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SUCTION AND ITS USE AS A MEASURE OF MOISTURE CONTENTS AND POTENTIALS IN POROUS MATERIALS

BY

E. PENNER

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LA SUCCION ET SON UTILISATION POUR MESURER LA TENEUR ET LE POTENTIAL D'HUMIDITE DES MATERIAUX POREUX

SOMMAIRE

De nombreux problèmes pratiques surviennent quand on utilise des matériaux de nature poreuse; ils résultent de l'action réciproque de l'eau et de ces matériaux. Il est donc nécessaire de décrire le degré d'humidité avec une méthode plus adéquate que celles basées sur un pourcentage de poids ou de volume. Le concept de la succion fournit une méthode rationnelle pour décrire et contrôler le degré d'humidité des matériaux poreux, particulièrement dans le cas de grandes humidités. La teneur en humidité de nombreux matériaux augmente considérablement sous l'influence d'un léger changement de la pression de la vapeur à une humidité relative supérieure à 0.95. Il devient alors très difficile d'établir directement une mesure et un contrôle précis de la pression de la vapeur et l'on doit, par conséquent, employer une autre méthode. Le concept de la succion est basé sur les équations de Kelvin et sur les équations concernant la hauteur de l'ascension capillaire. Ces équations établissent un rapport entre la diminution de la pression de la vapeur sur un ménisque dans un tube capillaire rempli d'eau, et la hauteur de la colonne d'eau que ce ménisque supportera. Selon cette graduation, une colonne d'eau d'une hauteur de 10,000 cm équivaut à une pression relative de vapeur de 0.993. Le log de cette graduation développée, basée sur la succion, est le pico-farad de Schofield. La facilité de détermination et de contrôle de cette méthode la rend des plus utiles pour de nombreuses études impliquant des problèmes d'humidité dans des matériaux poreux. L'auteur mentionne quelques-uns des travaux les plus importants effectués à l'aide de cette méthode.

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29. Suction and Its Use as a Measure of Moisture Contents and Potentials in Porous Materials*

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ABSTRACT

Many practical problems that arise with the use of materials of a porous nature result from their interaction with water. There is, therefore, a need to describe the moisture status in a more adequate way than on a weight or volume percentage basis.

The concept of suction provides a rational method for describing and controlling the moisture status of porous materials, particularly in the high humidity region. In many materials, moisture contents greatly increase with a small change in vapor pressure at relative humidities in excess of 0.95, and accurate measurement and control of vapor pressure directly is often so difficult as to preclude its use.

The concept of suction is based on the Kelvin and height-of-capillary rise equations relating the reduction in the vapor pressure over a curved water meniscus in a capillary to the length of the water column this curved meniscus will support. On this scale, a column of water 10,000 cm high is equivalent to a relative vapor pressure of 0.993. The log of this expanded scale based on suction is Schofield's pF. Its ease of determination and control makes it most useful in many studies in which moisture in porous materials is involved. Reference is made to some of the more important work in which it has been employed.

The determination of moisture content of porous materials may be required for a variety of purposes. In many instances the moisture content itself may be of immediate interest, in which case a method of measurement is required which responds directly to the moisture present. For many purposes, however, some index that is related to the potential at which the moisture is held in the material may be much more useful and more readily measured. One such index, commonly used, is relative humidity. For many cases it is possible, having established empirically the equilibrium relationship that exists between moisture content, temperature and relative humidity for a particular material, to predict moisture content from a measure of relative humidity. There is, however, another possible index, widely used by soil scientists and commonly referred to as "suction," which can also be applied in many problems involving moisture in rigid porous systems. It is not well known in this connection, and it is the purpose of this paper to discuss its usefulness and to provide references to some of the pertinent literature.

The general nature of the relationship between the moisture content of many common materials and the relative humidity of the surrounding atmosphere at the equilibrium condition is reasonably well known. The relationship for wood, shown in Fig. 1, is a typical example for some natural organic materials. The inevitable hysteresis between wetting and drying curves is shown in Fig. 1. Not shown is a secondary effect, that of temperature which causes a shift of the curves downward to lower moisture content levels as the temperature is increased. The effect of

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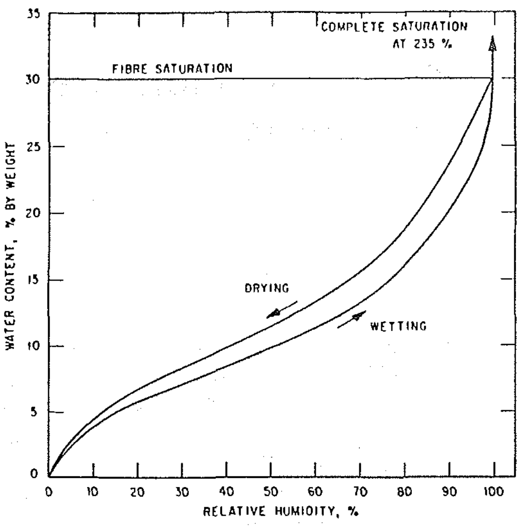

FIG. 1. Equilibrium moisture content for spruce at 20°C.

temperature is sufficiently small so that a change of a few degrees may usually be disregarded without serious error. The relative humidity-moisture content relationships are a function of the material and its structure and must therefore be determined experimentally.

Relationships between equilibrium moisture and humidity have been developed and are used most commonly for those materials in which the "natural" moisture contents more or less in equilibrium with the surrounding atmosphere are of particular interest. This applies particularly to plant products including wood, foods and fibers. Similar relationships can be established for the whole range of porous materials, both inorganic and organic, including building materials such as soil, stone and brick. Equilibrium moisture curves for many of these common materials are not widely used, at least outside the laboratory, because the levels of their moisture content in use are usually much closer to saturation and thus well above those corresponding to the usual ambient relative humidity levels. At high degrees of saturation, relative humidity normally ceases to be a useful index because its variation with increasing moisture contents close to saturation becomes disproportionately small, and it becomes extremely difficult to measure with useful accuracy. Recently a psychrometric method has been devised which apparently measures relative vapor pressures close to saturation with great accuracy.[1]

It has been common practice in the case of wood, for example, to terminate the curves of equilibrium moisture at the value of moisture content known as the *fiber saturation point* which corresponds to a relative humidity very close to 100 per cent (Fig. 1). This has been largely a practical matter in wood technology since this is the value of moisture content below which significant shrinkage takes place. The remainder of the curve to saturation is usually omitted, partly because it is of less concern and partly because it cannot usefully be displayed on the same relative humidity scale.

When the moisture contents of interest are in the range representing the progressive filling of large pores in the material as saturation is approached, it is clearly necessary to find some more convenient index and new instrumental techniques. The suction concept provides such an approach.

THE SUCTION CONCEPT

In simplest terms, suction is a measure of the affinity between water and a porous hydrophilic solid. Relative humidity is also such a measure though an inverse one, since it reflects the forces by which water is retained through the depression of its vapor pressure below that of free water.

Suction can be expressed simply in terms of the theoretical capillary rise corresponding to the forces by which water is held in the porous structure of a material. In the case of an idealized capillary, these are surface tension forces which are reflected both in the height of capillary rise and in the curvature of the meniscus. The relationship is:

$$gh = \frac{2\gamma}{dr} \qquad (1)$$

where

g = gravitational constant
h = capillary rise
γ = interfacial tension between water and air
d = density of water
r = radius of curvature of the meniscus.

The vapor pressure, p, over the meniscus is related to the curvature of the surface, and

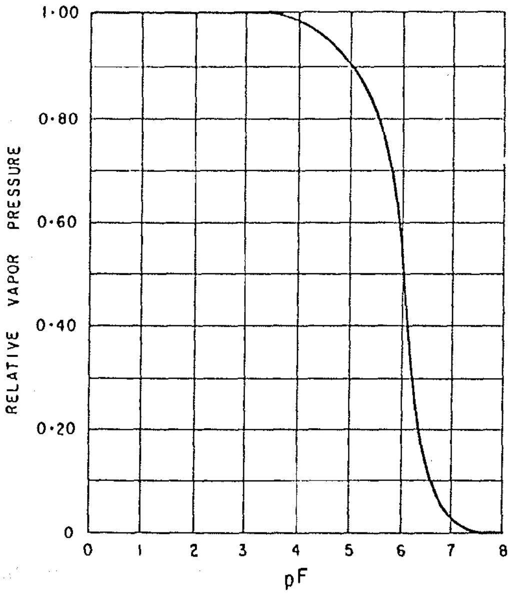

FIG. 2. Relationship between pF and relative humidity at 20°C.

differs from the saturation vapor pressure p_0 for a flat water surface by an amount equivalent to the weight of the vapor column having a height equal to the capillary rise, h. Since h and r are related, the vapor pressure over a curved surface can also be related to radius of curvature. This is given by the Kelvin equation

$$\ln p/p_0 = -\frac{2\gamma M}{rdRT} \tag{2}$$

where

M = molecular weight of water
R = gas constant
T = absolute temperature.

Combining Eqs. (1) and (2) establishes the relationship between capillary rise, h, the curvature of the meniscus, and the relative vapor pressure, as follows:

$$h = -\frac{RT}{Mg}\ln p/p_0 \tag{3}$$

This equation is true whether the column of water of height h is real or imaginary, and it relates capillary rise to the radius of curvature of the water surfaces occurring in the pores of the material. The value calculated from Eq. (3) is commonly referred to as the suction S for each corresponding vapor pressure.

The suction, usually expressed in centimeters, is an extremely sensitive indicator of very small changes in relative humidity near saturation. It will have high values for relative vapor pressures in the normal range. As a convenience, $\log_{10} S$ can be used rather than S, yielding numbers between 0 and 7 for most cases of interest. Units of suction or of negative potential expressed in this way are called pF, after Schofield.[1] Thus a suction of 100 cm of water becomes pF 2. A plot of pF *vs* p/p_0 is given in Fig. 2. The expanded scale provided above relative vapor pressures of 0.99 is evident. The relationships between relative vapor pressure, radius of curvature of the meniscus equivalent height of column h, and Schofield's pF are given in Table 1.

The validity of the suction concept is not dependent on knowing the water-retaining mechanisms that are at work. These may be adsorption, capillary or surface tension forces and, in the case of swelling clays, osmotic pressures which arise from the interaction of diffuse layers of exchangeable ions

TABLE 1. THE RELATIONSHIPS BETWEEN RELATIVE VAPOR PRESSURE, RADIUS OF CURVATURE OF MENISCUS, EQUIVALENT COLUMN OF WATER h, AND pF

p/p_0 (%)	Radius of Curvature (μ)	Height of Column of Water, h (cm)	h (psi)	Schofield's pF
0.08	0.000147	10^7	1.42×10^5	7
49.0	0.00147	10^6	1.42×10^4	6
93.0	0.0147	10^5	1.42×10^3	5
99.3	0.147	10^4	1.42×10^2	4
99.9	1.47	10^3	1.42×10	3
99.999	147	10	1.42×10^{-1}	1
100.0	0.0	0	0	—

between adjacent particles. There are porous materials which swell due to other reasons, and suction may be the result of still other causes, but the treatment can be much the same.

TECHNIQUES OF MEASURING SUCTION

Suction and its use as a measure of potential is applicable from the oven-dried state to saturation although it is normally convenient to use several techniques of measurement to cover the complete range. Relative vapor pressure methods are still best between pF 4 and 7, but with a new apparatus designed by Croney *et al*,[3] the original pressure membrane method of Richards[4] can be extended to pF 6.2 (1500 atms). The same moisture content *vs* potential relationships obtained from relative vapor pressure methods are obtained with Croney's new method, thus substantiating the theory on which the suction concept is based. The various techniques that have been developed and their useful ranges are given in Table 2. Most of these are described in a paper on suction techniques by Croney *et al.*[5]

TABLE 2. METHODS OF MEASURING MOISTURE SUCTION*

Method	pF Range
Direct	
Suction plate	0–3
Tensiometer	0–3
Centrifuge	3–4.5
Pressure membrane	0–4
Consolidation (for saturated clays only)	2–4
Road research new pressure membrane method	0–6.2
Indirect	
Vacuum desiccator	4.5–7
Sorption balance	4.5–7
Electrical resistance gauges (depending on pore geometry)	3–7

* Based on a table by Croney *et al.*[4]

Most of the methods used to determine suction do not require elaborate apparatus and are simple to carry out. The apparatus in Fig. 3, known as a combined suction plate and pressure membrane, is typical of this. Moisture potentials in the wet porous plate are established by increasing the air pressure in the chamber above atmospheric pressure. Hence the pressure drop across the wet porous plate determines the level of potential or suction. Any other porous material in contact with the porous plate inside the chamber will also become conditioned to the same potential. It is desirable to have a good contact so that the water films will coalesce and facilitate a rapid exchange of moisture. If the porous sample is at a higher suction, water will be withdrawn from the porous plate and the meniscus in the pipet will recede. If the suction is lower in the sample

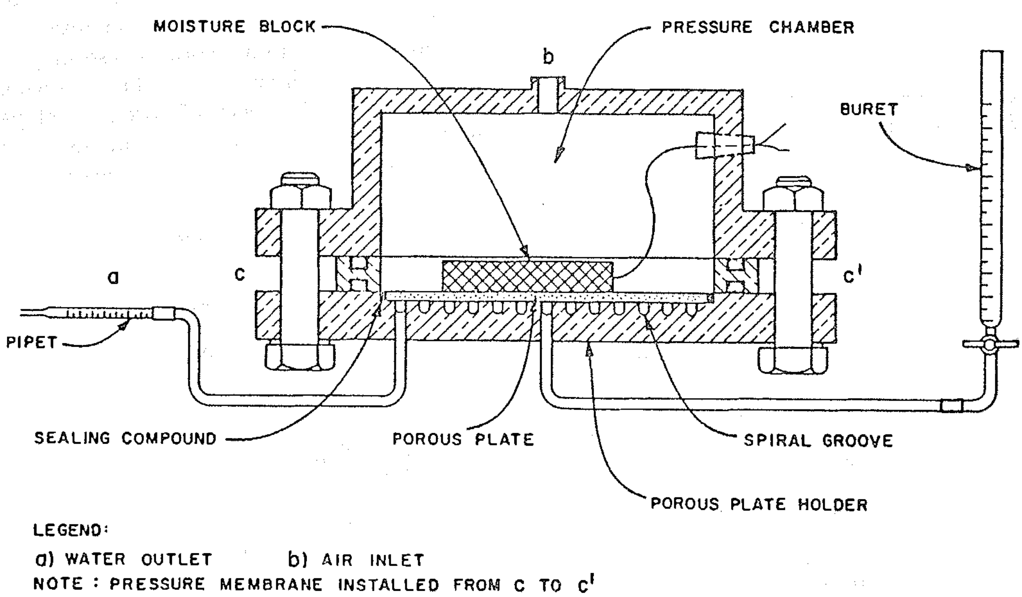

FIG. 3. Pressure membrane apparatus for moisture block calibration.

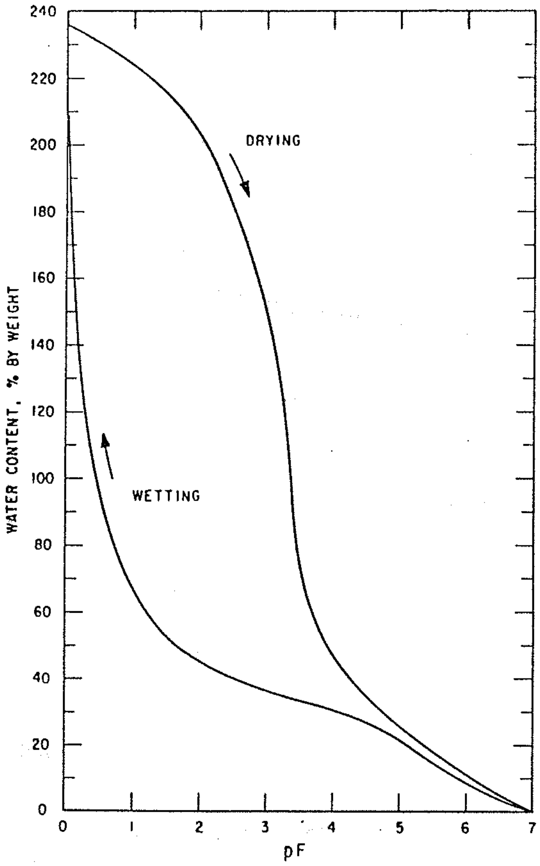

FIG. 4. Suction-water content curve for spruce at 20°C.

when it is placed in contact with the porous plate, water will be transferred to the plate and the meniscus in the pipet will advance.

Air pressure is applied in successive steps to the chamber, and the volume of water displaced is measured on the pipet between the various stages. Starting with a fully saturated sample and increasing the suction gives the drying curve. The wetting curve is obtained by reducing the pressure and noting the water intake.

The pF limits of this apparatus are determined by the largest pore in the porous plate, which in turn determines the air pressure at which the porous plate will no longer remain saturated. To continue to higher pF's a membrane such as Visking sausage skin is placed on top of the porous plate from c to c′ (Fig. 3). These membranes will usually remain saturated and not pass air until a pF of 5 is exceeded. Such membranes should not be used below pF 3 because of the low moisture transfer rates at low pressures.

SUCTION CURVE FOR SPRUCE WOOD AND CLAY SOIL

Suction curves for two common materials, spruce and clay, are given in Figs. 4 and 5 respectively. The possible value of such information at moisture contents up to saturation becomes apparent from a comparison of the appropriate portions of the curve in Figs. 1 with 4. The hysteresis effect between wetting and drying for both materials is clearly demonstrated. The theories advanced to explain hysteresis are discussed in detail by Carman[6] and are beyond the scope of this paper. It must be emphasized, however, that failure to recognize and take into account hysteresis effects has complicated many attempts to measure and predict moisture content and moisture movement. Some measure of potential such as that provided by the suction concept is essential to any study of hysteresis effects at moisture contents above those corresponding to pF 4, i.e., from relative humidity of 99.3 per cent to complete saturation.

APPLICATIONS OF THE SUCTION CONCEPT

Indirect Moisture Content and Potential Measurement with Suction Meters

Two wet materials placed in contact for a sufficient length of time will establish equal moisture potentials by water transfer. The equilibrium condition develops very slowly by vapor transfer but occurs very rapidly, as pointed out previously, when there is intimate contact and the water films coalesce. Moisture meters are based on this principle although as first used by Bouyoucos and Mick[7] only moisture contents were obtained; their use in measuring moisture potential was a later development.[4] These meters consist of plaster of paris blocks, nylon, glass fiber[7, 8, 9, 10] or other porous dielectrics in which the electrical resistance between two electrodes in the mass (or some other function highly sensitive to moisture changes such as capacitance or heat conduction) is measured as a

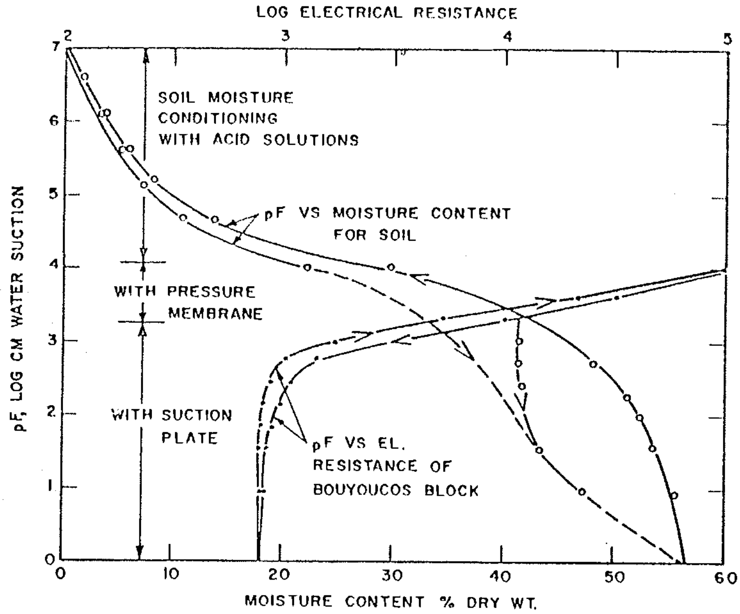

FIG. 5. Suction-moisture content relationship for sample of air-dried Leda clay and a Bouyoucos moisture meter calibration curve.

function of moisture content. They may be calibrated as a function of moisture potential and such a curve is shown in Fig. 5 for both the wetting and drying condition. Such calibrated meters installed in the soil give a measure of potential when moisture equilibrium is reached with the surrounding medium. Information on the moisture content of the mass, e.g., soil, can also be obtained if a potential moisture content curve is known. In fact, the establishment of such curves separately may be a much more satisfactory way of calibrating than to consider moisture content directly. The two curves together (moisture potential—electrical resistance for the block and moisture potential—moisture content for the soil) provide a way not only of estimating the potential of the soil moisture but its actual moisture content (Fig. 5). Although this is sound in principle such meters are only useful for measuring *moisture trends in practice* because hysteresis effects are unavoidably present and since, when selecting the appropriate calibration values for conversion to moisture content, it is seldom known precisely whether the soil and the meter are drying or wetting. This complication is not introduced by the suction concept, which serves in this case to show the limited performance of such meters.

Control of Water for Plant Growth

Moisture meters for moisture potential measurements have been a successful aid to economical irrigation practices. It is known that the ease of water extraction by plants from soil depends on the suction level and it therefore plays a major role in controlling crop production. Tensiometers[10] and moisture meters are both being used extensively as dryness indicators for all types of irrigated crops. Tensiometers are limited in practice to about 850 cm (water) suction but moisture meters can be used to extend this range well beyond the wilting point of most growing crops. When the pF range for the best production has been established these meters can be used to great advantage.

Moisture Redistribution in Soils

The actual moisture potential under field conditions which must take into account differences in elevation can be usefully expressed in terms of suction. Darcy's law for moisture flow applies equally to the unsaturated range but the coefficient k varies with changes in potential. This change in k depends on an accompanying change in moisture content with suction because a reduction in moisture content decreases the effective cross-sectional area involved in liquid flow.

Based on moisture potentials (not moisture contents) the direction of moisture flow can easily be predicted. The redistribution of water above a water table, when evaporation is cut off, can also be predicted by taking into account the overburden pressure, the compressibility of the soil and the height of the water table. Croney *et al.*[3] claim considerable success with a special method devised by them for this purpose as well as for predicting moisture potential and moisture content changes following a change in the overburden pressure in road embankment construction. This is an important consideration in many soil engineering projects.

Use of the pF Concept in Common Porous Materials

The behavior of moisture in the performance of porous building materials can often be readily studied in terms of this simple concept. It has already been used in studies of the setting of plaster[11] and may possibly be extended to studies of effects of plaster bases and plaster aggregates.

The rate of water absorption by bricks apparently influences the bond strength that develops between the brick and mortar of masonry walls.[13] Rate of water absorption is known to be a function of the driving force or potential and the conductivity. It is usually measured in bricks by a simple test[14] which unfortunately gives no information on the variations in its separate components. Suction techniques could be used to advantage in studies when the pore structure of the bricks is of interest. Similarly, the fiber saturation point in wood which does not yet appear to have been defined satisfactorily[15] could be readily studied and, if desired, established on the basis of suction potential.

Although the suction concept has been used for years in soil science its application to moisture movement during frost heaving is a recent development.[16] Studies of the strength properties of soils have shown that the degree of suction in clays influences the shear strength by adding to the effective stress. Aitchison[17] concluded that the variation of suction in the pore water for the Australian environment appears to be a major strength determinant for cohesive soils.

There are many instances in dealing with common materials when use is made of moisture content measurements obtained after conditioning in a supposedly saturated atmosphere. When the nature of relationships between relative humidity, suction and moisture content are appreciated, it may be concluded that such conditioning in order to establish a reproducible moisture content will often be futile. It is seldom that the degree of temperature control provided will permit the establishment of a precisely maintained relative humidity and the exchange of moisture in the vapor state is extremely slow. Conditioning in contact with suction and pressure plates that provide ready control of potential and also relatively rapid exchange of moisture by capillarity can be used to good effect when known equilibrium conditions at moisture conditions approaching saturation must be established.

SUMMARY

The suction concept provides a simple approach to the establishment and control of moisture potentials in the region of high relative humidity. Suction, unlike relative humidity, can be used conveniently as a measure of potential involved in water migration. There are also useful techniques of measurement which follow logically from the suction concept.

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