# LOAD BEARING BEHAVIOUR OF SETT PAVINGS

**Frohmut Wellner**
**Scientific Worker, Dresden, Germany**

## Summary

In order to determine the load bearing performance of sett paving constructions plate-bearing tests were carried out at a test stand of the Dresden University of Technology, Department of Civil Engineering, with a base surface of 3 * 10 $m^2$. There, the nonlinear elastic strain behaviour of the unstabilised structural courses located under the sett paving could be observed and separated from the behaviour of the sett paving by means of a test procedure modified in comparison to the conventional method. For an evaluation of these tests the course theory basing on the BOUSSINESQ half-space theory was used, with the modulus of elasticity of unstabilised road bases or foundations was applied in dependence on the effective stress. The present investigations provide fundamentals for an estimation of the load bearing behaviour of sett pavings using profound scientific findings. Both theoretical considerations and experimental investigations indicate that the load bearing behaviour of sett pavings is mainly determined by the foundation and road bases. The sett paving will hardly influence the total load bearing capacity of a construction. This does not mean that sett paving is without any importance for strain resistance during the service life of a road.

The load bearing effect found to be low bases on a certain transmission of shear forces from block to block by friction in the joints. Mathematically, this behaviour can be determined by constant course modulus. This was found out to be independent of the strain of the sett paving as well as of the shape (interlocking, rectangular blocks) and thickness of blocks (6, 8, 10 cm). The horizontal bond of the sett paving has hardly any impact on the load bearing capacity under vertical load. Likewise, the lateral restraint between the kerbs is not relevant.

## 1. Preliminary remarks

In Germany, sett pavings (small sett pavement) in the today's form were first used by GRAVENHORST in 1885. Up to now, it has proved effective even for heavy transport. A condition for this is a high wear resistance of the blocks as well as a sufficient bearing capacity of the overall construction. The first men’tiohed demand is met if adequate materials (such as granite, concrete with a compressive strength of > about 550 $N/mm^2$) are used. These building materials display a high resistance to climatic and transport impacts. The latter mentioned requires dimensioning of sett paving constructions. For this purpose it is required to define the input parameters of the calculation - modulus of elasticity (E-modulus) and possibly Poisson's ratio.

At the Dresden University of Technology, Department of Civil Engineering, investigations of sett paving constructions were conducted. At the test stand of the TU Dresden strain moduli were determined at various pavements by conventional plate bearing tests II], and on this basis a course modulus could be calculated by means of well-known layer theories basing on the theory of elasticity. The results profoundly documented are avialable (2,3), but they are not the subject of this paper.

The necessity of continuing investigations resulted from the following reasons: Unstabilised road construction materials display a nonlinear elastic behaviour (stress dependent strain characteristics, non-homogeneity). This fact is of particular significance, as sett paving courses are of very low thicknesses (6, 8, 10 cm) and in general base on unstabiliaed courses or constructions. With the evaluation of experimental investigations (plate-bearing tests) essential errors can occur due to neglection of these properties. Therefore , a calculation method was developed basing on the BOUSSINESQ half space theory, which takes the peculiarities of unstabilised road construction materials sufficiently into account [4]. However, this model in turn requires homogeneity of courses, i.e. strain characteristics apply to the entire course and thus they can only be calculated vertically according to the stress distribution or the material the course consists of. Even the sett paving course itself is actually inhomogeneous. However, with regard to the low course thickness and conse quently the weak impact to be expected of the overall load bearing capacity of the construction the simplified assumption of course homogeneity seems to be admissible. Test results have, to be discussed in terms of these problems. The applica tion of the finite element method to a simulation of block and joints will certainly not be reasonable, as the computing ef fort is in a poor relation compared to the accuracy degree to be expected.

One of the most important goals of the investigations was the description of the stress-strain behaviour of sett pavings and constructions in order to improve understanding of processes occurring with the level of traffic. Thus, a reasonable use of sett paving constructions is envisaged to avoid damages due to lacking load bearing capacity, as they had always and again happened in the past years.

## 2. Theoretical fundamentals

For a mathematical description of the nonlinear material beha viour of unstabilised road building materials an appraoch was required basing on metal-cutting mechanics. By means of consi derations at spherical models as well as with the help of HERTZ*equations on the contact of two finite bodies the fol lowing approach for the calculation of the E-raodulus was ob tained in a general from, determined by plate-bearing tests with gravel of a very good particle grading, with sandwashed crushed gravel and wet-mix macadam (2,4):

$$E = E_{0.1}\left(\frac{p}{p_{0.1}}\right)^{w} \qquad (1)$$

Moreover, the following equations are known in general form to determine the stress-strain behaviour of a two course system [1.2]:

- strain relation

$$\frac{E_H}{E_{ä}} = F_s = \frac{1}{n} * \left(\frac{E_1}{E_H}\right)^b \qquad (2)$$

- strain relation

$$\frac{\sigma_{zl,@}}{p} = \frac{\sigma_{zl}}{p} + \frac{@*g*h_1}{p} = m*\left(\delta\frac{E_1}{E_H}\right)^{-a} + \frac{@*g*h_1}{p} \qquad (3)$$

If unstabilised road building materials are used as a road base or foundation, pressure p in equation (1) has to be replaced by the effective vertical stress $\sigma_{Z1}$ in the course boundary of the two-course system. Hence, as

foundation modulus relation

$$E_H = E_{H;0.1} * \left(\frac{\sigma_{z1}}{p_{0.1}}\right)^{w_H} \qquad (1a)$$

from this the following implicit relationship between the inserted pressure and the equivalent E-modulus on the two-course system can be derived:

$$\frac{p}{p_{0.1}} = \frac{n}{m}^{\frac{a}{1-b}} * \left(\frac{Eä}{\delta E_1}\right)^{\frac{-a}{1-b}} * \left\{\left[ * \left(\frac{Eä}{\delta E_1}\right)^{\frac{1}{1-b}} * \frac{\delta E_1}{E_{H;0.1}}\right]^{\frac{1}{w_H}} - \frac{@*g*h_1}{p_{0.1}}\right\} \qquad (4)$$

| | | | |
|---|---|---|---|
| $Eä$ | - | [N/mm²] | equivalent E-modulus on the two-course system |
| $E_H$ | - | [N/mm²] | elasticity modulus effective on the foundation according to inserted stress (foundation modulus) |
| $E_{H;0.1}$ | - | [N/mm²] | foundation modulus effective at a reference stress of p = 0.1 N/mm² |
| $E_1$ | - | [N/mm²] | elasticity modulus of the course (course modulus) |
| $F_s$ | - | [ - ] | strain coefficient |
| m,n | - | [ - ] | coefficient of stress or strain relation (see table 1) |
| a,b | - | [ - ] | exponents of stress or strain relation (see table 1) |
| $\delta$ | - | [ - ] | factor for taking transverse strain into account |
| $\mu_{H/1}$ | - | [ - ] | Poisson's ratio of foundation or course |
| $\sigma_{z1}$ | - | [N/mm²] | effective vertical stress in the course boundary of the two-course system |

| | | | |
|---|---|---|---|
| p | - | [N/mm²] | inserted vertical compressive strain |
| $p_{0.1}$ | - | [N/mm²] | reference stress of p - 0.1 N/mm^ |
| $w_H$ | - | [ - ] | stress exponent |
| $h_1$ | - | [mm] | course thickness |
| @*g | - | [N/mm²] | dead weight of the course |

Because of the very low thickness of the sett paving (<10 cm) its dead weight could be neglected. Since the thickness of $h_1$ =6, 8, 10 cm for the wearing course and from experiments the relation $E_1/E_H$ = 5 ... 20 were known, exponents a and b as well as coefficients m and n could precisely be calculated on the basis of the nomograms and tables by HANK/SCRIVNER and JONES [5] as well as JELINEK/RANKE [6]. The results of these calculations are shown in table 1. Deviations between the values calculated by equation (1) - (4) and the initial values from literature turned out to be merely 2-3%, which is acceptable.

| coeffic. exponent | val. range loose load | formula | val. range rigid load | formula |
|---|---|---|---|---|
| m | $\frac{h_1}{r_0}$ = 0.4-0.7 | $0.8\,\frac{r_0}{h_1}$ | $\frac{h_1}{r_0}$ = 0.4-0.7 | 0.7 |
| n | | 1.0 | | 1.0 |
| a | | $0.41(\frac{h_1}{r_0})$ 0.7 | | $0.38(\frac{h_1}{r_0})$ 1.25 |
| b | | $0.40(\frac{h_1}{r_0})$ 1.0 | | $0.40(\frac{h_1}{r_0})$ 1.30 |

Table. 1 Coefficients m,n; exponents a,b

When two of the three elasticity moduli $E_1$, $E_{ä}$, $E_H$ included in equation (4) are known at a certain pressure level p the third value can easily be determined. As for the present investiga tion mainly the equivalent E-modulus Eä and course modulus E, are of interest the relations derived from equation (4) will be represented explicitely in the following:

$$E_{ä} = n*(\frac{mp}{p_{0.1}})^{\frac{(1-b)w_H}{1-aw_H}} *(\frac{E_{H;0.1}}{\delta E_1})^{\frac{1-b}{1-aw_H}} *\delta E_1 \qquad (5)$$

and

$$E_1 = [\frac{n^{1-aw_H}}{\delta} *(\frac{mp}{p_{0.1}})^{(1-b)w_H} * \frac{E_{H;0.1}^{1-b}}{E_{ä}^{1-aw_H}}]^{\frac{1}{aw_H-b}} \qquad (6)$$

Thus, equations relatively clearly and simply to handle are available for further calculations.

## 3. Interpretation of relationships

To illustrate the relations represented by equations (4) to (6) the relationship for wearing course thickness from 6 and 10 cm were calculated. These course thicknesses correspond to those common for concrete pavement. The results of these calculations are shown in figures 1 and 2. The following conclusions can be drawn:

1. With growing foundation modulus $E_H$, course modulus $E_1$ and growing course thickness $h_1$ the equivalent E-modulus is increasing, but to different extents for the individual parameters

2. The impact of the increase of course modulus $E_1$ on the total load-bearing capacity of the system is very low particularly with thin courses. With a wearing course thickness $h_1$ = 6 cm, a foundation modulus $E_H;0.1$ = 100 N/mm² and an assumed increase of the course modulus of $E_1$ = 500 N/mm² to 5000 N/mm² (to 100%) the equivalent E-modulus rises merely from Eg = 185 N/mm² to 225 N/mm² (to 122%) with a pressure p = 0.7 N/mm². With a wearing course thick ness of $h_1$ = 10 cm and equal initial values the equivalent E-modulus rises from Eä = 204 N/mm² to 304 N/mm² (to 149%). A tenfold increase of the course modulus will thus merely effect a growth of the total load-bearing capacity by 20... 50%.

3. The impact of an increase of the foundation, modulus $E_H;0.1$ on the total load-bearing capacity is considerably higher. With a wearing course thickness of $h_1$ = 6 cm, a course mo dulus $E_1$ = 1000 N/mm² and an increase of the foundation modulus of $E_H;0.1$ = 50 N/mm² to 100 N/mm² the equivalent E-modulus grows from Eä = 104 N/mm² to 197 N/mm² (to 189%) with a pressure of p - 0.7 N/mm² and with a wearing course thickness of $h_1$ = 10 cm from Ea = 130 N/mm² to 230 N/mm² (to 178%). The growth of the foundation modulus will also effect a rise of the equivalent E-modulus in an approxi mately equal order of magnitude.

The tenfold increase of the course modulus will therefore exert less marked effects on the total load-bearing capacity than the doubling of the foundationmodulus.

4. The calculations are a confirmation of the fact that re sults are obtained heavily deviating from each other com pared to the assumption of a constant elasticity modulus in dependence on the effective stress exponent of the founda— tion modulus $W_H$ Even for a two-course system with constant E-modulus of the course the equivalent E-modulus will be stress dependent. It varies according to the inserted pres sure p = 0.1 or 0.7 N/mm² by about 60...80 %, . (lower value for 10 cm, higher value for 6 cm wearing course thickness). This means that such a construction has less load-bearing capacity with lower load than higher load. Thus, with high load a more advantageous evaluation and consequently dimen sioning is enabled.

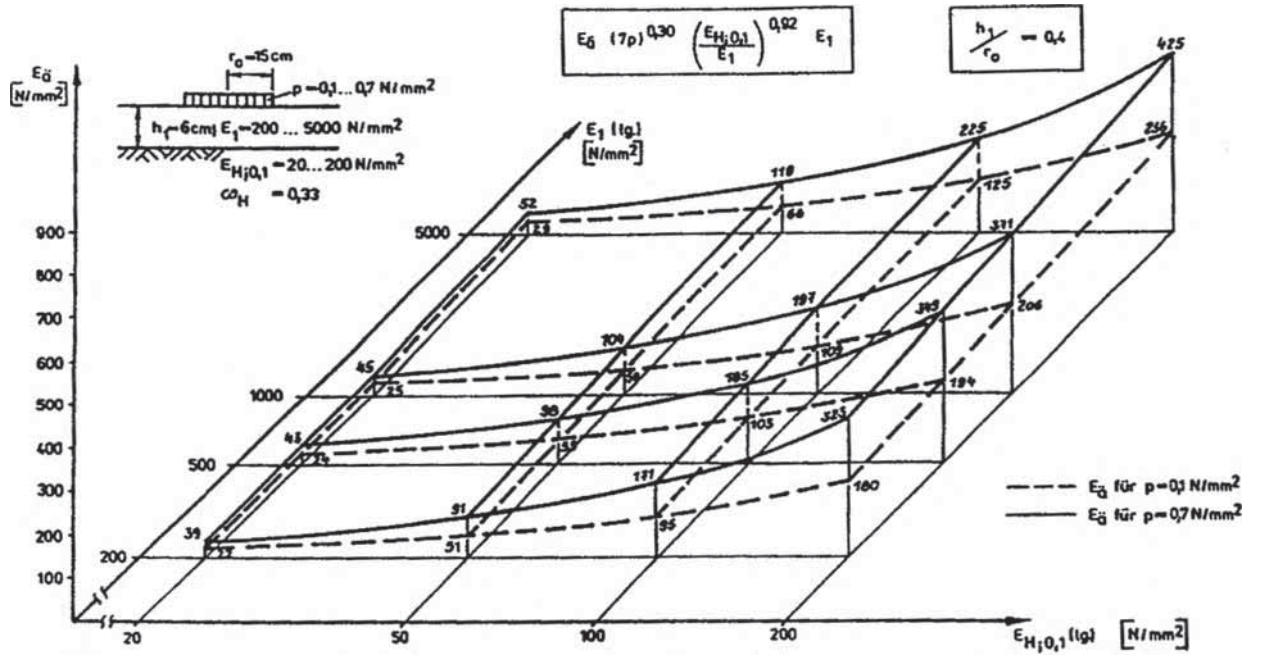



Fig. 1 Relationship between $E_H;0.1,E_1$, and Eä, course thickness 6 cm

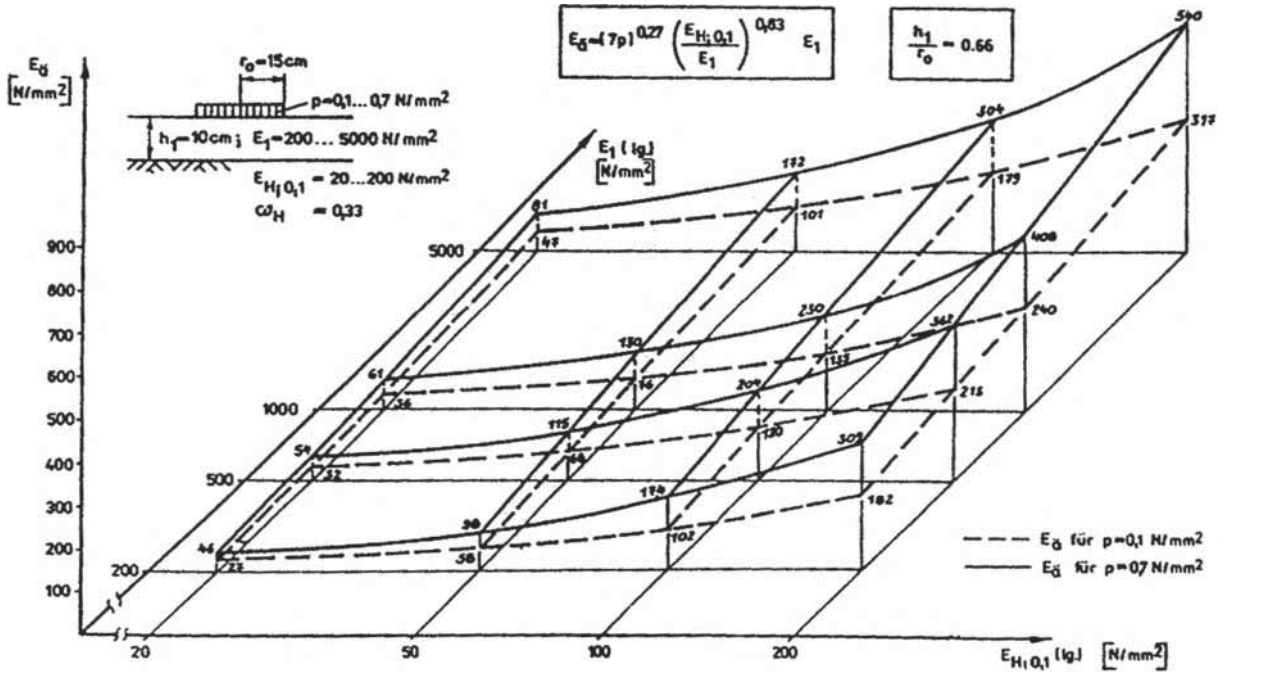



Fig. 2 Relationship between $E_H;0.1,E_1$, and Eä, course thickness 10 cm

## 4. Implementation of tests

As already mentioned, at the test stand of the Dresden Univer sity of Techniogy, Department of Civil Engineering, plate bearing tests on various concrete pavement constructions were conducted. By the conventional method of test implementation [1] the measured stress-strain function is approximated via a secant modulus, wich does not detect the nonlinear behaviour of unstabilised courses. Consequently, a modified test implementation was used (alternating load method) permitting the determination of stress dependent strain characteristics [2,3]. Furthermore, it is known that stabilised wearing cour ses built over unstabilised courses yield an increased strain resistance of the latter mentioned. It was to be expected that this effect would also occur when road bases without binders were built over in the test stand. It had to be avoided to at tribute this grown rigidness of road bases to the sett paving. Therefore, plate-bearing tests were always carried out at first on the undisturbed wearing course of sett paving. Then an opening, which was of the same size as the load plate of the plate-bearing test unit, had to be inserted into the sett paving. After this the plate-bearing test could be performed to detect the "foundation modulus" of the underlying courses or constructions, reap. Thus, an increased strain resistance due to the built-over construction could be proved. By means of the tests the equivalent modulus $E_a$ and the foundation mo dulus $E_H$ were determined, from which according to equation (6) the course modulus could be calculated.

The following constructions were investigated:

1. Wearing course of sett paving (joints filled with sand) on gravel sand foundation
2. Wearing course of sett paving (joints filled with sand) on crushed gravel road base on sand foundation
3. Wearing course sett paving (joints filled with sand) on wet-mix macadam on gravel sand foundation
4. Wearing course of sett paving (joints filled with sand) on cement stabilised soil on gravel sand foundation

For the wearing course of the. sett paving concrete blocks of 6, 8 ad 10 cm thickness were applied. Both interlocking concrete blocks of various shapes and rectangular blocks were investigated. The crushed gravel bases and the wet-mix macadam bases were 20 cm thick, the cement stabilised soil 17 cm. The thickness of the gravel sand foundation was about 1.5 cm.

Moreover, strain beside the load plate was measured. The investigations were focused on conclusions concerning the bearing capacity of various sett pavings by lateral strains. The results of these measurements are still to be discussed.

## 5. Test results, conclusions

At first the load-distributing effect of a concrete sett paving will be explained at the example of figure 3. Strains of a 6 and 10 cm thick concrete paving wearing course are plotted. As expected, the 10 cm thick course displays a better load distribution. On the one hand, this is to be seen by the more even position of the first, still loaded block beside the

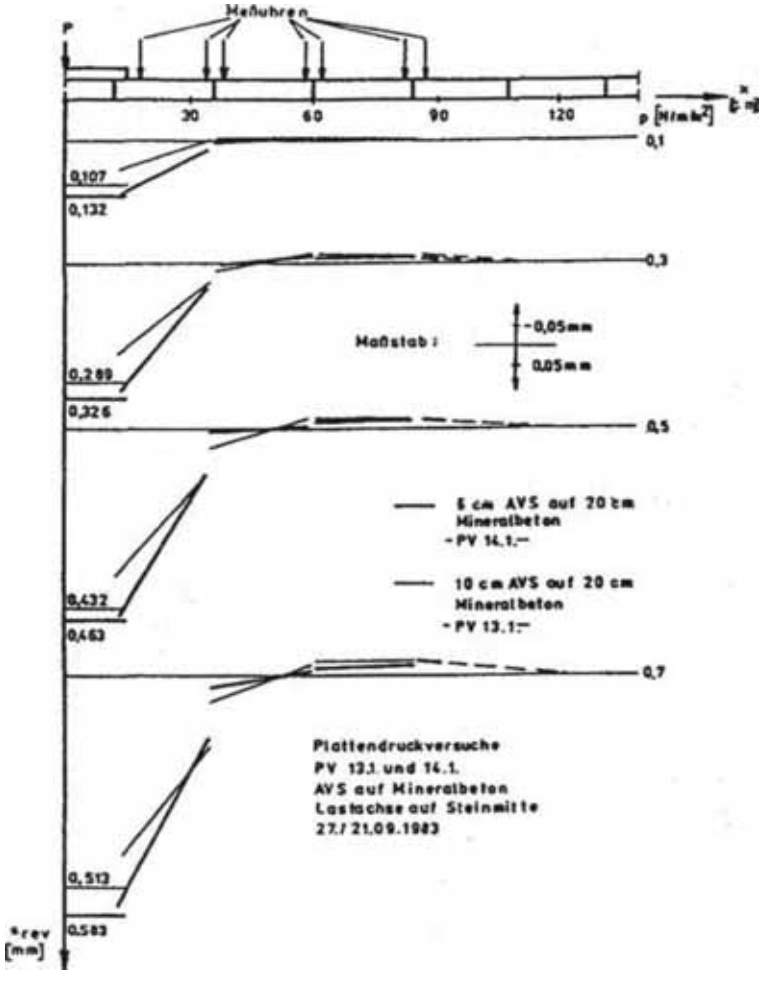



Fig. 3 Impact of block thickness on the strain of the sett paving

load area, and on the other hand, by the steeper position of the next, nonloaded block. The latter mentioned will also contribute more to load distribution with the thicker course, which can be explained by the larger friction surface in the joint between the blocks. The third block beside the load area and all the Subsequent ones display similar strain values, consequently, load distribution of the concrete paving was actually restricted to a very limited, area (about two blocks beside the load area). There is obviously a vertical shift in the joint between the first,, still loaded block and the next, unloaded block, as well. This means that shear forces are transferred from block to block exclusively by friction. The liftings are due to the behaviour of the underlying unstabilised courses.

As the joint filling is evidently of a certain significance it could be expected that by . lateral clamping of the course an increased bearing capacity of the sett paving and thus of the entire construction can be achieved. Likewise, it could be explored whether by a growing density of the joint, sand filling which will occur in any case during lifetime of the road, a remarkably impoved bearing capacity may be expected. As this clamping effect may become most evident for blocks without interlocking rectangular blocks were applied for these test. The sett paving course laid in walling bond was wedged toward the lateral constraint of the test stand (angular wall elements). The plate-bearing tests with or without lateral clamping were performed immediately one after another at the same metering

point. The blocks inserted for wedging could be taken off only heavily damaged or destroyed. Thereby, neighbouring blocks could not be prevented from loosening from the interlocking. During that time the plate-bearing test unit remained under weak load at the metering point (p = 0.2 $N/mm^2$). As a result, the total strain in the load axis turned out to be reduced without clamping from 0.7 mm to 0.66 mm with clamping with a load of 0.7 $N/mm^2$, i.e. by 0.04 mm. Related to the course modulus the following result was obtained:

$E_1$ = 2414 $N/mm^2$ with lateral clamping
$E_1$ = 2099 $N/mm^2$ without lateral clamping.

The weak effect of these differences on the total bearing capacity of a sett paving construction is illustrated by figures 1 and 2.

The test results from all test can be summarized as followes:

A dependence of the course modulus of the concrete paving on the shape of blocks (rectangular blocks, interlocked blocks), on block thickness (6, 8, 10 cm) as well as on the position of the load area on the paving course cannot be proved. The first statement permits the conclusion that the bond of blocks does not exert any impact on the load-bearing capacity of the sett paving under vertical load. From the tests the course modulus could be detected to be between

$E_1$ = 1670 ... 2750 $N/mm^2$

Therefore, for dimensioning a value of

$E_1$ - 1800 $N/mm^2$

is suggested. This course modulus applies to equation (4), (5) and (6) or of adequately derived relationships for multicourse systems [ 1 ].

If the value suggested for dimensioning is integrated into figures 1 or 2 it turns out that a course of 6 cm can raise the equivalent E-modulus by 7 % and for a course thickness of 10 cm by about 30 % (assumption $E_H$;0.1 - 200 $N/mm^2$). This is a value which should not be neglected, at least for the course 10 cm thick. However, in case of the plate-bearing tests it proved that the E-modulus will grow on gravel sand foundations merely by building over an unstabilised road base such as crushed gravel or concrete paving by about 20 %. This is the same order of magnitude as the increase of bearing capacity caused by the course 10 cm thick.

Obviously, even experimental investigations demonstrate that a significant increase of the bearing capacity of a road construction is not to be expected by a sett paving (joints filled with sand). The horizontal interlocking of concrete paving will certainly influence the behaviour towards shear forces, however, an improved bearing capacity compacted to vertical strain could not be proved. The well-known fact that a sett paving is as good as its subgrades has been confirmed again.

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