CONTRIBUTION TO THE RATIONAL CALCULATION OF THE BLOCK PAVING SYSTEM

Bruna Festa
Pietro Giannattasio
Mariano Pernetti
Department of Transportation Engineering,
University of Naples, Italy

SUMMARY

A rational calculation method of the block paving system is proposed, based on a procedure which considers the surface course the way it actually is: a set of single elements connected to each other by sand joints.
The main difficulties to this approach are the choice of an appropriate model of the set block-joints and the characterization of the joints, keeping in mind that their connecting action strongly depends upon the horizontal stress caused by both the compaction and the passages of the vehicles. A way to overcome these difficulties is shown in this study where an appropriate mesh of elements has been used, considering the blocks as parallelepipeds endowed with a linear elasticity, and the joints as elements having bending and shearing stiffness.
The lower layers have been visualized in the same way as for the other type of pavements.
The knowledge of the stiffness of the elements that represent the joints being fundamental for this method of calculus, a specific investigation has been carried out in the Research Laboratory of the Transportation Engineering Department of Naples University. It has been evaluated, for two types of blocks, the stiffness as well as its way to change in function of the lateral pressure between the blocks.

1 - INTRODUCTION

in any phenomenon study there is always a moment when we try to set up a model of rational calculation. This happens due to the appreciable advantages that derive from the use of this model that allows to be independent from the full scale experimentation which, as wide as it can be, does not cover all the possithe situations.

The surface layer block paving system is made up by a set of elements with a very high stiffness locked with sand joints that are far less stiff. This is the reason why it’s not easy to consider properly this layer in the mechanistic design methods. Many researchers in the past have considered it

as an homogeneous and isotropic layer and have used the elastic multilayer elastic theory. This process owns a proper validity as first approach, but it absolutely can't represent an arrival point. As a matter of fact the layer, because of its constitution, can't absolutely be considered homogeneous and isotropic. Anyhow another weakness of this method is the fact that it still keeps a strong link with the "in situ" tests, which constitute the only valid means to determine the equivalent modulus of the layer.

The best way to proceed is to use those calculation methods that respect the real paving morphology and to model it in the most concrete way possible, without using too simple schemes. Furthermore this approach allows to operate using only data obtained from laboratory experimental tests.

By the Transport Engineering Department of the University of Naples we are working towards a complete realization of this program. Our goals are:

a) to find a structural model which is enough faithful to realty and, at the same time, usable with any medium capacity personal computer;

b) to perform a simple laboratory test to determine some characteristic parameters of the model.

2 - METHODOLOGY

The "finite elements method" is the one which better takes ac count of the real morphology of the block paving system. In fact this method considers the structure "divided" in a fini te number of elements connected among themselves.
Usually the elements used for modeling the structure are the parallelepipeds with 8 nodes , one in each vertex, only in one layer they are substituted by a truncated pyramid elements, al ways with 8 nodes, and pyramid elements.

About the materials, we assume that they are homogeneous, ela stic and resistant to compression and traction stresses. We ma ke also the assumption of isotropy except for some fictitious layers, which we will deal with later.
The hypothesis of resistance to tensile stress of the sand joints may have its reason in the selfloking that as we know is a kind of prestress.Concerning the subgrade and no bound mate rial layers this hypothesis is generally accepted due to interloking of the aggregates and the possible cohesion. Otherwise differents methods will be needed that, while keeping the structural proposed modelation, take care of the lack of the tensile resistance.In this case we will need to use high capa city computers.

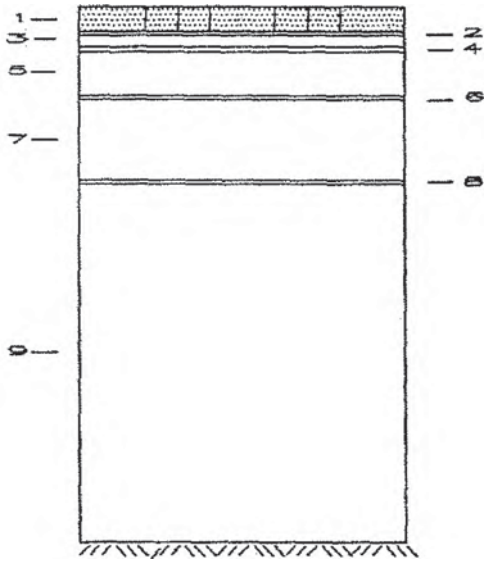
The link between the stress vector and strain vector is gi ven by the following matrix where appear the elastic modulus E, the Poisson ratio μ and the shear modulus G.

$$
\begin{bmatrix}
1/E_x - \mu/E_y & & 0 & 0 & 0 \\
1/E_y & - \mu/E_z & 0 & 0 & 0 \\
 & 1/E_z & 0 & 0 & 0 \\
 & & 1/G & 0 & 0 \\
\text{symmetric} & & & 1/G & 0 \\
 & & & & 1/G
\end{bmatrix}
$$

3. - SCHEMATIZATION

We hypothesize that the set structure-subgrade is made up by 9 layer of finite dimension, (fig. 1) :

- the surface layer,
- a fictitious connecting layer between the surface layer and the sand bed below,
- the sand, bed,
- a fictitious connecting layer between the sand bed and the road base if it exists,
- the road base (if it exists),
- a fictitious connecting layer between the upper layer and the subbase,
- the subbase layer,
- a fictitious connecting layer between the subbase and the subgrade,
- the subgrade.



1	surface layer
2	first ficticius connecting layer
3	sand bed
4	second ficticius connecting layer
5	road base
6	third ficticius connecting layer
7	sub base
8	fourth ficticius connecting layer
9	subgrade

fig. 1 - Section of set structure-subgrade

The function of the connecting layers is to simulate the non perfect adherence between the real layers.

Special attention is needed for the schemata.nation of the surface and the connecting layer below, as we will observe later.

The horizontal extension of the pavements to be analyzed and the number of elements for each layer division depends on the capacity of your computer. The choice of the restraints is influenced by the load position: far from the edge of the paving or near them etc. Here we can only state that having considered the subgrade of finite deepness the displacements of the subgrade bottom will be zero.

3.1 - Surface layer

The blocks are generally disposed in a herring-bone pattern (see fig.2). This type of disposition, besides being the most common, gives the best diffusion of the actions transmitted by the vehicles.

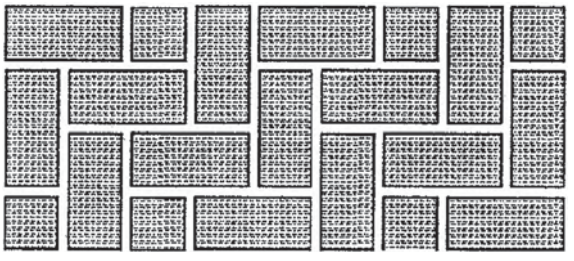


fig.2 - Surface layer

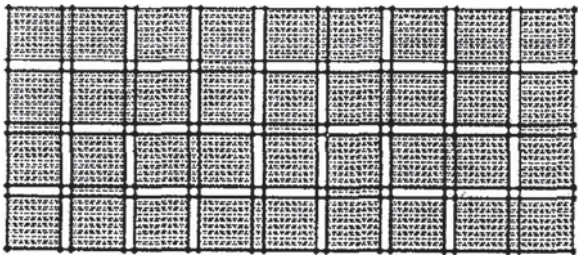


fig.3 - Scheme of the block-joint set

The scheme of the blocks-joints set is done in fig.3. As you can see each block is divided in three elements, one of these is very thin; each sand joint, instead, is made up by only one rectangular element located between other two very small square elements. The number of nodes that comes out is quiet

high. In the case of load placed far from the edges of the pavements, and if you consider a model almost 2,5x2,5 m with the blocks 11.1x22.5 cm located 0,3 cm from each other, you need 2*2116 nodes and 1936 elements only for the surface layer (considering the thickness of the elements equal to the thickness of the layer). The number of nodes and elements decreases to 2*529 and 484 respectively if you accept the hypothesis of the double symmetry. A problem in this type of scheme is the input phase of the elements. Although this can be overcame doing an automatic generation program in which you have to remember that the elements present two types of recurrent dispositions (see fig.3):

a) each row of elements having the same wideness of the blocks is composed of a "block" alternated with a "sand" element, but every 4 repetition the "sand" becomes a "block" element;

b) each row of elements having the same thickness of the joint is made up by a repetition of seven "sand" elements and one "block element".

In order to simplify the analysis we suppose the blocks as parallelepipeds with a rectangular base. This hypothesis can be always valid if the data, used for the characterization of the joints, came from a type of test, of which we will talk later, that is able to estimate the global characteristics of the joints.

The material of the blocks is characterized by the elastic modulus E and by the Poisson ratio /x, identical in every direction. The shear modulus G is then given by the formula:

$$G = \frac{E}{2^* (1+\mu)}$$

The material of the sand joints is also characterized by E, μ and G, identical in every direction, where G should be eva luated with a test like the one we will describe later.

3.2 - I° connecting layer

The structure layers are laid one upon the other without any care to obtain a strong shear connection, the only resistance being the friction. As a result there will be some slidings under load. In order to take account of it in the calcula tion, without having great complications, you have to inter pose a thin fictitious layer which creates an elastic con nection between the layers.

The connecting layers mechanical characteristics have to be ca refully examined because they don’t have to present any structural contribution, except for the connection and absolu tely they can’t be a weak element. So we must give very low values, theoricaly null, to the elastic modulus in the horizon tal direction; on the contrary we should give very high value

to the vertical elastic modulus. The first expedient gets a bending stiffness practically null for these layers. With the second expedient we are sure that the connecting layers are not soft. The value G depends from the thickness given to the layers and from the "elastic" adherence hypothesized bet ween them. Given an adherence K (expressed as shear stress/mutual displacements) and a contact area A between the layers, in order to have an horizontal mutual displacement δ, fig.4, we need a force T given by :

$$T = K * A * \delta$$



fig.4 - Displacement between two superimposed layers

On a parallelepiped element with a base area A and a thickness S sufficiently thin, the force which produces the displacement δ between the two bases, fig.5:

$$T = \frac{\delta}{S} * G *$$

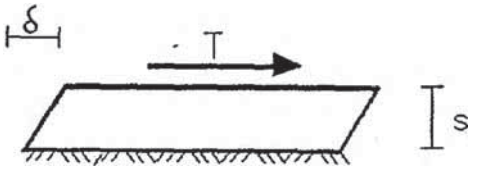


fig.5 - Thin parallelepiped displacement

From the two formulas we have:

$$G = K * S$$

When no particular problem arises and the calculation program allows it, we suggest to make equal the vertical displacements of the nodes of each single connecting layer, placed on the same vertical line, in this way you can reduce the number of the unknows (nodes displacements) and, as a consequence, reduce the number of equilibrium equations to resolve: for each couple of nodes placed on the same vertical line, instead of 6 equations there will be 5. In this case the elastic modulus in the vertical direction of the connecting layer becomes practically uninfluential.

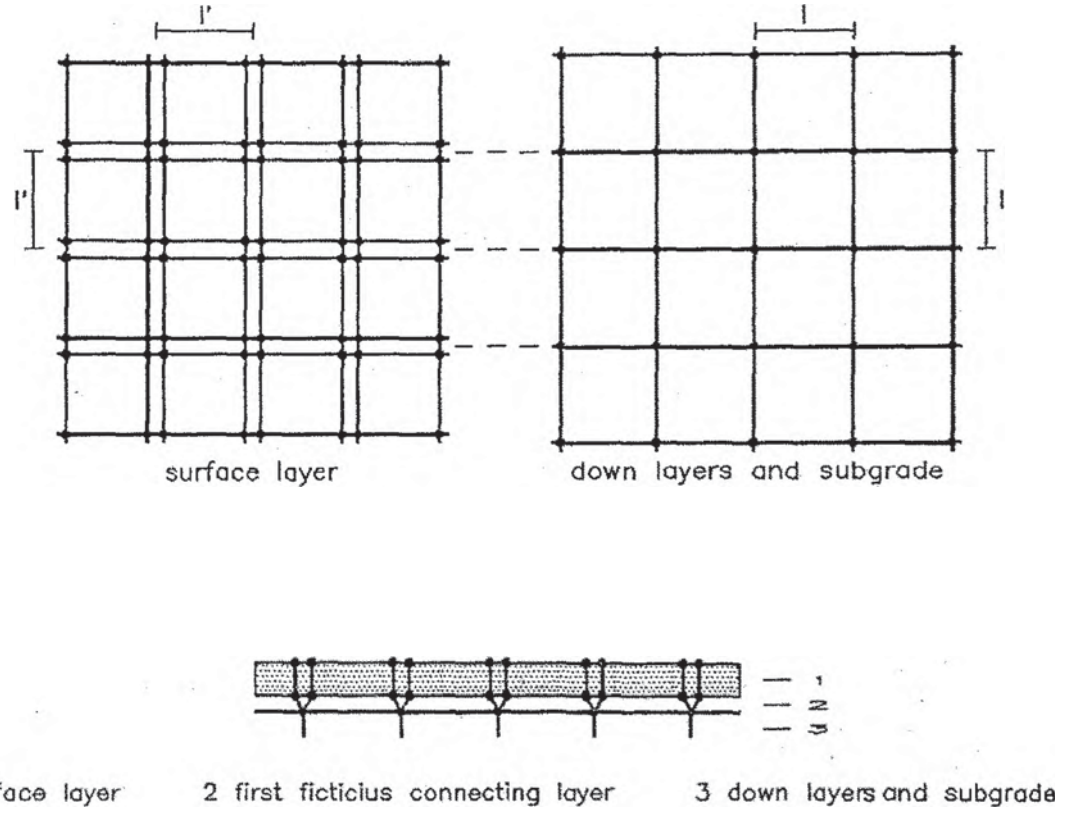


fig. 6 - change of schematization from surface to down layers and subgrade

The first connecting layer not only allows to connect the surface layer and the sand bed, as mentioned before, but also to pass from the schematization used in the surfaces to a simpler one valid for all the lower layer and subgrade (see fig.6). This expedient helps to reduce the problem remarkably. For example for a model 2.5x2.5 m wide with blocks 11.1x22.5 cm and sand joints width 0.3 cm instead of 1936 elements we needs only 576 for each layer (considering the thickness of the elements equal to the thickness of the layers). The elements needed to allow the passage from one schema to the other, are the truncated pyramid and the pyramid, both at a square base(fig.6). If the calculation program we dispose of does not use the pyra-

mid elements we can refer only to the first ones considering as not existing the second ones. This approximation will not influence the problem considerably, because it decreases only slightly the structural power of this layer which is already scarce. Of corse for this connecting layer it is not possible to apply the suggestion previously given to make equal the vertical displacements of the nodes belonging to the same vertical .

3.3 - Sand layer, base layer, and subbase layer

All these layers have been schematized as an assembling of parallelepipeds at a square base in elastic, homogeneous and isotropic material. Therefore there are characterized by the elastic modulus E and by the Poisson ratio.

If the road base is a bituminous mix we should refer to the complex modulus and to the complex Poisson ratio considering that the loads are generally dynamic and the material is viscoelastic.

If the road base is cement-treated we have to choose a reduced value for the elastic modulus because the layer is generally cracked. Neglecting the subdivision in elements depending from cracking we can simply refer, as it is usual for semirigid pavements, to a reduced elastic modulus.

For the bituminous mix it is not possible to give any indication as the modulus depends on the temperature, on the contrary for cement-treated material we can say roughly that the modulus varies from 4.000 to 7.000 MPa.

For the sand layer and subbase layer, when the load is dynamic, we should refer to the resilient modulus.

3.4 - 11°, III° and IV° connecting layers

To deal with these layers we can state anything that was already said for the 1st connecting layer with these exceptions:
1) the elements here have a parallelepiped shape;
2) for these layers it is possible to apply the suggestion to make equal the vertical displacement of the nodes belonging to the same vertical.

Going from the 1st to the 2nd connecting layer and so on, the G modulus is higher since the friction between the paving layers increases.

3.5 - Subgrade

The subgrade is considered of finite dimensions leant on a rigid plane. Its thickness should be calculated according to the depth where the stress produced by the vehicles is practically null. If the load is placed far from the paving side edges this thickness can be considered equal to double of the diameter of

the charged area on the top of the subgrade. The number of the elements to considerate along a vertical line derives from the approximation degree that we would like to reach in the evaluation of the permanent deflection and from the capacity of the computer available.

Also here the elements are parallelepipeds at square base in elastic, homogeneous, and isotropic material; therefore characterized by elastic modulus ("resilient modulus" in the presence of dynamic loads) and by the Poisson ratio.

4 - USE OF THE CALCULATION RESULTS

The stress and deformation state obtained with the described rational calculation helps to verify pavements considering the most important elements that modify its duration: the deflection that appear on the surface.

The verification consists in the estimation of the permanent surface deflection that occurs during the design life and afterwards to compare it with the maximum limits compatible with the water drainage and with the effectiveness of the surface (roads, parking lots, areas of storage, etc.). The estimation is made dividing the pavement and the subgrade in different layers in which the stress may be considered almost uniform and summing the permanent shortenings that are produced in each of them. These shortenings, based on the results of cyclic laboratory tests on samples, depend from the materials characteristics, the stress and the number of vehicles expected during the design life.

In presence of the bituminous mix layer the stress calculation, due to the high sensitivity of the elastic modulus to the temperature, has to be repeated for all the different climates periods in which the year may be divided.

A more sophisticated calculation of the permanent deflection should take care that the stress state varies with the increasing degradation of the bound material layer, whether it is in bituminous mix or in cement-treated material.

Besides what we have already said, the knowledge of the stress state gives the possibility to understand the needed intensity for the self locking (which we can influence through the compaction) so that the surface layer has its own load bearing capacity. The action of prestress caused by the self locking should succeed in eliminating nearly all the tensile bending stress caused by the vehicles transit. In case this not happen the sand joints, that are not resistant to tensile stress, will not be able to assure an effective transmission of the forces between the blocks.

5 - EXPERIMENTAL PROGRAM

The aim of the experimental program was to determine the parameters of the various elements of the pavement (modulus of

blocks, joints, etc.) as input data required from the proposed design method.

Materials

We tested two types of concrete blocks among those mainly used (fig. 7) and a limestone sand with appropriate grading (fig. 8) as joints.

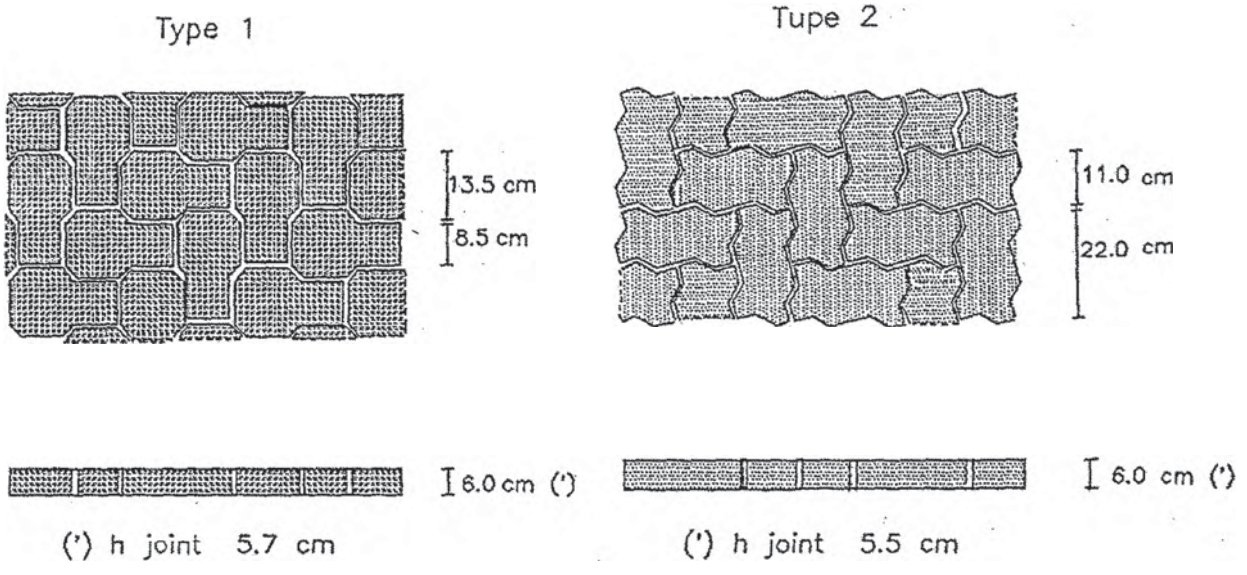


fig.7 - Types of blocks used in the experimentation

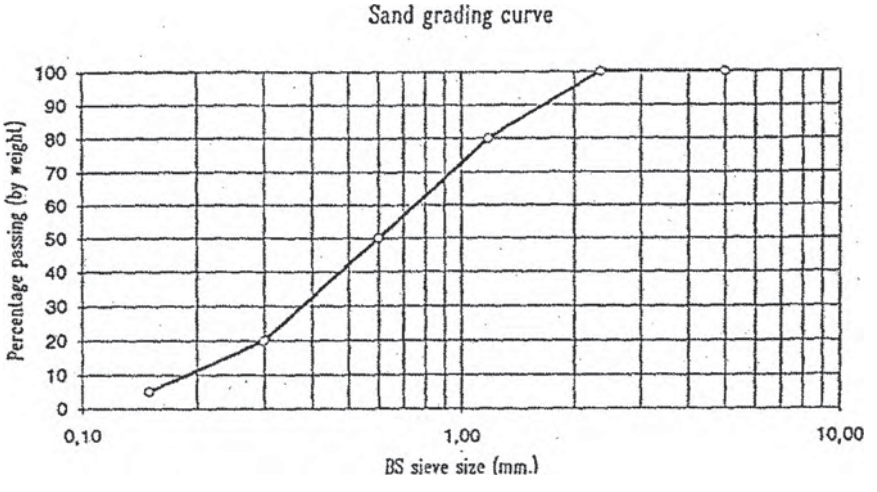


fig.8 - Grading curve of the sand joints

Apparatus

Hydraulic jack able to produce 55000 N
Servohidraulic testing system able to control the speed of the load appliance and hold it.
Small device studied to contain a pavement sample and able to pass on the horizontal load produced by the jack, made up by a steel frame (fig. 9).
Tensotast with a sensibility of 0.001 mm.

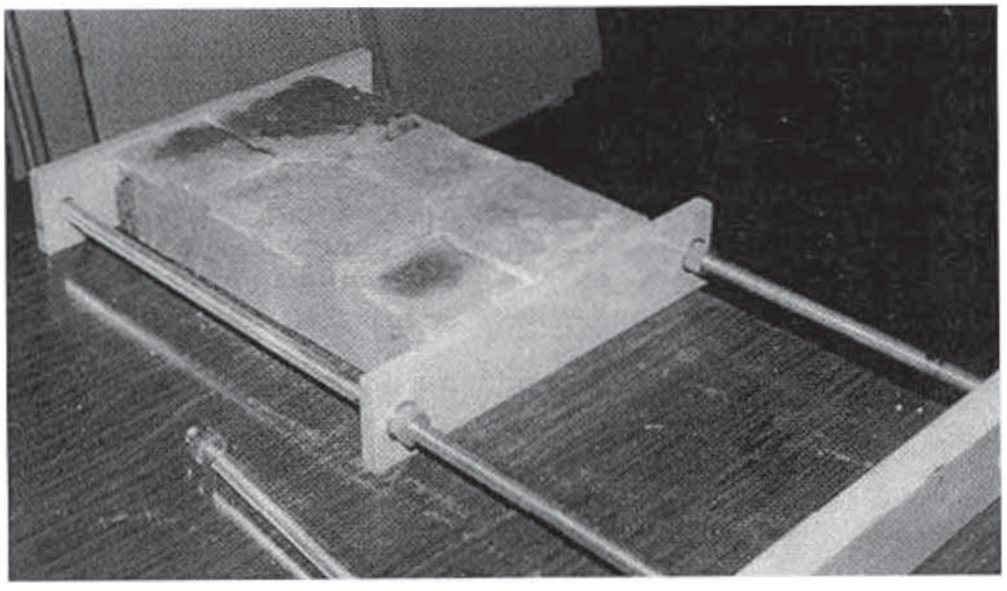


fig.9 - Pavement sample in the stell frame

Procedure

a) Evaluation of the blocks characteristics
For the two types of blocks we made a loading test. From the relationship stress-strain we obtained the modulus of elasticity, together with the strength a.

type	E MPa	σ MPa
1	53000	53,3
2	22000	24,2

b) Evaluation of the joints characteristics
In order to measure the sand joints elastic modulus E we placed two blocks in the steel frame and we put carefully the sand between the blocks until we obtained the joints width of about 3 mm. We loaded the frame with the jack and read the strain

with the tensotast. In the fig.10 is showed a diagram a,e. The value of E=σ/ε secant modulus as a function of a is represented in fig. 11

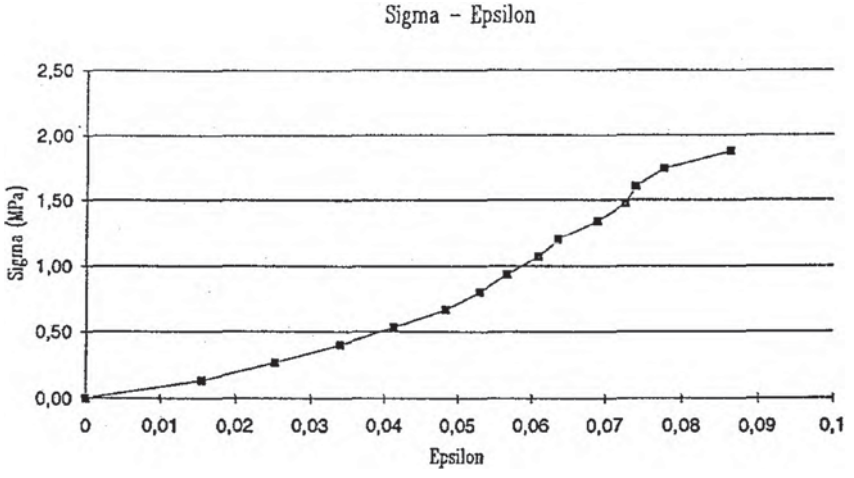


fig.10 - Diagram σ-ε for the sand joint (block type 1)

For measuring the modulus G, we rebuilt, instead, with the help of the steel frame, a paving element (for each type of block), which contains two sand joints. Then we placed the assembled frame, with the sand and the blocks, between the universal testing apparatus' plates. While the sides of the frame were charged we loaded the central block with a load increasing, at a speed of 100 N/s, up 5000 N (fig.12).

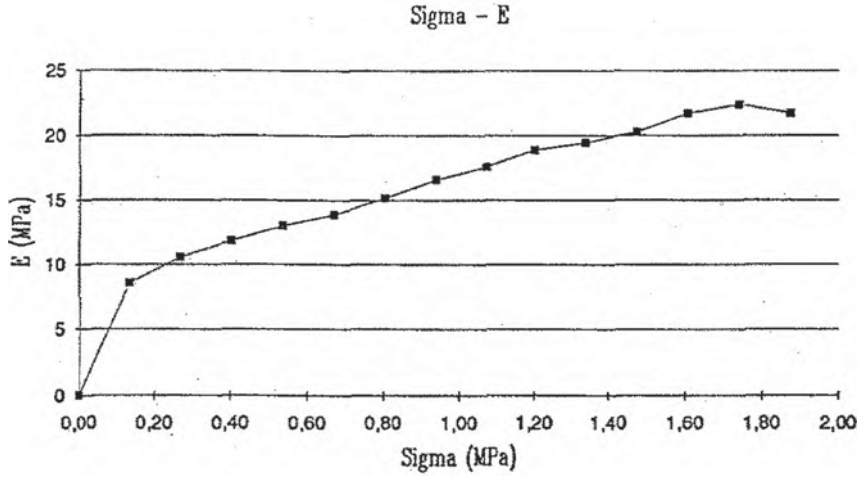


fig.11 - diagram σ-ε of the sand joint (block type 1)

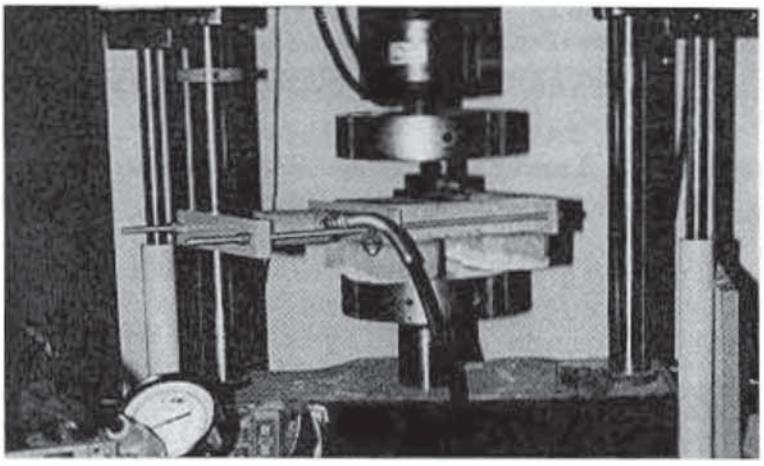


fig.12 - Apparatus during the test

The stress (τ) transmitted from the blocks to the joints crea tes a displacement δ and a shearing strain = δ/s (where s is the thickness of the joint). In fig.13 is showed a one of the diagrams τ, γ for a given horizontal stress a. The constant G = τ/γ was calculated using the restituted shearing strain .

In the tab.1 beneath are shown the G values for each block type for various values of the a.

Tab.1 - G values for various values of the σ

type 1		type 2	
σ (MPa)	G (MPa)	σ (MPa)	G (MPa)
0,13	4,7	0,33	6,5
0,27	5,2	0,44	7,9
0,40	5,8	0,55	9,8
0,54	7.3	0,66	11,7
0,71	8,9	0,77	13,6
0,80	10,4	0,87	15,5
0,94	12,1		

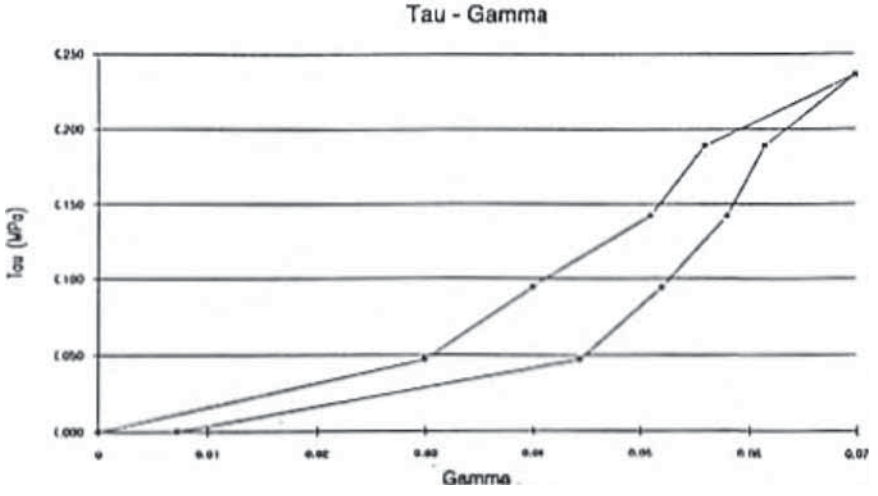


fig.13 - Diagram for τ-γ a given horizontal stress of the sand joints (block type 1 and σ=0.4O2 MPa)

For a values more than 0,7 MPa the behavior of the sand joint was fully elastic.

The failure shear stress for the type 1, evaluated at σ=0,938 MPa was found to be τ =1,23 MPa

6 - CONCLUSIONS

The finite elements method and the schematization realized modeling quite faithfully the surface layer and dividing the complex pavement-subgrade in 9 layers, of which 4 are fictitious, allow to learn, with the aid of an average capacity computer, the stress and deformation state of each point of the structure. The availability of this cognitive instrument is very useful whether for practical or theorical purposes.

The input parameters of the proposed model concerning the sand joints are obtained from easy laboratory tests set up on purpose by the Department of Transportation Engineering of the University of Naples. They take care of the total joint characteristics including the shape and the roughness of the side surfaces of the blocks.

2 - REFERENCES

[1] TIMOSHENKO S., GOODIER J.N., - Theory of elasticity - McGraw Hill Book Company, 1951

[2] ZIENKIEWICZ O.C. - The Finite Element Method - McGraw Hill Publishing Company Limited, 1967

[3] FRANCIOSI V. - Scienza delle costruzioni - Liguori, 1985

[4] PER ULLIDTZ - Pavement analysis - Elsevier, 1987

[5] WATSON J. - Higway construction & maintenance - Longman Scientific & technical, 1989

[6] BARKSDALE R.D, - Laboratory evaluation of rutting in base course material - 3rd Int. Conf, on the design of asphalt pavements, London 1972

[7] MONISMITH C.L., OGAWA N., FREEME C.R. - Permanent deformation characteristics of subgrade soil due to repeated loading - Transport Research Record 537

[8] SYSTEM CONCRETE S.p.A - Guida alle pavimentazioni autobloccanti in calcestruzzo tipo "Concretelie" - S.Pier D'Isonzo (GO), Italy

[9] LIVNEH M., ISHAI I., NESICHI S. - Development of a pavement design methodology for concrete block pavement in ISRAEL - 3rd International Conference on Concrete Block Paving, Roma 1988

[10] HOUBEN L.J.M, JACOBS M.M.J - Wheel track testing and finite element analysys of concrete block pavements - 3rd International Conference on Concrete Block Paving, Roma 1983

[11] KASAHARA A. - Estimation of apparent elastic modulus of concrete bloclk layer - 3rd International Conference on Concrete Block Paving, Roma 1988

[12] HOUBEN L.J.M. and others - The dutch design method for concrete block road pavements - 3rd International Conference on Concrete Block Paving, Roma 1988

[13] HOUBEN L.J.M., VAN VER VLIST A.A. - The design concrete block pavements for urban roads - 6th International Symposium on Concrete Roads, Madrid 1990

[14] RADA G.R., MILLER J.S., WITCZAK M.W. - Structural design of concrete block pavements - Journal of transportation engineering, 1991