STANDARD CONCRETE BLOCK PAVEMENT STRUCTURES IN ROTTERDAM

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SUMMARY

The Municipality of Rotterdam gained much experience in concrete block pavements over the last decades. Over the years, this experience has led to two standard concrete block pavement structures. One with a base, and one without a base. This paper deals with the engineering principles of these structures. The paper also presents a procedure to estimate the structural effect of resilient behaviour of granular materials in concrete block pavements. This stress-dependent behaviour is expressed in load equivalency exponent variable to applied axle load.

1. INTRODUCTION

On a yearly basis, approximately 1.5 million square metres of paving is carried out in the Municipality of Rotterdam. Until a few years ago the technical design of concrete block pavements was mainly based on experience. The performance of in-service concrete block pavements has led to two standard pavement structures: one with a base and one without a base layer. This paper covers the engineering principles of these pavements. Major engineering aspects with respect to the performance of concrete block pavements are: the thickness and shape of the concrete blocks, the bond, joint width, edge restraint and cross-sections. More recently, concrete block design methods have become available. In certain cases, the concrete block pavements are designed using the Dutch Design Method. With help of this mechanistic design method, the desirebility of a base layer and sensitivity of the design parameters can be assessed. This method also enables an economic comparison with other types of pavements.
Most design methods make use of a design load in which the actual traffic is converted on a basis of equivalent damage. In most methods, a single load equivalency is used. Since granular materials are known to react stress-dependent and especially in concrete block pavements, the resilient stiffness of granular materials and soils is a function of the principal stresses and hence of the applied load. The load equivalency is proportional to the magnitude of the load, however positive effects due to resilient behaviour of granular materials under traffic toads are neglected. Therefore a better design approach seems to be:

- use of the actual traffic load distribution;
- use of resilient stiffnesses to model the granular materials.

The necessity of such an approach is investigated in this paper.

2. ENGINEERING PRINCIPLES [1]

In order to get an understanding in the performance of in-service pavements, some general information on the subsoil is given. Rotterdam is situated in the western part of the Netherlands. The subsoil consists of a wide variety of mostly weak layers with a low bearing capacity. The geotechnical profile is characterized by 0.5 to 3.0 m silt-containing sand, with clay and peat layers upto a depth of approximately 17 m. The geo-technical profile of the harbour area consists of a somewhat better subsoil. Figure 1 gives an impression of the subsoil bearing capacity.

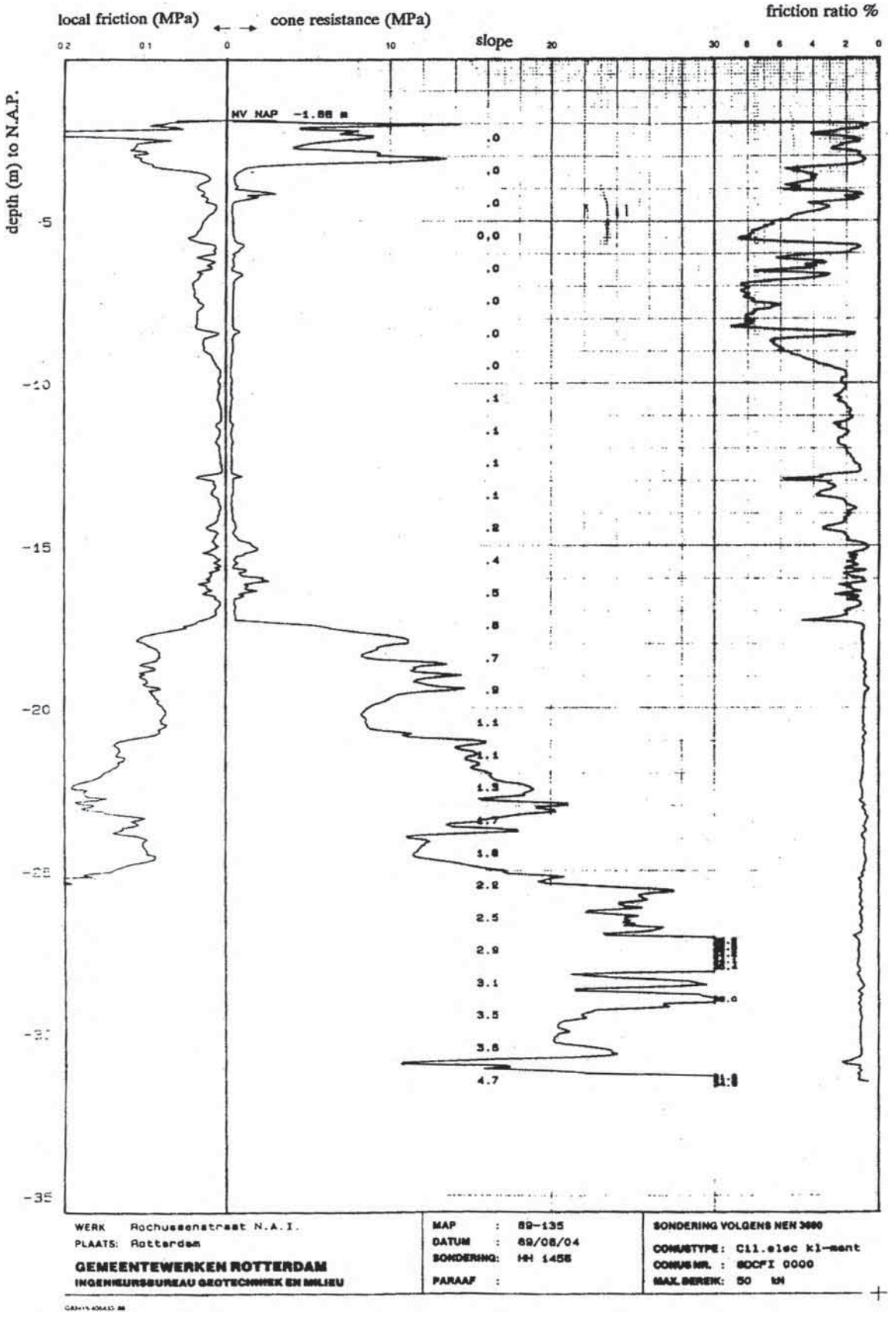


Figure 1: Characteristic sounding of the Rotterdam subsoil.

In order to improve the bearing capacity of the subsoil, usually a sand layer is applied. This sandlayer is placed directly over the weak subsoil and can be assumed to be the pavement subgrade. The subsoil is sensitive to settlements. The subsoil conditions have their implications on the selection of the pavement type. In general it can be stated that the weaker the subgrade, the more flexible the pavement structure should be. Amongst other reasons concrete block pavements are often used in areas with soft subsoils.

2.1 Block shape

In general, two types of block shapes are available; rectangular blocks and profiled blocks. For historical reasons rectangular blocks are generally used in the Netherlands [2]. With respect to the profiled shape, the advantages of rectangular blocks are:

- consistency of size easier to archieve;
- a narrower joint width is possible;
- restricted variety of products;
- less susceptible to breakage;
- easier re-paving and local repairs.

Certainly in situations where the subsoil is weak, paving with profiled blocks turns out, in terms of behaviour, to be hardly any different, if any at all, from paving with rectangular blocks. The advantages of the rectangular blocks are therefore thought to at least balance the assumed advantage of an increased load transfer between profiled blocks.

2.2 Block thickness

The block thickness requirement is primairily determined by the traffic induced stress and magnitude of the traffic load. The thickness has a theoretical influence on rutting, as the degree of load transfer is determined by the joint width and filling, the block shape and the block thickness. On a basis of practical experience, it has been shown that a thickness of 80 mm is almost always adequate. This finding is supported by research of Public Works Rotterdam [3] and research by the GR.O.W Working Group D3 [4].

The standard concrete block thickness is 80 mm. The requirements for concrete blocks are listed in the Dutch Standard NEN 7000. The minimum flexural strength is 5.9 MPa.The blocks are of the cobble format type in the dimensions of 211x105 mm^2. Larger block thicknesses are only desirable in case of large concentrated loads and/or high torsional loads. In these situations, a minimum thickness of 100 mm is used.

2.3 Bond

The bond has influence on both the structural performance e.g. rutting and creep behaviour of the pavement. The creep is defined as movement of the pavement in the direction of the traffic. It has shown that elbow bond and especially herringbone bond perform better than other types of bond such as stretcher bonds.

2.4 Joint width

Besides the block shape and thickness, the load transfer between blocks is determined by the joint width and the quality of the joint filling. The load transfer can be divided into slide resistance and rotational resistance. It is obvious that slide and rotational resistance decrease with an increasing joint width. The minimum possible joint width is determined by the consistency of the dimensions of the blocks and the paving method. The optimal joint width is approximately 2 to 3 mm. It is of importance that the joints are well filled. Adequate attention to this last aspect frequently leaves something to be desired. Blocks with a so-called ’splinter-free head’ are being used more and more. This results in a decrease of the risk of corner splintering in situations of narrow joint width and/or considerable bending.

2.5 Cross-section

The cross-section of the pavement should be such that rapid sky-water drainage is ensured. The modified camber profile for the roads in Rotterdam is shown in figure 2 [1]. For roads wider than 4.0 m, a cross-fall of 0.03 m/m is used. A cross-fall of 0.04 m/m is used for narrower roads.

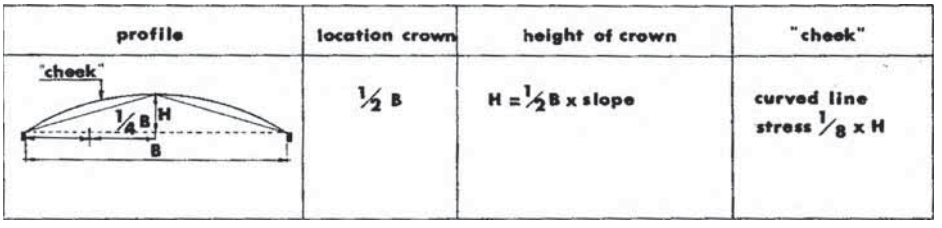


Figure 2: Modified camber profile.

2.6 Edge restraint

A good edge restraint is essential for the performance of the pavement. The two most important functions are:

- preventing the blocks being 'driven out';
- preventing the sand underneath the blocks from being pushed away laterally.

In an ergonomic study into the feasability of lighter paving elements, the minimal weight of a kerb has been determined. Due to a load exerted by a heavy truck, the minimum weight of the kerb is approx. 150 kg [5]. The kerbs used in Rotterdam have dimensions of 180/200x250x1,000 mm. The kerb is placed in cementitious mortar on a sufficient wide base. The kerb is also supported by a concrete ridge.

3. STANDARD CONCRETE BLOCK PAVEMENT STRUCTURES

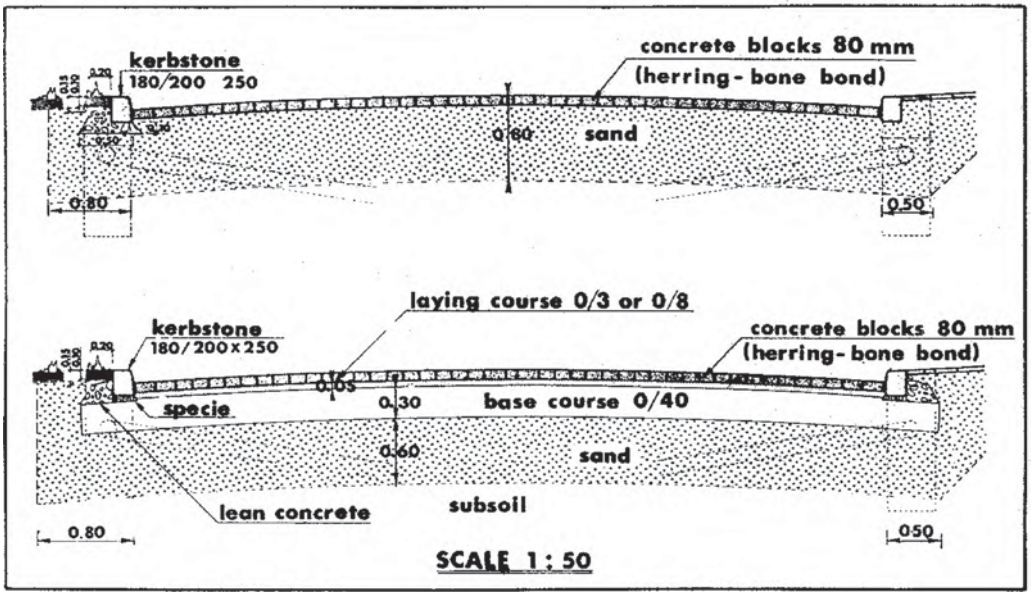


Figure 3: Standard concrete block pavement structures in Rotterdam.

Figure 3 gives the two standard concrete block pavements, one with and one withouth a base layer. The block layer includes a layer of nominal 50 mm sharp breaker sand or rubble 0/8. Breaker sand is applied in case of manual paving, rubble 0/8 is applied in case of manual or mechanical laying.
The base is built up by a mix of recycled building and demolition waste. It is a mixture of granulated concrete and brickwork in a 0/40 gradation, to which a stabilizer is added. This base of recycled material has been used since 1980 as a result of an active environment policy of the municipality of Rotterdam with respect to re-use. The base, if applied, is placed on a sand layer. The minimal thickness of this sand layer is 600 mm.

The application of concrete block pavements varies from lightly-loaded residential roads to heavily-loaded industrial roads. The choise between the two standard structures is made with respect to the subsoil conditions, traffic load, expected settlements and the presence of cables and piping. A base layer is almost always necessary. Concrete block pavements without a base are only applied in case of large, uneven settlements and in case of very lightly-loaded roads. They are also applied as a temporary pavement to construction sites. After completion of the building activities, the final pavement structure is carried out.

4. DESIGN

The Dutch Design Method [4,6] for concrete block pavements is used to determine the thickness of the base layer. This method provides a sound comparison with other construction types. In this design procedure, use is made of a standardized axle load. The actual traffic axle loads are converted into this standard axle load on the basis of an equivalent pavement damage by means of an AASHTO-type of power relationship:

$$l_e = (L/L_{st})^m \qquad (1)$$

where: 1_e = load equivalency factor;
L = axle load (kN);
L_{st} = standard axle load (80 kN);
m = load equivalency exponent.

The damage of an actual load is expressed in the relative damage of the standard axle by means of a load equivalency exponent. The magnitude of the load equivalency exponent is dependent on the pavement type, subgrade stiffness, base material (thickness and type) etc. For each pavement a different exponent is used. With respect to the resilient behaviour of granular materials, the load equivalency concept is questionable. The response due to stress-dependency in a concrete block pavement can be substantial. In many design methods an equivalency exponent of approx. 2 to 4 is used. Due to the behaviour of the granular materials, one expects a lower load equivalency exponent, since the pavement reacts stiffer to relatively higher loads. In this chapter an estimate of the load equivalency exponent for different load levels is presented.

4.1 Resilient behaviour of granular materials

Today's mechanistic pavement design procedures are based on the principle of calculating stresses and strains and comparing the calculated values to allowable values. The analytical backbone of these design procedures is formed by computer programs such as BIS AR. In these models the pavement layers are decribed by a thickness, a Young's modulus and a Poisson ratio. The pavement materials are assumed to behave isotropical and linear elastic. The use of a single Young's modulus for a whole layer of unbound material is theoretically incorrect. Unbound granular materials have a stress-dependent stiffness and since stress varies throughout the pavement layer, the modulus will vary too. For practical purposes, one single Young's modulus for the granular base can be used, provided the main structural element of the pavement

is formed by relatively stiff layers, eg. asphalt layers. Especially in concrete block pavements the granular materials have a structurally important role. Stress-dependent behaviour of granular materials should not be ommitted. The parameter most widely used nowadays to characterize the elastic stiffness of soils and granular materials is the resilient modulus M_r. The resilient stiffness of granular materials and soils is a function of the principal stresses and hence of the applied load. The stress dependency of granular materials is described by:

$$M_r = k_1 \theta^{k_2}$$

where: M_r = stress dependent modulus (MPa);
θ = sum of the principal stresses (kPa);
k_1 = material constant (Mpa);
k_2 = material constant.

4.2 Design criterion

Concrete block pavements are based on semi-mechanistic design methods. For the design of small element pavements, with unbound materials only, use is made of the Dutch Design Method. Since permanent deformation of the pavement structure is the predominant structural deficiency, this and other design methods are based and developed on the rutting behaviour of in-service pavements. For reasons of road safety and ride-ability, the degree of rutting (rut depth under a 1.20 m long rule) and extend of rutting (area affected) before a pavement has to be overhauled is limited to a characteristic rut depth of 15 mm, affecting 30 % of the pavement surface in the wheeltracks [7].

4.3 Concrete block pavement

The effect of resilient behaviour is estimated for a concrete block pavement consisting of 80 mm thick concrete paving elements with horizontal dimensions of approx. 200 mm x 100 mm. The elements are paved on a substructure of a 200 mm thick mixture of granulated concrete and brickwork base, which is placed on top of a 1.0 m thick sand layer. The typical subgrade stiffness is 60 MPa. This pavement structure can according to [4], sustain 1.5 million load applications of a standardized 80 kN axle before a rut depth of 15 mm is reached. For a 200 mm thick mixture of granulated concrete and brickwork base layer on a 1.0 m thick sand layer placed over a clay subgrade, a load equivalency exponent of 3.00 is used in the Dutch Design Method.

4.4 Pavement model

When trying to use the resilient stiffness as input in a multi-layer program like BISAR, one encounters the problem that proper values of θ and thus of M_r cannot be obtained. In some cases the value θ can become tensile which is unrealistic.

The solution to the problem of isotropic, linear elastic analysis not being able to deal properly with structurally important granular bases lies with the finite element approach. Each element can be given a resilient stiffness constistent with the stress in that particular element. Taking account of the stress-dependency requires very detailed computational work. As an alternative, use can be made of an anisotropic, linear elastic model [8]. The anisotropical material behaviour is described by means of different moduli in horizontal and vertical directions. In this model each pavement layer is horizontally divided into sublayers with a resilient stiffness. In such a model the horizontal modulus is lower than the vertical modulus. As a result the sum of the principal stresses cannot become tensile.

The effect of different load levels on the decribed pavement is determined for different axle loads. The pavement is modelled using θ - M_r relations with constant Poisson ratio as given by Sweere [9]. The θ -

M_r relationship is used in its simplest form with a constant Poisson ratio. For the base respectively the sand layer, k_1- values of 12.1 and 9.8 MPa are used. The k_2- values are respectively 0.59 and 0.54. The anisotropical ratio is arbitrarily set at 4. This means that the vertical response of the granular layers is four times stiffer than the horizontal response. In this pavement model an elastic modulus of 1000 MPa is given to the concrete block layer, including 50 mm sand. The modelling is performed in a trial-and-error manner until the calculated M_r lies within the limits of an accuracy of 10 per cent of the predeceasing model The result of this modelling is given in table 1. As can be seen in table 1, the granular layers react stiffer to relatively higher axle loads. Although the pavement model has its limitations, the resilient behaviour of the granular layers is obvious.

Depth below surface	Axle Load (kN)					
mm	10	30	50	80	160	200
130	103	197	263	347	528	603
230	61	116	157	208	312	356
430	20	36	47	61	88	100
630	18	32	42	54	78	88
830	15	26	33	43	63	71

Table 1: Resilient stiffness as a function of the axle load

4.5 Estimation of load equivalency exponent

As stated earlier, permanent deformation is the most important structural defect of concrete block pavements. The design is such that the maximum allowable rut depth of 15 mm is not exceeded before a predefined number of axle load applications. Veverka has developed a rut depth prediction model, which is as [10]:

$$\mu_p = \mu_{el} * a * N^b \qquad (3)$$

where: μ_p = permanent deformation (mm);
μ_{el} = elastic deformation due to load (mm);
N = number of load applications to cause μ_p;
a,b = constants.

In this model the permanent deformation of the overall pavement structure is calculated directly from the elastic deformation of the overall construction instead of cumulating the permanent deformation of the individual layers. This implies that the constants a and b are related to the behaviour of the overall pavement structure. For design purposes, Kellersmann et al [11] suggest values of 0.2 and 0.3 to be used in the rutting prediction model for respectively a and b. The derived pavement models are used to estimate the load equivalency exponent of axle loads of 10, 30, 50, 160 and 200 kN to the standardized 80 kN axle load. The results are given in table 2.

Axle Load kN	Relative damage with an equiv. exponent of 3.00	Relative damage with resilient behaviour	Ratio Relative damage	Load Equiv. Exponent
10	0.002	0.019	9.83	1.90
30	0.053	0.166	3.16	1.83
50	0.244	0.433	1.78	1.78
80	1.000	1.000	1.00	—
160	8.000	3.585	0.45	1.84
200	15.625	5.292	0.34	1.82

Table 2: Load equivalency exponent variable to axle load.

Table 2 shows the relative pavement damage of different axle loads to the standardized 80 kN axle. Column two gives the relative pavement damage as calculated with a load equivalency exponent of 3.00, whereas the third column gives the relative pavement damage assuming resilient behaviour. From table 2 it can be stated that, due to the stiffening effect under relatively higher loads, the detrimental effect of heavy loads is less than can be expected based on an exponent of 3.00. On the other hand, lower loads are more detrimental than has been assumed so far. The last column gives the load equivalency exponent in the power law. Due to the difference in structural behaviour to the applied load, the exponent varies between 1.78 and 1.90.

4.6 Conclusions

It is not suggested that the outcome of this study is complete. Further investigations in the structural behaviour of granular materials in road structures is certainly necessary and recommended. However, the results are of interest. The results indicate that the following conclusions are appropriate:

a. The resilient behaviour of granular materials has a substantial effect on the structural behaviour of the whole pavement structure.

b. For the pavement structure under study, the load equivalency exponent varies to the applied load. The exponent varies between 1.78 and 1.90.

c. Because of their detrimental effect, relatively low axle loads may not be ommitted in the design of small element pavements. Relatively low axle loads cause more damage to a concrete block pavement than has been assumed so far. Relatively higher loads cause relatively less damage.

d. Since the load equivalency exponent varies to load, the design of a concrete block pavement should, especially with relatively low axle loads, be based on an axle load spectrum instead of a single standardized load.

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