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G. Leblanc

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16. Abstract

Pointing out that today's expensive new fighter and large-capacity transport aircraft require that stopping distances and, consequently, the necessary runway lengths, no longer be left up to chance, but be reproducible, and that the methods for predicting them be defined for different touchdown velocity, wind and runway conditions, the author discusses distance predicting methods in the case when braking is not limited by the brakes, but by the characteristics of tire-runway contact.

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BRAKING PERFORMANCE

Georges Leblanc,
Technical Service of the Aeronautic Industry, Paris, France

1. Introduction /1*

Braking performances incident to landing or an abandoned takeoff have not yet become the object of such in-depth studies as flight performances, perhaps because this aspect is less profitable or -- and wrongly so -- because it does not exert the same appeal on aeronautics specialists. Yet it seems well established, as all pilots questioned have confirmed, that the braking phase can become dangerous under certain unfavorable runway, wind or touchdown velocity conditions.

Today's expensive new fighter and large-capacity transport aircraft require that stopping distances and, consequently, the necessary runway lengths, no longer be left up to chance, but be reproducible, and that the methods for predicting them be defined for different touchdown velocity, wind and runway conditions.

The purpose of the present paper is to make a few remarks about distance predicting methods in the case when braking is not limited by the brakes, but by the characteristics of tire-runway contact. These remarks were occasioned by the results of sliding tests conducted on a Caravelle aircraft equipped with a SPAD device on four different airfields (three concrete runways, one asphalt runway).

Much of the analytic work and many of the tests were undertaken by researchers mainly in the USA and the United Kingdom to

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* Numbers in the margin indicate pagination in the foreign text.

explain friction phenomena and develop methods for predicting braking distances. The tire-runway braking problem appears much more complicated than the problem of performances connected with the aircraft's aerodynamics; factors such as tire flexibility, tread design and coating surface roughness practically preclude any purely analytic approach unless simplifying hypotheses based on test results are made.

This paper has been inspired largely by the American and British studies and, especially, the theoretic study of Mr. Walter B. Horne and his team's set of important studies. /2

2. Parameter Acting in Tire-Runway Friction

2.1. Friction Coefficient

By definition, the friction coefficient μ is the ratio of the horizontal force Fx developed in the tire-ground contact area to the vertical force Fy applied to this contact area. It appears that for an aircraft the friction coefficient to be taken into consideration is that for which the vertical force represents the sum of the vertical components on the main braking wheels, the weight of the aircraft, the lift and the vertical forces of inertia introduced by the aircraft and the runway profile.

Also used is a generalized friction coefficient μ_G for which the total force (weight - lift) is assumed to be applied to the main wheels.

Knowing the instantaneous generalized friction coefficient and the vertical forces allows us to calculate the braking distance D. Neglecting the "aircraft-runway" forces of inertia, this distance can be represented by the following approximate relation:

$$D = \left| \int_0^V \frac{m \cdot V \cdot dV}{\mu_G (mg - Rx) + Rx + Fr} \right|$$

in which:

V = speed of aircraft in m/sec

m = mass in kg

g = acceleration due to gravity = 9.81 m/sec^2

Rz = lift in N

Rx = drag in N

Fr = reverse thrust of jet engines in N.

2.2. Parameter Acting in Tire-Runway Friction /3

Friction or the longitudinal generalized friction coefficient depends on 17 independent parameters:

-- runway (6): texture or shape, η_p viscosity, Ep elasticity, H water height, η_e viscosity of water, ρ_e volumetric mass of water.

-- tire (8): texture or initial form, wear, R radius, η_c viscosity of water, Ec equivalent elasticity of tread, ρ_c volumetric mass of rubber, t temperature, Cp specific heat.

-- vehicle (3): Fz resultant vertical force, V speed, ωR tangential speed of the undeformed wheel (this parameter takes into account the applied braking couple), R radius of tire.

It is easy to see that the test conditions must mention these parameters. Fortunately, a certain number of these parameters are constants, and dimensional analysis shows that judicious grouping permits the most influential dimensionless parameters to be diminished in a useful manner.

2.3. Most Influential Parameters

It is customary to regard the following parameters as the most influential on friction:

-- the sliding s defined by $s = (V - \omega R)/V$. Fig. 1 shows the classical variation of the friction coefficient with sliding, all the other parameters being constant. It would be illusory to compare different test results if this parameter were not known or, better, if it were not kept constant. "Antiskid" devices that yield a mean sliding law must be employed to make braking distances reproducible.

-- runway texture seems to act in two different forms: (a) the macrotexture, or physical irregularities, generally defined by a mean height of fine sand or grease masking all asperities. The macrotexture is reponsible for hysteresis friction, tearing friction, water flow under the tire tread; (b) the microtexture, irregularities less than 1/10 of a millimeter, whose least obvious effect seems to involve mainly adhesion friction, the deep origin of friction. Braking distances are much influenced by runway texture. It is necessary to take this parameter into account when predicting braking distances.

-- the reduced water height H.V., whose effect makes itself felt especially for values of H less than the macrotexture and for high enough values to permit taxiing. The parameter H.V. is the simplified writing of the total Reynolds number Rg at the beginning of the real tire-runway contact area: /4

$$Rg = (H.V).\ \frac{\rho_e}{\eta_e}$$

-- the reduced tire speed V/P, which marks the influence of the speed alone and is the simplified writing of the Sommerfeld number So:

$$So = \frac{\eta_e \cdot V}{P \cdot R}$$

-- the dynamic pressure ratio $(\rho_e \cdot V_2)/2p$. The influence of this ratio begins to make itself felt under the tire tread at speeds much less than the taxiing speed.

-- the reduced contact area $Fz/(P \cdot R_2)$, or reduced deflection of the wheel, which is practically proportional to the ratio AO/R_2, AO being the apparent tire tread-ground area.

With the aid of these six reduced parameters and bringing into play the nine independent parameters: V, R, ρ_e, η_e, H, P, R, Fz and runway texture, friction can be represented when the parameters connected with the rubber, i.e., the energy dissipated by hysteresis, and the proper tire effect, which is regarded as a constant element, are neglected. The results are therefore valid only for a given tire quality. Predictions would have to be made for a given aircraft with the different types of tire that are earmarked for use.

3. Summary Indication of Principles Underlying Different Antiskid Systems

The primary function of an antiskid system is to diminish the pressure of the brakes when the tire has a tendency to be blocked, i.e., when its angular deceleration becomes higher (in absolute value) than an estimated limiting value. The different existing systems can be approximately schematized by four fundamental principles.

3.1. All-or-Nothing Pressure System

Braking pressure is suppressed as soon as deceleration reaches a predetermined constant value or threshold.

3.2. Predetermined-Threshold Modulated Pressure System /5

In this system, braking pressure is a function of the measured deviation between real deceleration and predetermined threshold.

3.3. Variable-Threshold Modulated Pressure System

The threshold is variable in order to take into account the variations in the available friction coefficient with the state of the runway (dry or wet). The principle of this system differs from the preceding in that the threshold is determined either as a function of speed or in such a way that the variation in the deviation of deceleration (between real deceleration and threshold) remains proportional to the variation in the braking pressure.

3.4. Constant or Adjustable Sliding Rate System

Braking pressure is regulated in such a way that the sliding rate measured aboard the aircraft will be constant or such that the friction coefficient or the aircraft's deceleration will be at the peak of the curve $\mu = f(s)$ or $dV/dt = f(s)$. This is the system that was used incident to the sliding tests on the Caravelle; it is designated by the acronym SPAD.

4. The Three Operating Conditions of a Tire on a Wet Runway

The first available results of the sliding tests on the Caravelle have been the object of different theories of synthesis based on different models in order to explain the apparent scattering in the results. At this stage of the study, it appeared that a model based on that proposed by Gough in 1959 permitted better synthesis of the results, then a probable physical understanding of the friction of a tire against a wet runway.

Fig. 2 shows the model adopted, in which the tire-ground interface is decomposed into three arbitrarily distinct zones:

A zone I of dynamic flow, a zone II of laminar flow, and a zone 3 of "pseudodry" contact. In this latter zone, the tire is in partial contact with the runway and keeps trapped a certain amount of water in which a viscous pressure proportional to the speed is developed. Practically speaking, zone III is the only zone that gives rise to adhesion, tearing and hysteresis friction.

A theoretical study based on this concept of three successive zones makes it possible to show that, depending on the height of water and the speed, there are three distinct operating conditions as illustrated in Fig. 3. These are:

a) operating conditions A: at low speeds and low water height, only the "pseudodry" contact zone exists. Contact is partially dry as a function of the quantity $(H - g_p)$, g_p being a dimension representing the macrotexture and H being generally less than g_p. The part remaining wet in the tread, with negligible adherence, develops a viscous pressure proportional to this speed. These considerations show that the friction coefficient can be expressed in the following approximate form:

$$\mu = \mu_s - K1.H.V.$$

μs is the friction coefficient on a dry runway at the considered speed V.

K1 is a coefficient that takes into account the macrotexture, grain shape and runway porosity. Fig. 4 shows the variation of the friction coefficient μ at a constant speed V under operating conditions A for the Caravelle on the Brétigny airfield.

(b) operating conditions B: for a given value of HV, at a constant speed V/P, the critical height hc, defined by a critical Reynolds number such that:

$$Rc = \left| \frac{\rho_e}{\eta_e} \; V . \; hc \right|$$

becomes equal to the water height h. At this instant, a viscous flow appears (zone II) and the part in front of the tread is raised. This case of transitory operation is probably fugitive; it corresponds to Fig. 3 A-B. As soon as the speed increases, the critical height hc decreases, zone II is shifted to the back of the tread and zone I appears immediately. A frontal bead develops. The height ha of the point A at the front end of the tread increases with speed, then decreases.

The ratio ha/H is a function of the parameter: $(\rho_e \cdot V_2)/2p$.

The bounding line between operating conditions A and B shown in Fig. is defined by the following approximate relation:

$$H^2 = K2 \cdot \frac{\eta_e}{\rho_e} \cdot \frac{R}{V}$$

K2 is a combined coefficient that depends on tire shape and wear and runway texture. Thus, at a constant speed V/P under operating conditions B, ha/H and hc are determined, and so is the geometric shape of the tread and, consequently, the "pseudodry" contact area. Therefore, the friction coefficient becomes practically independent of the height H.

(c) operating conditions C: taxiing or pure dynamic flow /7
operating conditions. The water height permitting, and for a value of $(\rho_e \cdot V2)/2p$ greater than a value of about 1.45 (depending

on tire shape), viscous flow zone II and "pseudodry" contact zone III may disappear, and the tire will taxi. The water height h necessary for such a phenomenon to take place at the minimum speed of $V_p = \sqrt{2p/(\rho_e \cdot Cz)}$, with $Cz \simeq 0.70$, would theoretically be too great to be frequently encountered in practice; on the other hand, for greater speeds the water height necessary for taxiing decreases, and the phenomenon can be observed. Taxiing operating conditions C were not obtained during the tests conducted on the Caravelle aircraft. By way of illustration, a possible zone for these operating conditions has been plotted on Fig. 5 for the particular case of the Brétigny airfield. The increase in zones I and II by viscous pressure and dynamic pressure diminishes "pseudodry" contact zone III, which is practically the only zone to generate the friction coefficient.

5. Prediction of Braking Distances

The rather customary presentation of the results shown in Fig. 5 should not be used for the prediction of braking distances. Preference should be given to the representation $\mu = f(H \cdot V, \frac{V}{P})$ or $\mu = f(HV, \frac{Vpo}{P})$ for speeds corresponding to operating conditions A and B as illustrated in Fig. 6 and the representation $\mu = f(\frac{H}{R}, \frac{\rho_e \cdot V^2}{2p})$ for speeds corresponding to operating conditions B and C.

Under these conditions, the prediction of braking distances on a given airfield becomes feasible by virtue of knowing the networks preestablished for this airfield and the aircraft under consideration, of the curves $\mu = f(HV, \frac{V}{P}, \frac{\rho_e V^2}{2P}, \frac{H}{R})$. It is then possible to calculate the braking distance according to the relation given in Section 2.1.

It would seem preferable, however, and just as precise, to determine directly the networks of the curves yielding

$\frac{D}{m.V^2} = f(HV, \frac{V}{P}, \frac{\rho_a.V^2}{2P}, \frac{H}{R})$ without passing by way of the friction coefficient. Indeed, braking distances cannot be predicted unless the piloting law is fixed, i.e., unless the touchdown speed is proportional to the square root of the mass and if the incidence to the ground is kept identical, i.e., the constant[1] dimensionless parameters: $\frac{\rho_a.S.V^2}{m.g}$, S/R^2 and the parameter $\frac{V}{P}.g.R^2.\frac{\rho_a}{\eta_e}$ already included in the form of the parameter V/P, to almost constants. The reduced braking distance $D/m.V^2$, which is the simplified writing of $\frac{D}{m.V^2}(\rho_a.S^{3/2}.g)$, can then be represented by parameters identical with those of μ. Figs. 7 to 10 show the results for four different airfields. The influence of the two operating conditions A and B and the magnitude of the macrotexture effect can be seen in these figures. The best airfield from the point of view of braking is that with a large-grained, porous, asphalt coating. Fig. 11 permits comparison of the four airfields at the same incipient braking speed of 45 m/sec (87.5 Kt).

Remarks

(1) The purpose of the model proposed above is to permit development of a simplified method for predicting braking distances on the basis of different measurements that have a bearing mainly on the texture, in particular by developing special vehicles.

(2) The water height that acts in determining the friction coefficient, as was seen in Section 4 (a), must include the water lodged in the asperities of the runway coating; that is why it seems preferable to measure the water height by a neutron probe[2], such as was done during these tests.

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[1] In these relations the new parameters introduced are connected with the aircraft and the air: ρ_a: volumetric mass of air, S: reference surface of aircraft and m: mass of aircraft (in addition to mg).

[2] The neutron probe practically measures the volume of water contained per unit surface.

(3) Fig. 12 shows the results for the stopping distances of NASA's DBV[3] vehicle. Comparison of these results with those of Fig. 11 shows that the ratio of the braking distance for the wet case to that for the dry case varies for the aircraft and the vehicle in an approximately identical manner from one airfield to the other, but that the Roissy DBV is better than the Bricy, while for the Caravelle, the case is practically contrary. As soon as the incipient braking speed of the aircraft varies, immediate comparison of the results shows considerable scattering.

"A universal relation between the indication furnished by a friction measuring vehicle and the performances of an aircraft has not yet emerged. It is not very likely that such a relation will be found." But this pertinent reflection can be gainsaid if we make sure (for example on the DBV) that the incipient braking speed is representative of that of the aircraft. Finally, a method for transcribing performances can be developed soundly only with the aid of a test vehicle on which a great number of tests can be conducted on different coatings.

6. Reflections on Lateral Friction /9

Available lateral friction is not usually examined for an aircraft from the standpoint of braking performances incident to landing, for it does not come directly into play, as does longitudinal friction, in determining braking distances. Nevertheless, it must be taken into consideration for the following two essential reasons:

(a) lateral control on the ground, with free wheels, in case of sudden engine failure incident to takeoff (VMCG).

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[3] Vehicle developed by NASA, which measures the stopping distance, with two diagonal wheels locked and the other two free, beginning with V = 60 mph.

(b) lateral control on the ground, with braked wheels, in case of a crosswind.

In case (a), for aircraft with rear main landing gear, at VMCG, the aerodynamic surfaces alone ought to be able to ensure directional control of the aircraft, but the yawing torque required by the surfaces will be all the weaker as the skidding introduced by the yawing torque due to the motors will cause a considerable opposite yawing torque due to lateral friction of the wheels on the ground. According to recent tests, it seems that the maximum lateral mismatch observed, defining VMCG, is connected with the heading variation at the time of engine failure; thus, it appears that the wet runway condition becomes an important criterion in justifying VMCG.

Free-wheel lateral friction by its influence on VMCG would thus contribute to defining takeoff performances for transport aircraft.

In case (b), incident to braking on landing or acceleration stop, lateral friction must permit the aircraft to be kept on the runway in a crosswind. All along the trajectory, enough available lateral friction must exist to compensate for the lateral aerodynamic forces. It is possible that this friction, for certain runway conditions, is obtained for a sliding less than that giving maximum longitudinal friction. Safety rules insist in this case that there be a reduction in sliding; therefore, a certain degradation of braking distances.

Braked-wheel lateral friction by its influence on safety would thus contribute to defining landing and acceleration stop performances for all types of aircraft.

Fig. 1 shows the typical curve of the available lateral friction coefficient for a constant skidding (or drift) angle.

7. Conclusions

The results of braking studies in the USA and the United Kingdom have made it possible to gain a better understanding of friction phenomena and to develop testing methods for predicting aircraft braking distances.

Tests on the Caravelle have shown that Gough's model of three contact zones was satisfactory to interpret the results. It seems that there are three different operating conditions for a tire on a wet runway: operating conditions where the tire's entire tread is in "pseudodry" contact with the runway, conditions where the front part of the tread is separated from the ground by a dynamic flow followed by a laminar flow, and taxiing conditions.

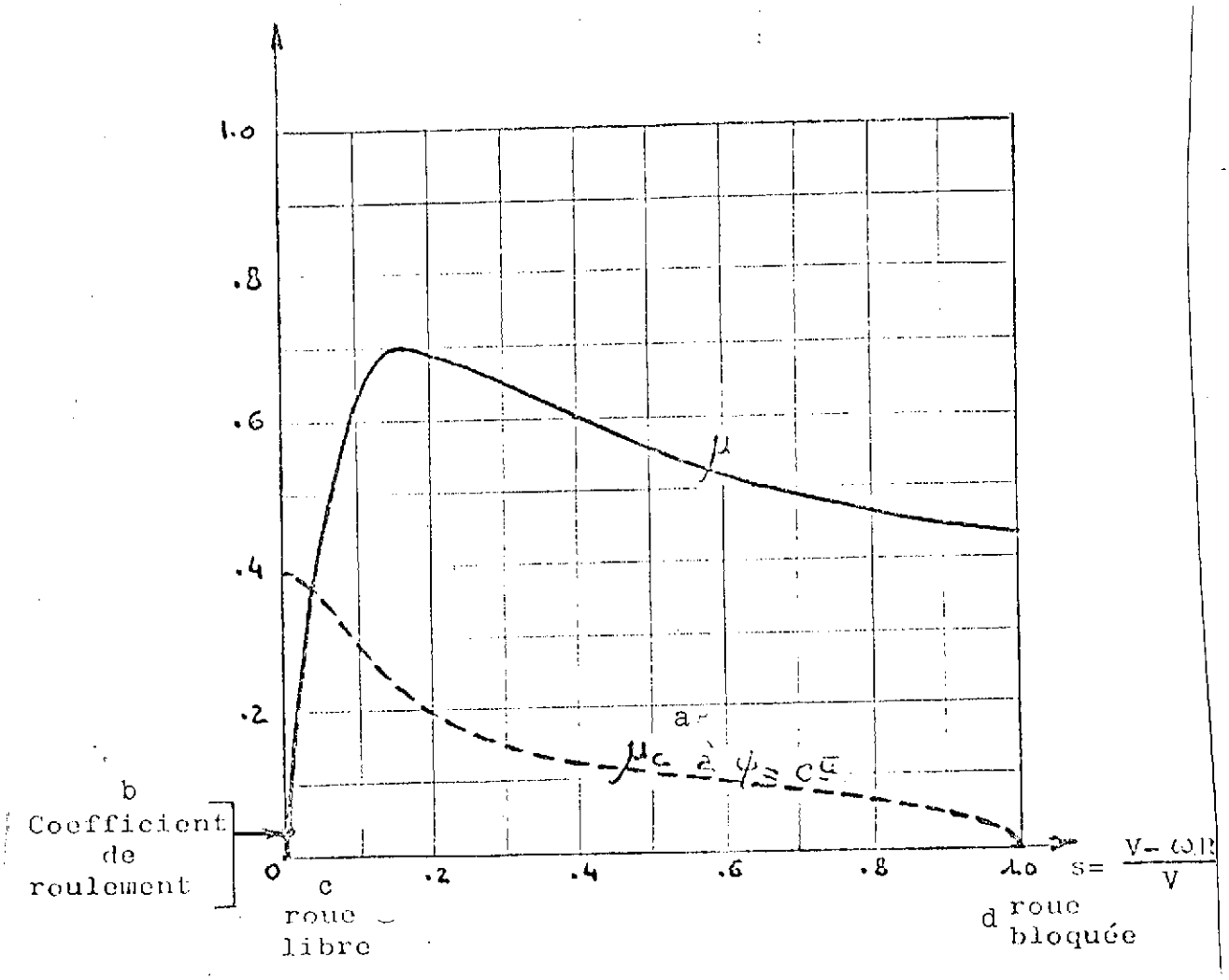
Taxiing conditions were not achieved during tests on the Caravelle.

Our present knowledge in the matter of friction and the test results are not yet sufficient to predict braking distances in a simple and satisfactory manner. Prudence is necessary before working out principles, procedures, or even regulations with regard to aircraft braking.

Theoretical studies must be conducted by aeronautics specialists to determine the deep causes of adhesion, which is the fundamental friction parameter inasmuch as the other parameters generally act as friction reducing agents.

Tests on aircraft, special research vehicles or mock-ups must be developed to determine the influence of tire characteristics (mixture, shape, tread design, wear), runway texture, and the nature of contaminants.

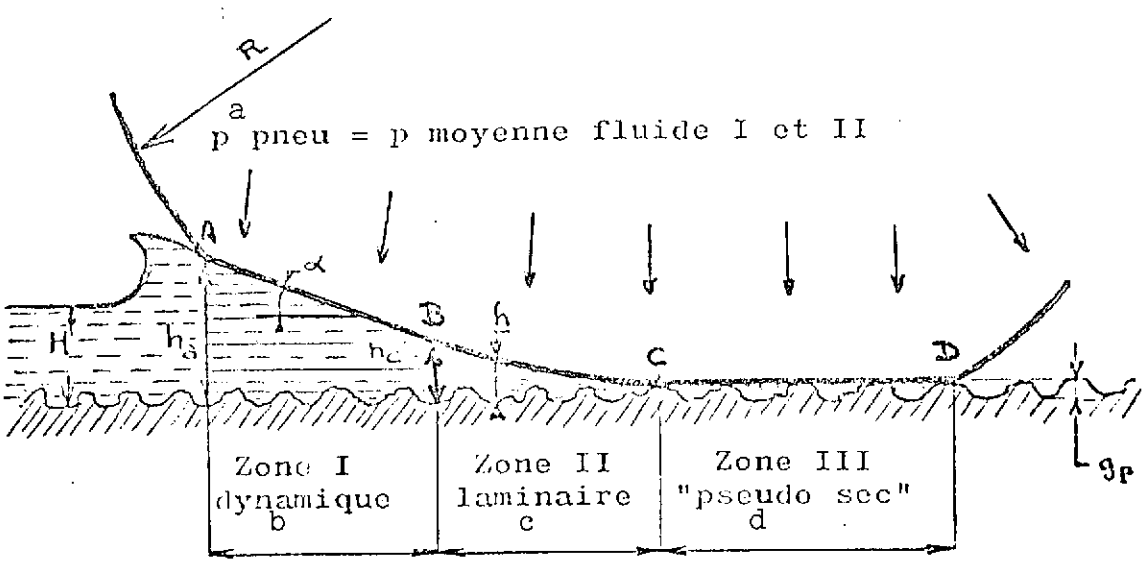
Aircraft braking performances on the ground have not been examined in the past with the same attention as traditional flight performances. Accident statistics due to the proper characteristics of aircraft (navigability) show that the braking phase is among the most critical. Pilots who have been questioned acknowledge that this braking phase is the most dangerous in view of the number of avoided accidents. To aid the development of air travel it is imperative to strike a happy medium between traditional flight performance studies and braking performance studies.



μ and μ_c are coefficients connected with the vehicle's direction and not with the wheel's plane of symmetry.

Fig. 1. Typical variation of the coefficients of longitudinal friction μ and available lateral friction μ_c with the sliding s.

Key: a. at
b. Taxiing coefficient
c. Free wheel
d. Locked wheel



$$\frac{H}{h_a} = f\left(\frac{H}{R}, \frac{\rho_e . V^2}{2p}\right)$$

$$h_c^2 = K_2 . \frac{\eta_e . R}{\rho_e . V}$$

$$\text{zone I} \rightarrow \alpha = K_3 . \frac{2p}{\rho_e . V^2}$$

$$\text{zone II} \rightarrow \alpha = K_4 . \frac{h^2 . p}{R . \eta_e . V}$$

with η_e = viscosity of water
ρ_e = volumetric mass of water

Fig. 2. Gough model of three zones.

Key: a. p tire = p fluid mean I and II
b. Dynamic
c. Laminary
d. "Pseudodry"

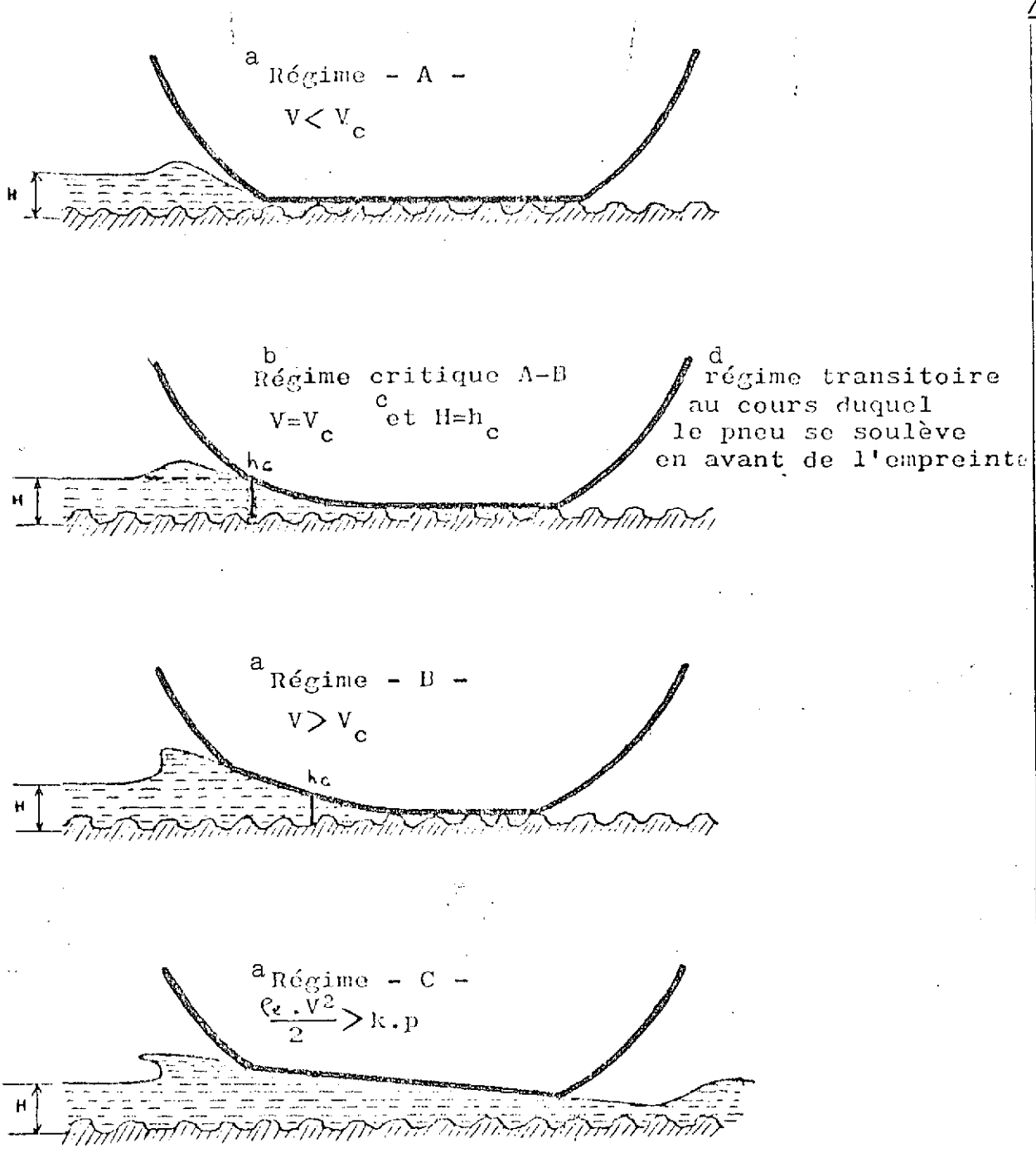


Fig. 3. The three operating conditions of a tire on a wet runway.

Key: a. Operating conditions ...
b. Critical operating conditions A-B
c. and
d. Transitory operating conditions during which the tire is lifted ahead of the tread

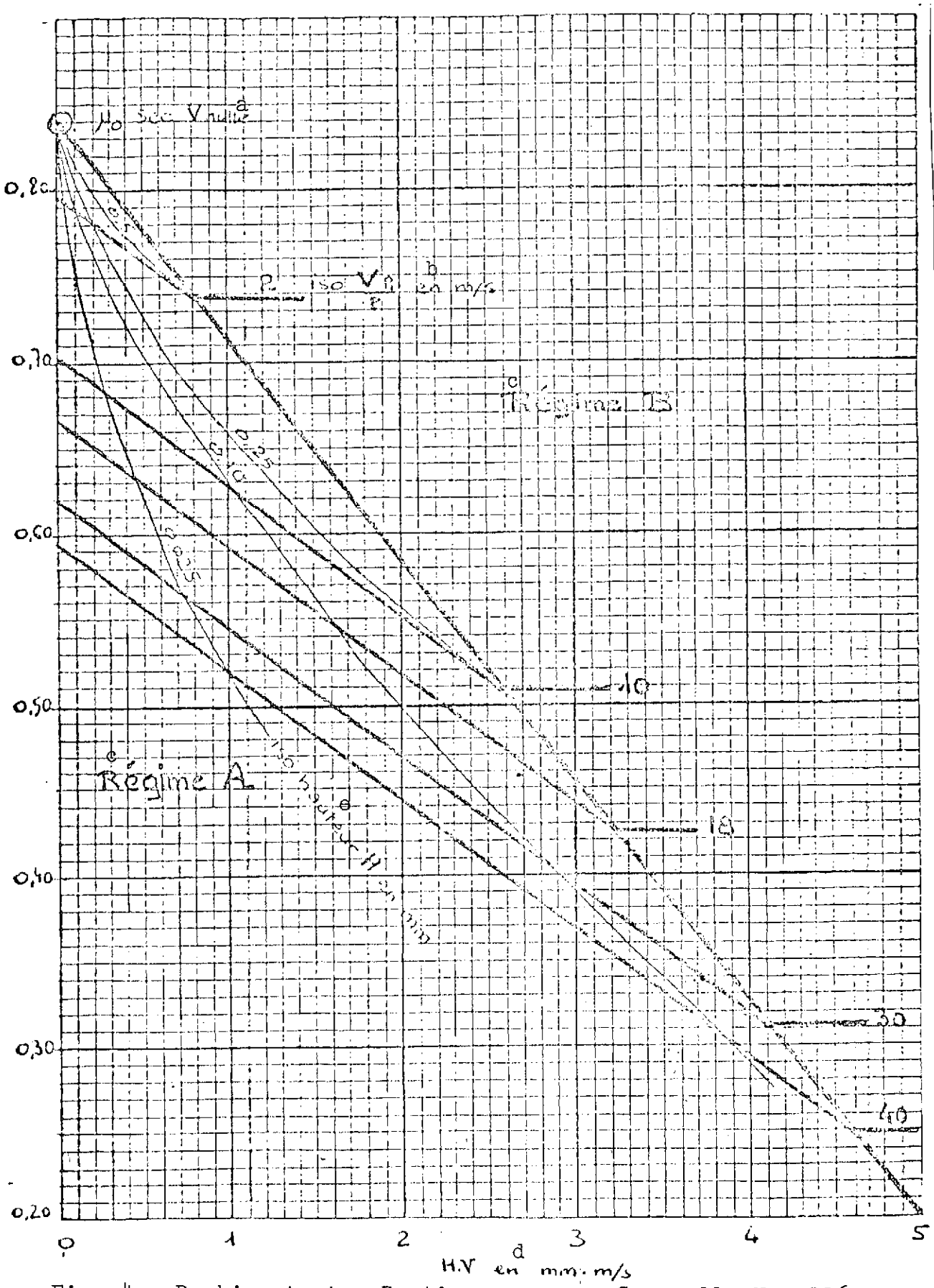


Fig. 4. Braking tests, Bretigny runway, Caravelle No. 116, equipped with SPAD, mean mass: 36,000 kg.

Key: a. zero; b. in m/sec; c. Operating conditions; d. in mm; e. Isoheight in mm

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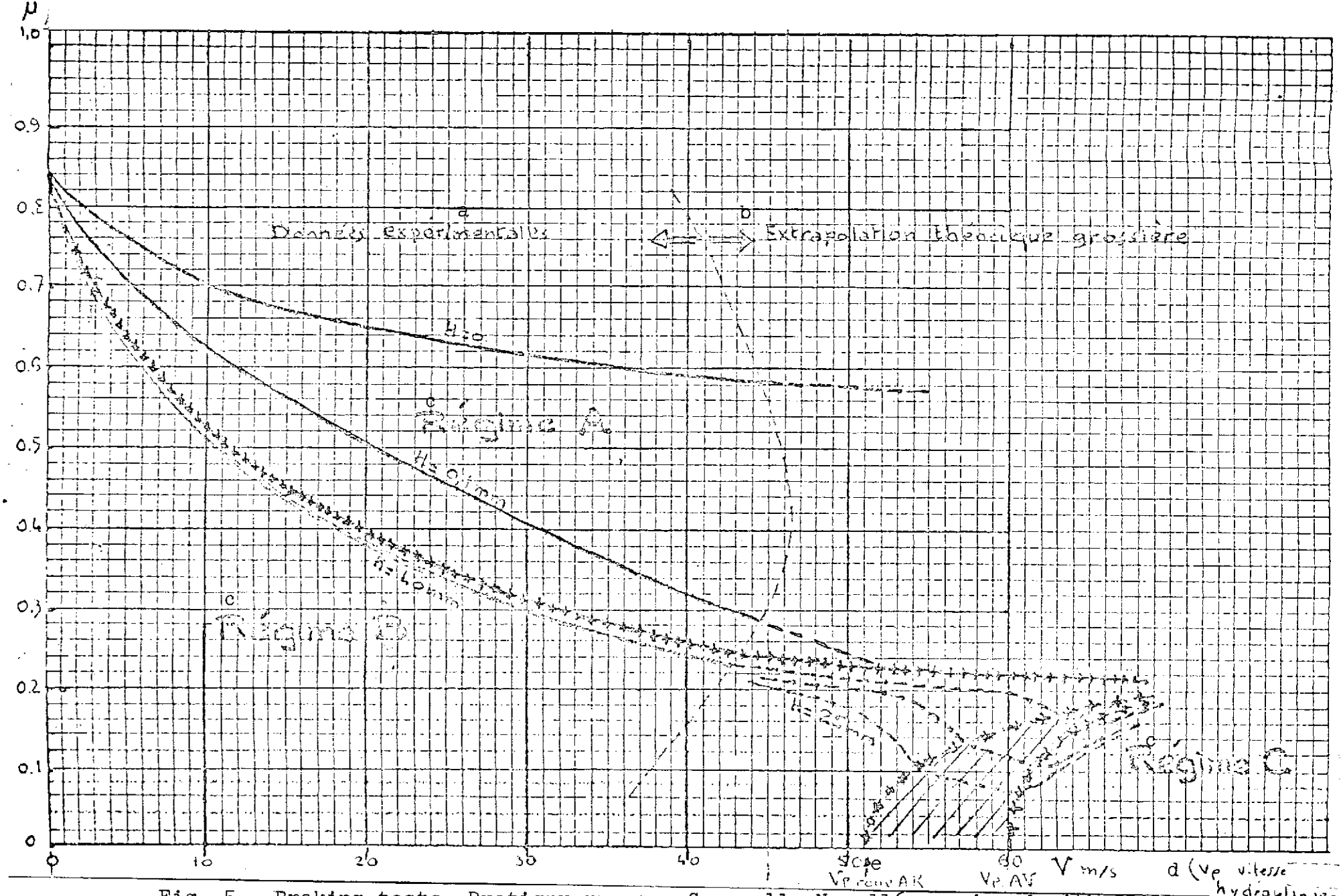

Fig. 5. Braking tests, Bretigny runway, Caravelle No. 116, equipped with SPAD, mean mass: 36,000 kg.

Key: a. Experimental data; b. Gross theoretic extrapolation; c. Operating conditions ... d. (... taxiing speed); e. V_p wheel AK

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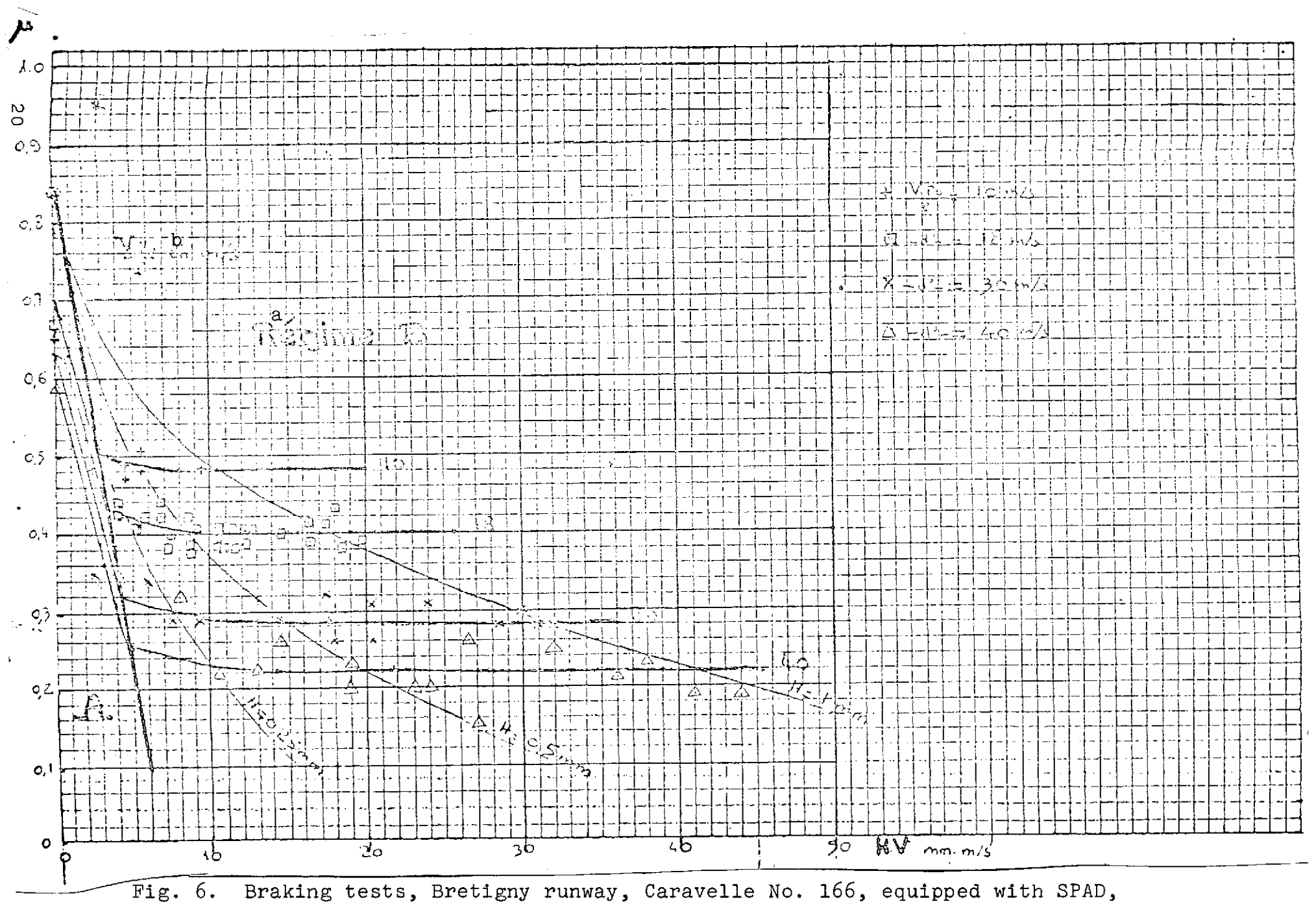

Fig. 6. Braking tests, Bretigny runway, Caravelle No. 166, equipped with SPAD, mean mass: 36,000 kg

Key: a. Operating conditions; b. in

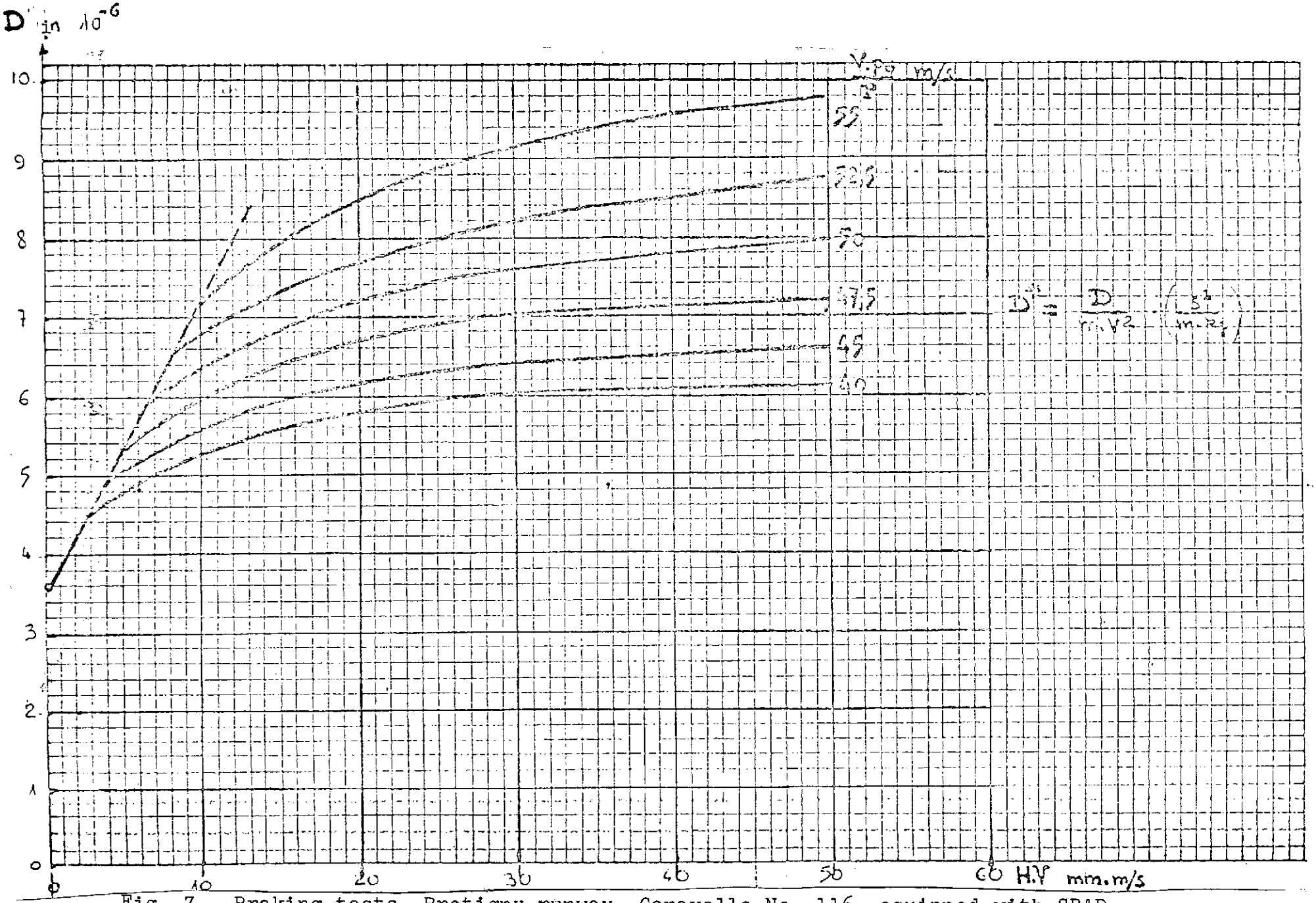

Fig. 7. Braking tests, Bretigny runway, Caravelle No. 116, equipped with SPAD, mean mass: 36,000 kg.

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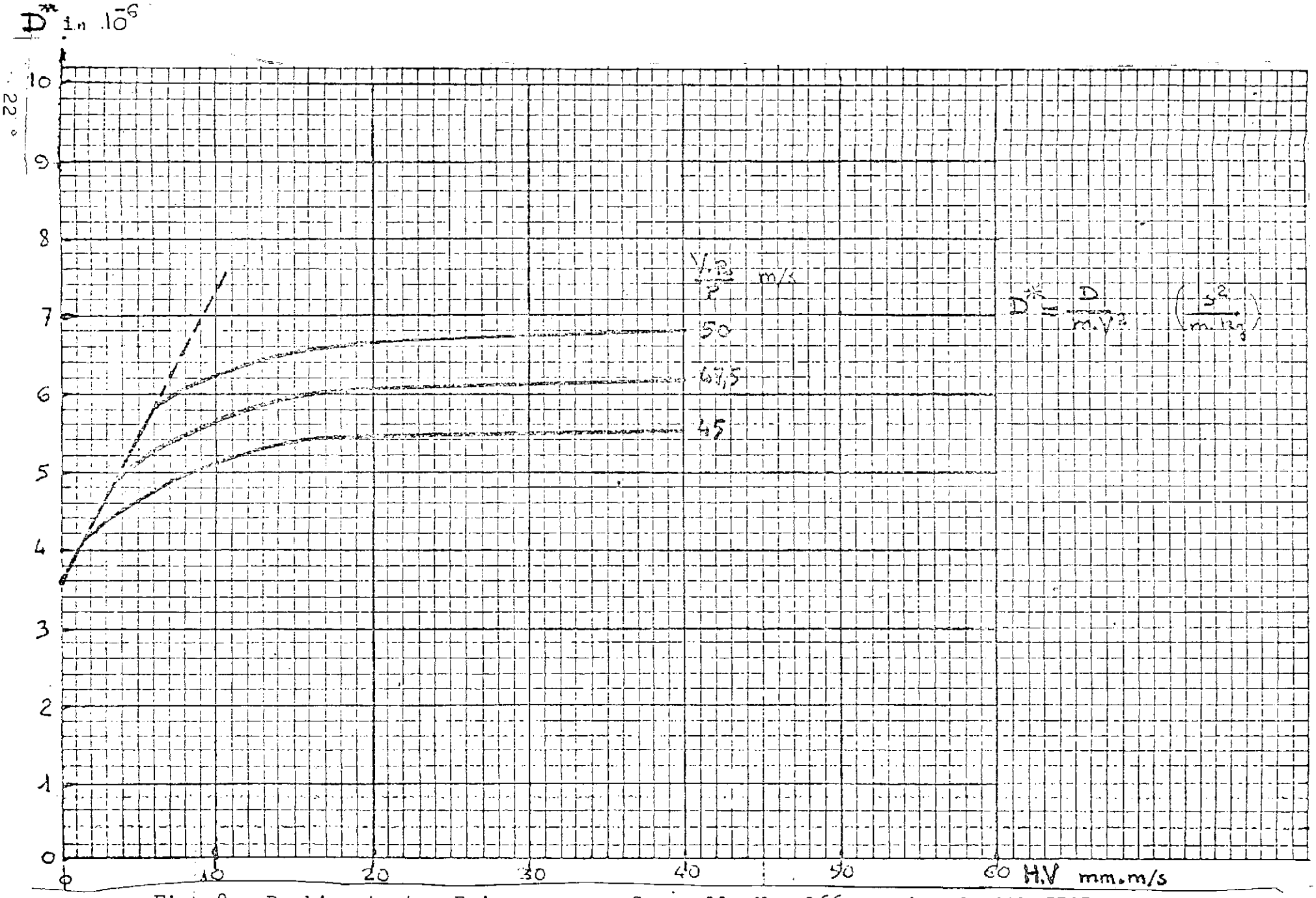

Fig. 8. Braking tests, Bricy runway, Caravelle No. 166, equipped with SPAD, mean mass: 36,000 kg.

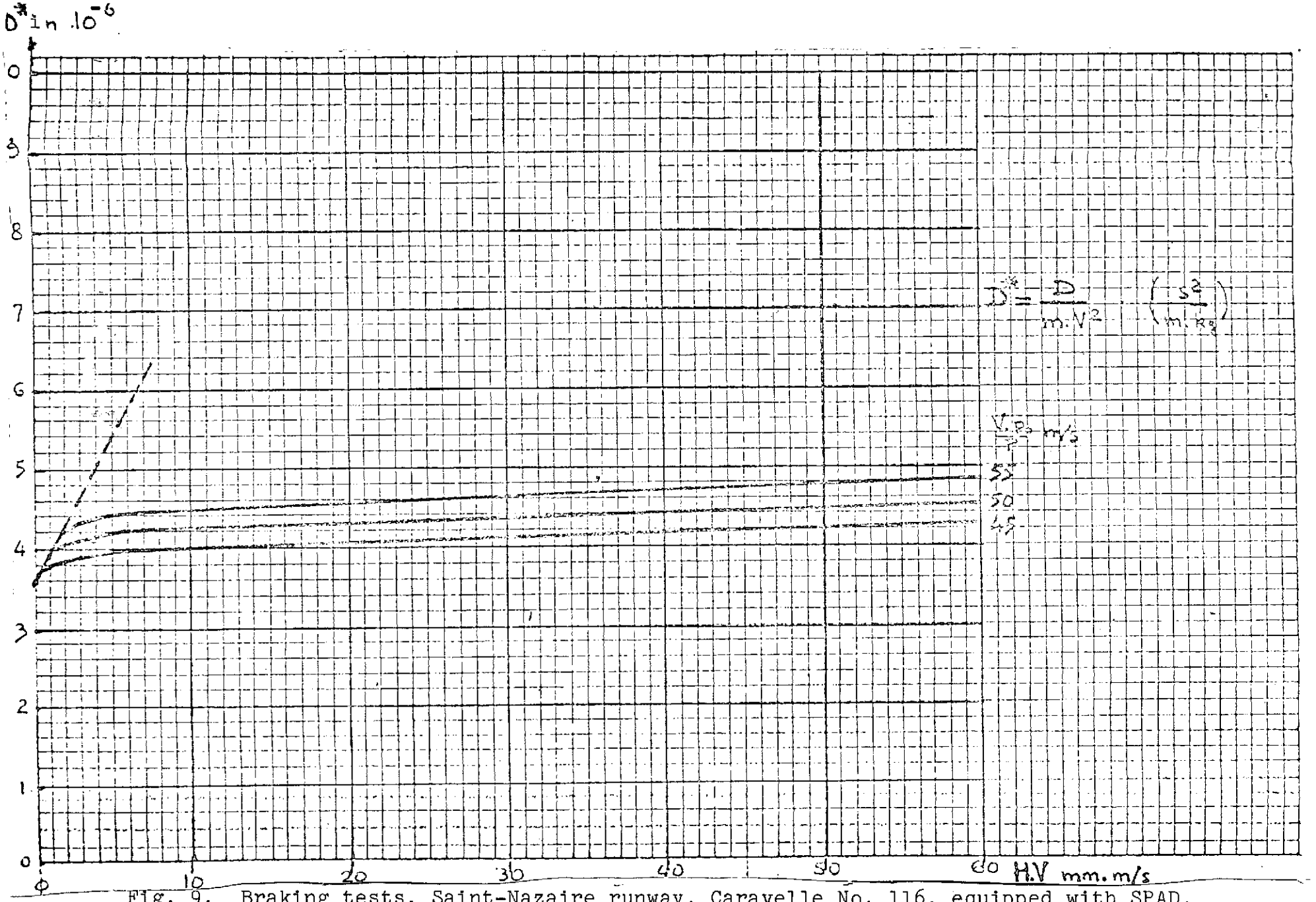

Fig. 9. Braking tests, Saint-Nazaire runway, Caravelle No. 116, equipped with SPAD, mean mass: 36,000 kg.

Fig. 10. Braking tests, Roissy runway, Caravelle No. 116, equipped with SPAD, mean mass: 36,000 kg.

Fig. 11. Braking tests, comparison of four runways at the same incipient braking speed of 45 m/sec, Caravelle No. 116 equipped with SPAD, mean mass: 36,000 kg.

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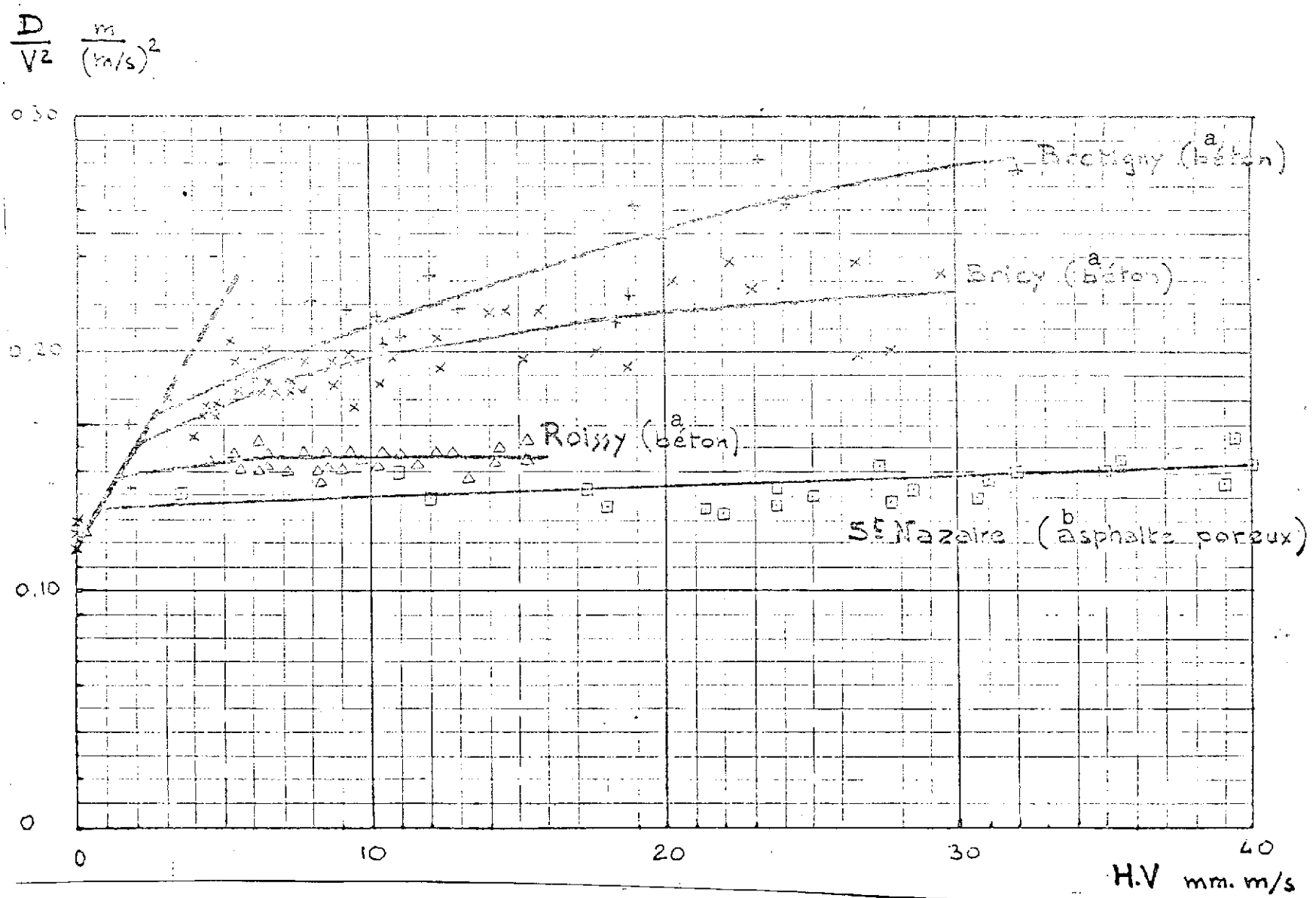

Fig. 12. Braking tests, DBV stopping distances, incipient braking speed: 60 mph on four runways utilized by the Caravelle No. 116.

Key: a. (concrete)
b. (porous asphalt)

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