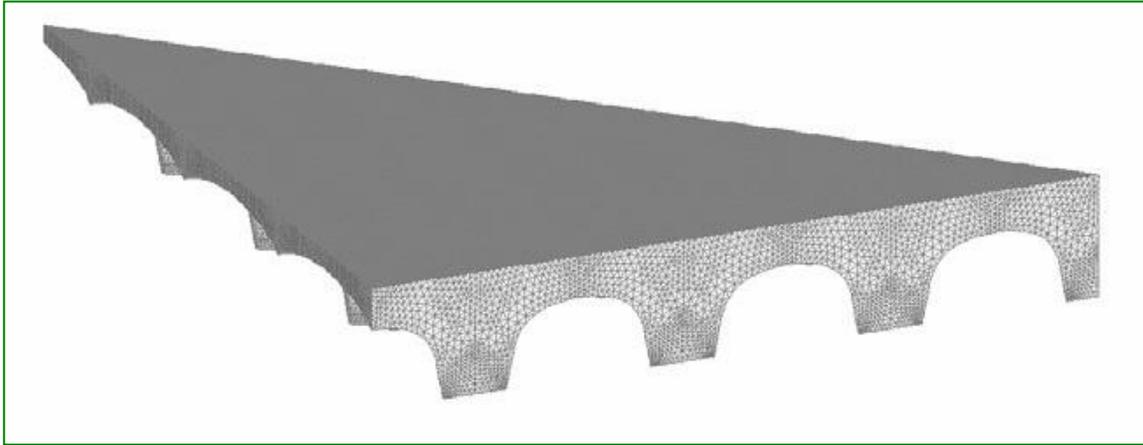


Figure 6. Finite element mesh for 3D analysis (top, 1/8 of the whole domain) and corresponding

The constitutive model used to describe concrete response is the Mohr-Coulomb (e.g. D. R. J. Owen, E. Hinton, 1980) criterion ($\phi=65^\circ$ and $c=2.0$ MPa), whereas the soil response was modeled using linear and non-linear elastic springs, whose calibration was performed on the basis of plate test results (Table 1 -) and back-analysis of full scale tests.

Figure 7 (left) depicts the trends of the vertical displacement for the typical case of PDSE slab resting on sub-grade S1 (height = 260 mm plus 50 mm of casted concrete). Both elastic and elastoplastic analyses were performed and referred as fem_23a and fem_23b respectively.

The overall behavior of the PDSF slab has been compared with that provided by the classical solution formed by the concrete full slab, characterized by an equivalent thickness of 75mm, casted necessarily on the gravel sub-grade (figure 7 on the right).

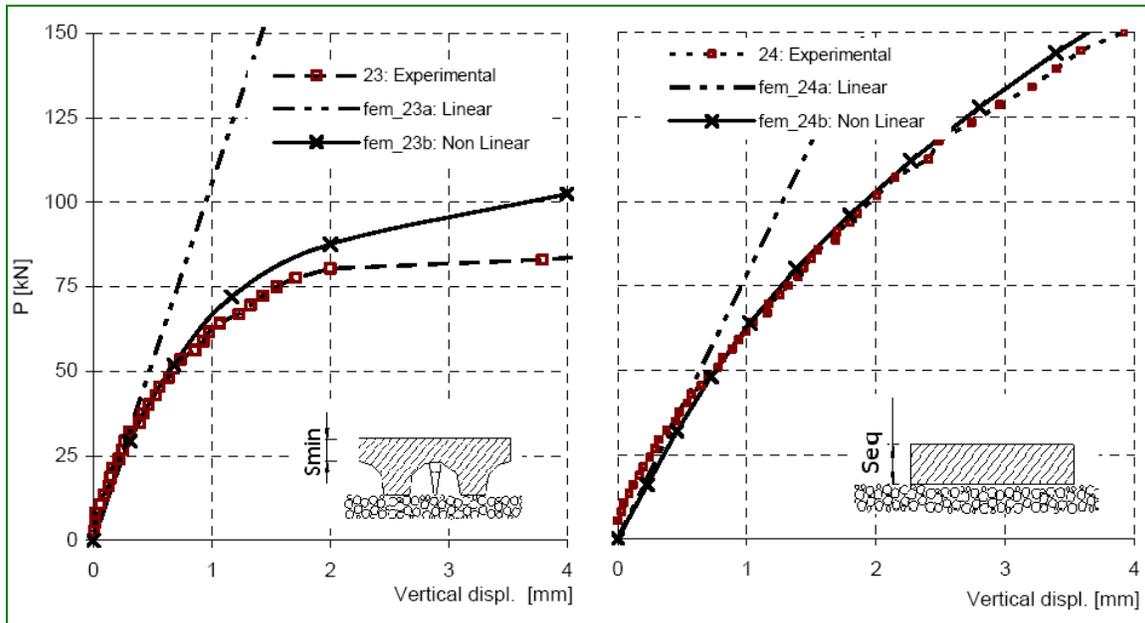


Figure 7. Load vs. vertical displacement DZ4: PDSE (left) full slab 7.5 cm thick (right)

Features to note are:

- The initial response of PDSF slab is stiffer than the one given by the full slab, almost up to $P_{\min}=30$ kN, which may represent a possible upper bound for the limit condition;
- A fully plastic behavior is observed for PDSF slab above $P=80$ kN, whereas the complete final rupture by punching occurs at $P=160$ kN for the classical full slab solution;
- Beyond $P_{\min}=30$ kN, the concrete plasticization begins to occur: this load, divided by a concrete safety factor, may therefore represent an upper load in service condition.
- The finite element analyses carried out with the non linear material models seem to describe properly the experimental results for both PDSF and classical slab;

Below $P_{\min}=30$ kN, the overall behavior of the classical full slab on the gravel layer can be considered totally equivalent to the PDSF slab, which can be therefore easily modeled with 2D shell elements interacting with the soil characterized by non linear springs.

Comparing the results obtained from 3D analyses with the equivalent 2D approach it is possible to propose the following equivalence between the minimum thickness s_{min} of the concrete slab casted above PDSF elements and the thickness of the classical full slab s_{eq} .

$$s_{eq} = f(k, s_{min}) \cdot s_{min} \quad (1)$$

The homogenization ratio f depends on the shape of the plastic dome element, on the soil stiffness and on the minimum thickness s_{min} of the above casted concrete.

Function (1) provides values always above the unity, whereas the limit $f=1$ is reached by increasing significantly s_{min} . The major advantages of using PDSF, due to their particular dome shape, are obtained with thickness s_{min} in the range 40÷80 mm, beyond which the dome effect decreases significantly towards a mechanical behavior typical of the full slab with $s=s_{min}$.

The stiffness equivalence holds only within the concrete linear response that is for $P < P_{min}$ and the results of the above analysis may be applied to other cases only if the above hypothesis is satisfied. Figure 8 illustrates the trend of f as a function of s_{min} for both sub-grades S1 and S2, in the case of stiffness $k_{S1} = 80 \text{ N/cm}^3$ and $k_{S2} = 200 \text{ N/cm}^3$ (referred to the standard 30 cm diameter plate).

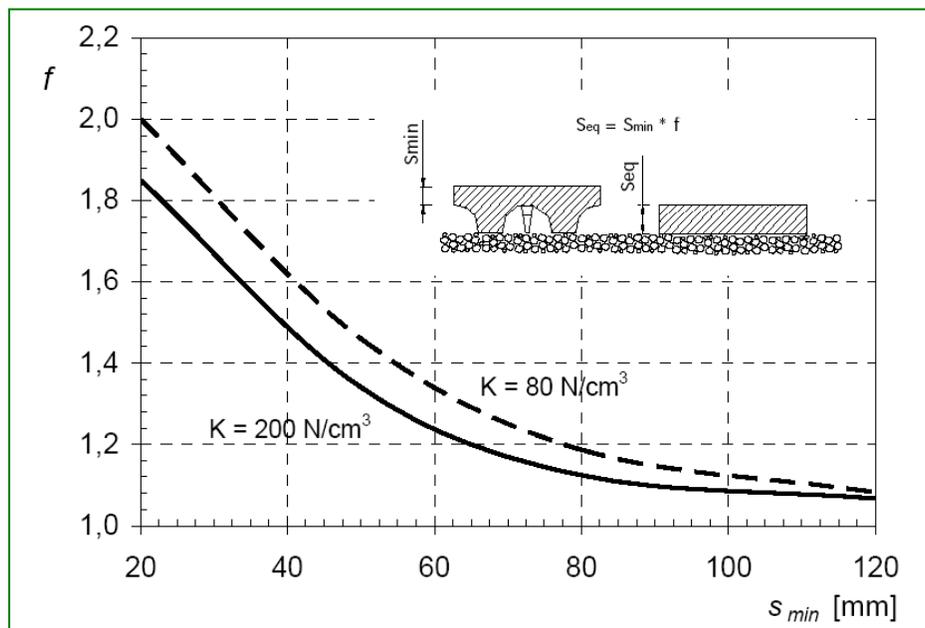


Figure 8. Equivalent thickness ratio vs. minimum thickness of the PDSE slab.

The influence of different soil condition has been considered by analyzing the results of two typical experimental tests and modeled with the finite element method. A typical case of a DPSF slab with total height equal to 340 mm (260 mm plastic dome shaped elements plus 80 mm casted under reinforced concrete) was studied using the 2D approach with an equivalent thickness $t_{eq} = 80 \cdot f = 96$ mm. Material models are linear elastic for concrete and non linear hyperbolic for both sub-grade S1 and S2.

Figure 9 compares the results of experimental tests and numerical analyses. It is interesting to note that, up to loads $P \approx 75$ kN, the numerical results fit rather well the experimental data even though only the soil non linearity is taken into account. In other words, the simplified 2D analysis with non linear hyperbolic sub-grade seems able to describe the overall DPSF slab response up to relatively large loads, exceeding serviceability condition.

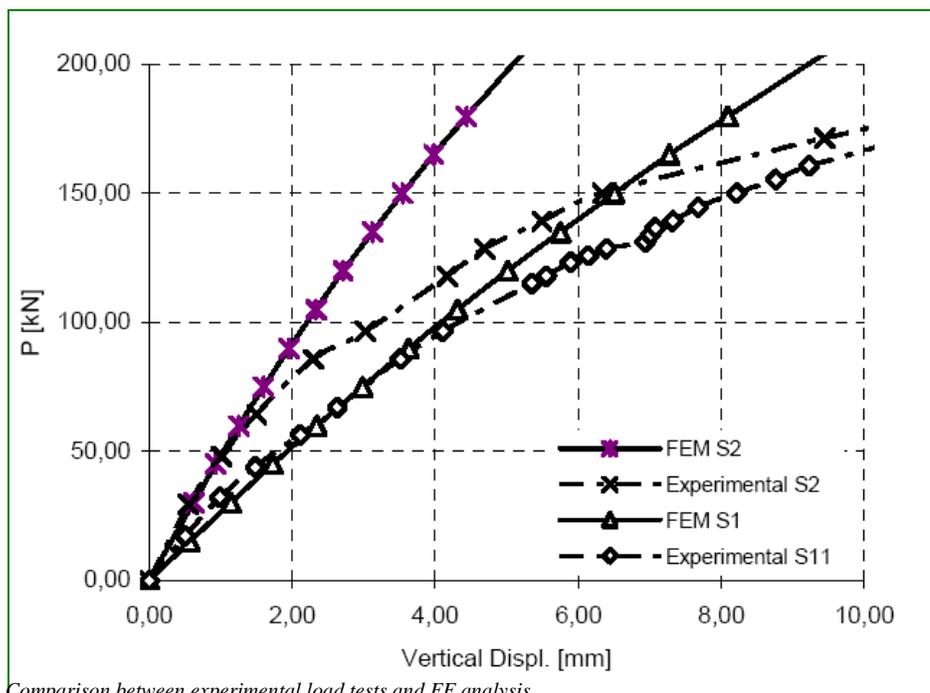


Figure 9. Comparison between experimental load tests and FE analysis.

The effect of soil type is clearly evident: the gravel layer provides a relatively stiffer response with respect to the natural silty sand. However, it is important to note that the maximum vertical displacement at the centre of the slab is in both cases very small and, within loads of $P=40$ kN, does exceeding 2 mm. The stiffness of the DPSF system reduces, in fact, the influence of sub-grade type on the overall response, thus allowing for the direct installation of DPSF on the compacted natural ground (no gravel layer interposition), when the sub-grade condition are not excessively poor. In this latter

situation, possible introduction of welded wire fabric may increase the slab stiffness as a compensation of reduction of sub-grade properties.

3. Conclusions

The effectiveness of DPSF system as alternative technique to realize industrial pavement has been evaluated through a full scale experimental investigation. A finite element approach to describe the overall pavement behavior has then been used to model the experimental results. On the basis of the experimental research and numerical analysis carried out so far, the following main conclusions can be drawn:

- The model tests provided relevant information on the mechanical response of the PDSF slabs as function of soil conditions, type of dome-shaped plastic element and thickness/reinforcement;
- The soil response was measured through plate load tests, whose results have been interpreted and modeled using an hyperbolic load-displacement model, implemented in the finite element model;
- Within serviceability condition, the DPSF system showed a stiffness comparable to that provide by the classical full slab posed on a granular interface layer;
- The PDSF slab behavior is characterized by a punching failure mechanism of the concrete slab whereas classical full slab shows a continuous hardening up to larger loads;
- 3D finite element elasto-plastic finite element analysis, calibrated on the results of experimental test results, was capable to properly model the soil-dome shaped slab interaction, even approaching the failure condition;
- On the basis experimental test results and of the 3D finite element analysis, a simpler and quicker 2D finite element approach has been evaluated, by introducing an equivalent thickness to reproduce the response of the complex dome shaped slab;
- Within loads in serviceability condition, the simple 2D analysis coupled with non linear springs seems to be able to describe the PDSF slab behavior and can be proposed as simple and economical method for the design of this type of pavement.
- The effect of sub-grade stiffness seemed to play not a relevant role in serviceability condition for this type of pavement, that is, if natural sub-grade not excessively poor, the PDSF elements can be posed directly on to the compacted natural soil, thus saving the interposition of the granular layer.

4. References

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