EFFECTS ON HIGHWAY SUBDRAINAGE OF GRADATION AND DIRECTION OF FLOW WITHIN A DENSELY GRADED BASE COURSE MATERIAL

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Because of the relatively high content of fine-grained particles, densely graded base course aggregates will not readily drain once saturated with water. An investigation of permeability and its effect on drainage of densely graded base course material specified by the Maryland State Highway Administration was conducted using a prototype permeameter. The experimental permeameter provided values of permeability of a compacted sample both in the vertical and horizontal direction without removing or disturbing the compacted specimen. The horizontal permeability was found to be only slightly greater than the vertical permeability. Experimental permeability data were applied to an example of lateral drainage from the midpoint of a roadway to a shoulder drain under conditions proposed by the Army Corps of Engineers for base course drainage. The direction of flow in the base course material was found to have little effect on the drainage characteristics; fines content is the more significant factor in determining the rate of highway subdrainage.

•ADEQUATE drainage of base course materials has long been considered essential for maintaining the integrity and service life of highway wearing surfaces. Surface water that infiltrates through minor cracks and other openings in the pavement may become trapped between the slab and an impermeable base. Pumping may result when vehicles passing over concrete slabs force water and suspended fines upward through expansion joints and cracks, leaving voids in the base course. The resultant nonuniform slab support may lead to major cracking and failure of pavement sections. In addition, water trapped between a wearing surface and base may contribute to pavement failure by creating a potential for deleterious frost action. Recent studies and examples of highway failure due to excessive quantities of water within the structural section are reported by Cedergren, Arman, and O'Brien (1).

The Army Corps of Engineers (2) has proposed a base course drainage criteria for airfields by which adequate drainage is said to be achieved if a 50 percent reduction in water drainable by gravity from an initial saturated condition occurs within a 10-day period. Barber (3) and Strohm, Nettles, and Calhoun (4) have stated that this criterion as applied to highway base courses may not be met if the gradation of the base contains fine material in excess of 5 percent passing the No. 200 sieve. Excessive fines tend to lower the hydraulic conductivity or permeability and provide poor drainage by sealing the water-transmitting void network within the base course aggregates.

When a highway pavement is constructed over an impervious subgrade soil that is prone to pumping, such as silt and clay, water beneath the pavement cannot percolate vertically into the subgrade. The primary lines of seepage are restricted to a horizontal direction through the base and into the shoulder area, where a lateral drain pipe

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system is sometimes provided. Horizontal permeability values would therefore appear to be more applicable than the traditional vertical values in determining the rate of water movement through the base course to the intercepting laterals.

According to Reeve (5), horizontal permeability of homogeneous gravel beds may be considerably greater than its vertical permeability. This condition may be greatly amplified in a nonhomogeneous material. Thin interstratified layers of fine material may occur during the construction of a highway base course when compaction is performed in layers and fines accumulate between the compacted layers. It is suspected that the interstratified layers of fines decrease the vertical permeability of the total section while not appreciably changing its average horizontal permeability.

This layering phenomenon may similarly occur when permeability test samples are compacted in layers within a cylindrical mold in the laboratory. Because only vertical permeability values are reported from such tests, these values may be overly conservative when applied to horizontal drainage situations. The dual purposes of this study, therefore, are to develop an apparatus that can determine and compare horizontal and vertical permeabilities of stratified granular base course samples and to investigate the effects of fines content in general on both vertical and horizontal permeabilities. Previously, a permeameter similar to the prototype apparatus described in the following was developed by Post and Jouanna (6) to measure only the horizontal permeability of a nonstratified granular earth dam fill material.

DEVELOPMENT OF A HORIZONTAL PERMEAMETER

The basis for the prototype apparatus was a standard vertical permeameter consisting of a 6-in. inside diameter compaction mold conforming to ASTM D-1883-67, a mounting plate, a collar, and a top plate. The assembled permeameter was made watertight by the installation of neoprene ring gaskets at each joint of the individual components. The vertical permeameter is shown in Figure 1.

Several modifications to the standard assembly were necessary before horizontal flow could be induced and the horizontal hydraulic conductivity thus evaluated. An inflow pipe, perforated along its length, was installed at the center of the permeameter mold and drain holes were drilled into the body of the mold on the same horizontal planes as the perforations in the inflow pipe. The detailed modifications to the standard permeameter are shown in Figure 2. A complete description of the prototype permeameter was given by Moynahan (7).

Water introduced under pressure into the center pipe flowed horizontally through a compacted soil sample and emerged from the drain holes in the body of the mold. The seepage lines resembled a radial-horizontal flow pattern analogous to the flow net of a recharge well in a confined aquifer. The confining layer within the modified apparatus was a 6-in. diameter copper bearing plate that pressed against the top of the sample and restricted the flow to the radial-horizontal direction.

The ability to evaluate vertical coefficients of permeability was retained in the prototype horizontal apparatus by providing a seal for the inflow pipe and plugs for the drain holes in the body of the mold. The installation of the watertight seals and plugs restricted the flow to a vertical direction and did not appreciably disturb a sample that had previously been tested for horizontal values. The modified apparatus prepared for vertical testing is shown in Figure 3.

EQUATIONS OF FLOW

The equations governing the flow for both the vertical and horizontal directions are derived from Darcy's Law:

$$Q = KiA \tag{1}$$

where Q = flow rate, K = hydraulic conductivity, i = hydraulic gradient, and A = sectional area through which the flow passes. The equations derived to evaluate the vertical hydraulic conductivity for both the constant and variable head flow conditions of this study are

Figure 1. The standard permeameter.

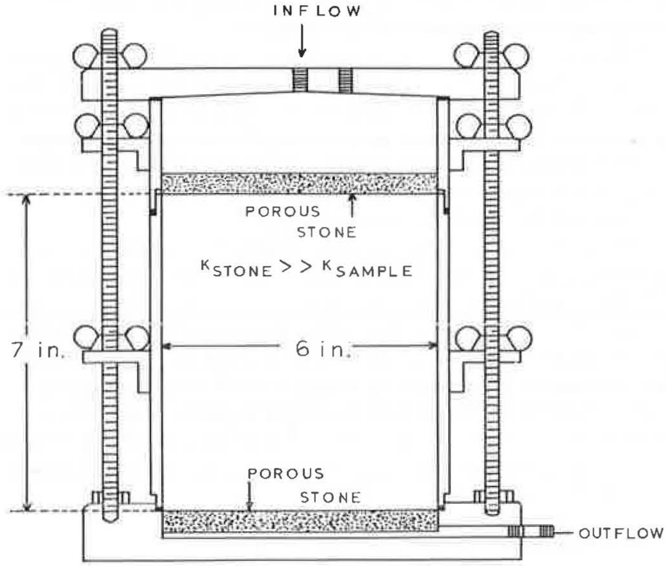


Figure 2. The modified permeameter in the horizontal test configuration.

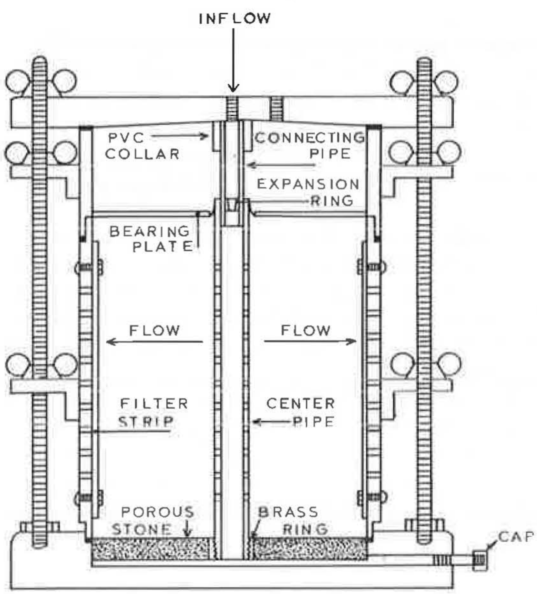


Figure 3. The modified permeameter in the vertical test configuration.

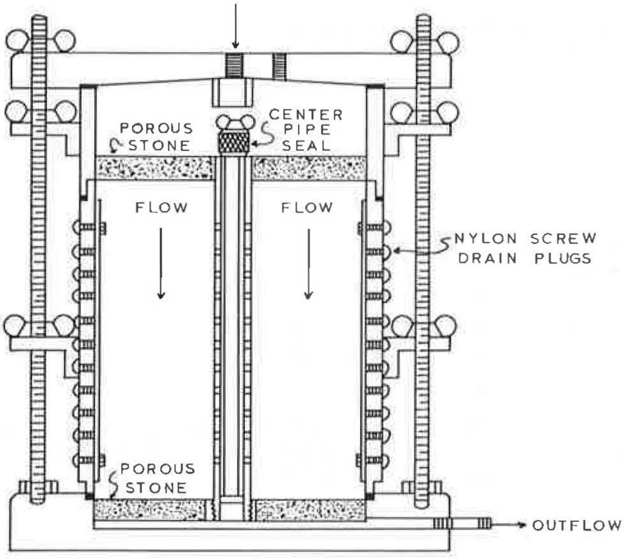
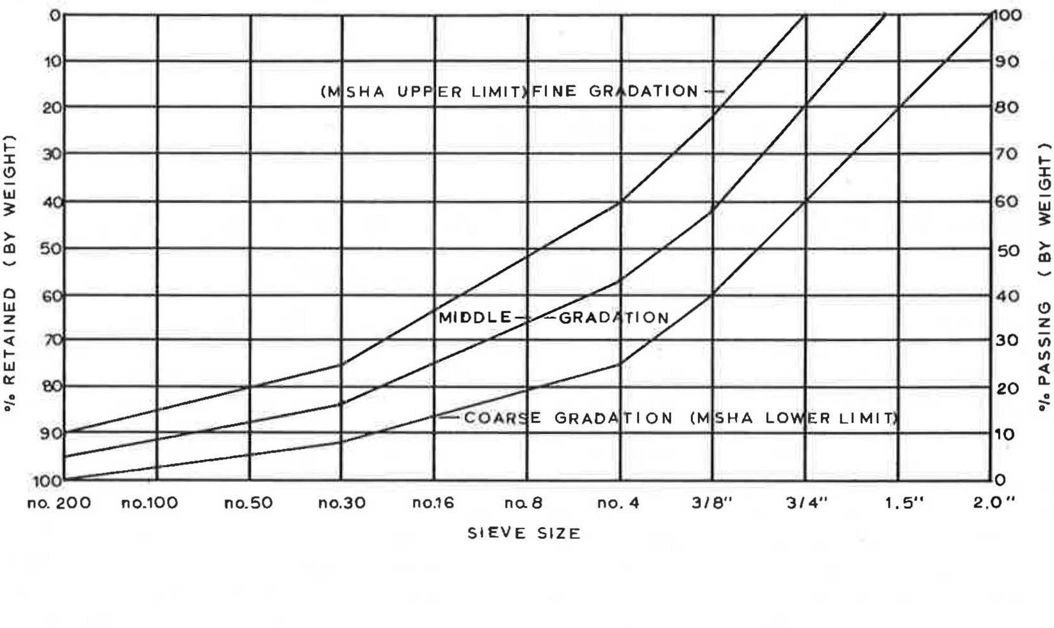


Figure 4. Experimental gradation curves.



$$K_v = \frac{q \cdot L}{\Delta t \cdot A \cdot (h_1 - h_2)} \quad \text{(constant head)} \qquad (2a)$$

$$K_v = \frac{\pi \cdot r_s^2 \cdot L}{\Delta t \cdot A} \ln\left(\frac{h_i - h_2}{h_f - h_2}\right) \quad \text{(variable head)} \qquad (2b)$$

where

K_v = vertical hydraulic conductivity,
q = volume of discharged water,
L = height (length) of sample,
Δt = duration of flow,
A = sectional area of sample through which flow passes,
h_1 = height of water in standpipe during steady flow,
h_2 = height of water in the permeameter holding basin,
h_i = initial height of water in the standpipe during non-steady flow,
h_f = final height of water in standpipe during non-steady flow, and
r_s = inside radius of the standpipe.

The following equations relate the horizontal hydraulic conductivity to the constant and variable head flow conditions respectively for the horizontal test configuration; these equations were derived from Darcy's Law by methods employed in well flow analysis:

$$K_h = \frac{q}{2 \cdot \pi \cdot \Delta t \cdot L (h_1 - h_2)} \cdot \ln\left(\frac{r_m}{r_o}\right) \quad \text{(constant head)} \qquad (3a)$$

$$K_h = \frac{\ln\left(\frac{h_i - h_2}{h_f - h_2}\right) \cdot r_s^2 \cdot \ln\left(\frac{r_m}{r_o}\right)}{2 \cdot L \cdot \Delta t} \quad \text{(variable head)} \qquad (3b)$$

where q, L, Δt, h_1, h_2, h_i, h_f, and r_s are as defined earlier and

K_h = horizontal hydraulic conductivity,
r_m = inside radius of the permeameter, and
r_o = outside radius of the center flow pipe.

The physical parameters on the right side of Eqs. 2 and 3 are determined experimentally in the laboratory, and hydraulic conductivities are calculated from the ensuing data.

SAMPLE DESCRIPTION AND PREPARATION

The base course material tested in this study was crushed limestone with a gradation within the allowable range for densely graded aggregates as specified by the Maryland State Highway Administration (MSHA). Densely graded aggregate was chosen for testing because it provided a wide range of fines content relative to other base course aggregates specified by state agencies. The range of fines, from 0 to 10 percent by weight, was necessary for the investigation of the proposed effect on directional permeability by fines accumulation in layers during compaction and the effect of fines content in general on both vertical and horizontal permeability.

The MSHA allowable range for gradation of densely graded aggregates is shown in Figure 4. The fine gradation of this study corresponded to the upper limit of the MSHA range and contained 10 percent fine material by weight passing the No. 200 sieve. The coarse gradation was identical to the lower limit of the MSHA band, with 0 percent fines passing the No. 200 sieve, and the middle gradation was the median of the upper and lower limits, with 5 percent fines passing the No. 200 sieve.

The original quantity of base course aggregates received from the producer was sieved into its constituent sizes and remixed according to the three experimental curves described. In accordance with AASHO T-180, Method "D", aggregates retained on the 2-in. sieve were discarded. The aggregates passing the 2-in. sieve and retained on the ¾-in. sieve were removed and replaced by an equal weight of material smaller than ¾ in. and larger than No. 4.

Base course samples were compacted in the prototype horizontal permeameter mold at optimum moisture content to a dry density at least 96 percent of maximum dry density. The compaction technique employed a 10-lb hammer with an 18-in. drop falling alternately on 5 equal layers 86 times each. The total compacted height of the sample was 7 in. After compaction, the samples were immersed in water and allowed to reach saturation before permeability testing commenced. Vertical permeability tests were also conducted with a standard permeameter as a control for both the density and the vertical coefficients of permeability obtained with the modified permeameter.

EXPERIMENTAL RESULTS

Experimental values of permeability are shown in Figure 5. These values have been corrected for temperature variations within the permeating water by the following equation:

$$K_{20} = \frac{\mu_t}{\mu_{20}} \cdot K_t \tag{4}$$

in which

K_{20} = standardized coefficient of permeability at 20 C,
K_t = coefficient of permeability determined at test temperature t,
μ_t = viscosity of water at temperature t, and
μ_{20} = viscosity of water at 20 C.

The experimental permeability values obtained from the standard permeameter and from the vertical test of the prototype permeameter are shown in Figure 6. An analysis of variance revealed that the mean of the prototype vertical permeability values is significantly larger than the mean of the standard values at the 0.05 level of significance in all the gradations tested. The difference, which was unexpected, was initially attributed to possible variation in dry densities whereby the dry densities of the modified method were less than those of the standard permeameter. However, an analysis of variance for the dry density data suggested that there was no difference between the mean of the prototype dry densities and the mean of the standard dry densities at a level of significance of 0.05.

Another explanation for the greater values of vertical permeability in the prototype apparatus was that the addition of the center pipe increased the net outflow from the permeameter during the vertical test. Possible sources of extraneous flow were seepage through the center pipe caused by a leaky center pipe seal and seepage between the granular sample and the outside surface of the center pipe. Either occurrence would result in greater flows and larger permeability values when using the prototype vertical permeameter.

In order to account for the effects of the center pipe, correction factors were determined. The ratios of the standard to the modified vertical coefficients of permeability were calculated for samples of similar dry densities within each gradation. The average of the ratios was used to adjust the modified permeability values as shown in the following equation:

$$K_{vadj} = \frac{\sum_{i=1}^{n} \frac{K_{vstd}}{K_v}}{n} \cdot K_v$$

where

K_{vadj} = vertical permeability coefficient of the modified permeameter adjusted for center pipe effects,
K_{vstd} = vertical coefficient of permeability from the standard permeameter,

Figure 5. Experimental data.

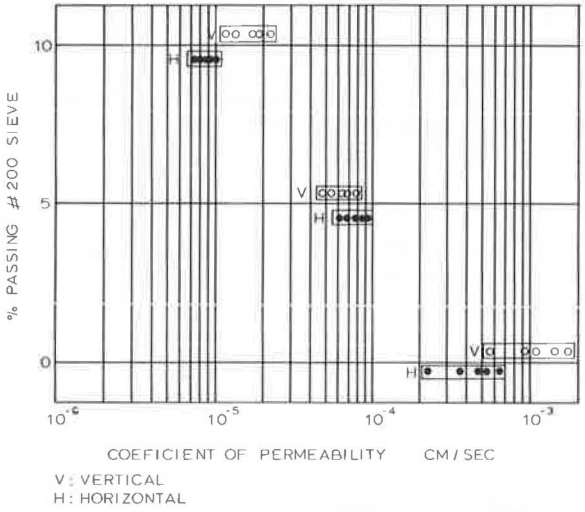
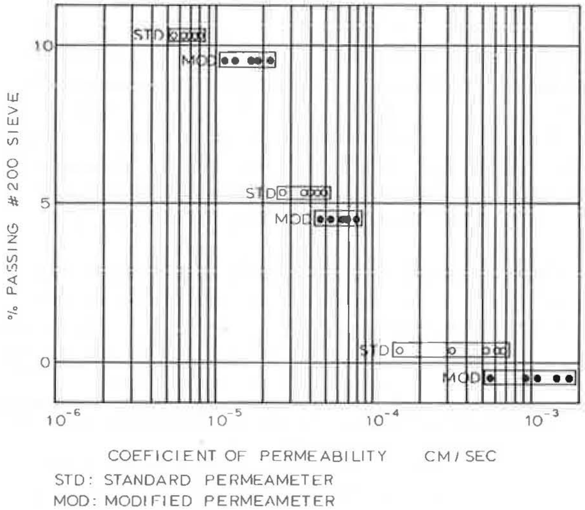


Figure 6. Vertical permeability values.



K_v = vertical coefficient of permeability from the modified permeameter, and
n = number of tests for each gradation.

The correction factors were found to be 0.35 for the coarse gradation, 0.70 for the middle gradation, and 0.41 for the fine gradation. The adjusted vertical coefficients of permeability are shown in Figure 7.

A comparison of the results by gradation in Figure 7 indicates that the samples containing fines of 10 percent passing the No. 200 sieve have the lowest coefficients of permeability, followed by the progressively higher values for each reduction in fines content. The average experimental coefficients of permeability for each gradation are given in Table 1. In general the values for hydraulic conductivity differ by an order of magnitude, with the coarse gradation having values on the order of 10^{-4} cm/sec (approximately 1.0 ft/day), the middle gradation having values of 10^{-5} cm/sec (0.1 ft/day), and the fine gradation having values of 10^{-6} cm/sec (0.01 ft/day).

The average horizontal coefficients of permeability were found by an analysis of variance to be statistically greater than the vertical values for both the middle and fine gradations. No difference could be detected between the means of the horizontal permeability values and the adjusted vertical coefficients of the coarse gradation. These findings would appear to be the result of fine material accumulating between the compacted layers within the samples. Since the coarse gradation contained no fine material, the layering effect could not theoretically occur. Consequently, no detectable difference was found between vertical and horizontal permeability of this gradation.

APPLICATION OF RESULTS TO CORPS OF ENGINEERS DRAINAGE CRITERIA

Relating the experimental permeability results to the Corps of Engineers airfield base course drainage criteria as applied to highways by Strohm et al. included the following equation for predicting the time t_{50} required for 50 percent drainage to occur from a saturated state:

$$t_{50} = \frac{n_e \cdot D^2}{a \cdot K \cdot H_o}$$

where

t_{50} = time in days required for 50 percent drainage to occur from a saturated state,
n_e = effective porosity or specific yield,
D = horizontal drainage distance in feet,
K = permeability of the base course in feet/day, and
H_o = hydrostatic head in feet.

Figure 8 shows the relative positions and dimensions of a highway pavement, base course, and underdrain system. The parameters determined for the experimental densely graded base course are given in Table 2, with the corresponding times for 50 percent drainage in the last column. The times for both the horizontal and vertical hydraulic conductivities are listed for comparison.

The times required for 50 percent drainage given in Table 2 indicate that the experimental data do not agree with Barber's statement (1) that only base course aggregates containing fines less than 5 percent passing the No. 200 sieve will meet the Corps of Engineers drainage criteria. The coarse gradation of this study with no fine material would have been expected to drain within the 10-day limit; however, the data in Table 2 indicate that the Corps drainage criteria will be satisfied only after a lapse of approximately 30 days from initial saturation. The direction of flow does not appreciably affect the times required to meet the Corps criteria.

CONCLUSIONS

It is believed that the following conclusions are warranted based on the data obtained in this study:

Figure 7. Adjusted vertical permeability values.

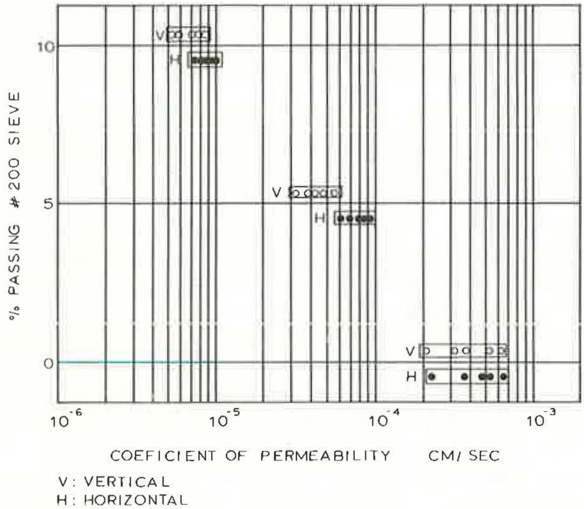


Table 1. Average experimental coefficients of permeability.

Gradation	Percent Passing No. 200 Sieve	Coefficient of Permeability (cm/s) Vertical	Horizontal
Coarse	0	4.06×10^{-4}	4.53×10^{-4}
Middle	5	4.27×10^{-5}	7.60×10^{-5}
Fine	10	6.80×10^{-6}	8.48×10^{-6}

Figure 8. Corps of Engineers drainage diagram.

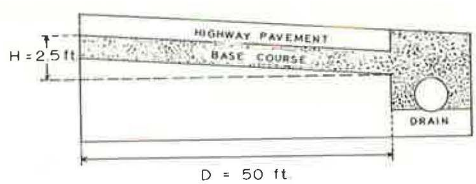


Table 2. Data for Corps of Engineers drainage criteria.

Gradation	γ_{dry}	Percent Passing No. 200 Sieve	S_y, n_e	Coefficient of Permeability (ft/day) Vertical	Horizontal	Time t_{50} (days) Vertical	Horizontal
Coarse	143.06	0	0.071	1.15	1.28	31	28
Middle	149.95	5	0.057	1.21×10^{-1}	2.15×10^{-1}	236	133
Fine	149.18	10	0.043	1.92×10^{-2}	2.40×10^{-2}	1,120	896

1. The horizontal permeability of a densely graded base course sample is only slightly greater than its vertical permeability.
2. The greater horizontal permeability values are attributed to the effect of interstratified fine material that accumulates between compacted layers.
3. Both the vertical and horizontal permeabilities of densely graded base course mixes were found to be inversely related to fines content.
4. Even the most permeable samples of a densely graded base do not provide acceptable drainage under the Corps of Engineers drainage criteria as adapted to highway base courses by Strohm, Nettles, and Calhoun (4).

As Cedergren et al. point out (1), base course materials with permeabilities as low as those found in this study should be restricted from highway subdrainage systems if competent drainage of the structural section is to be accomplished. The possibility that horizontal flow within a densely graded base course may be sufficiently large to exhibit acceptable subdrainage characteristics was not substantiated by the findings of this study. These conclusions are valid only for densely graded base course samples, and further research should be conducted on base or filter material where horizontal flow predominates.

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