5. AQUAPLANING

THE BRITISH MINISTRY OF TECHNOLOGY PROGRAMME

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SUMMARY

Research at the College of Aeronautics, Cranfield, using a Hawker Siddeley Hunter F.6 has been concerned with discovering the minimum depth of standing water required to support an aquaplaning tyre and to evaluate the effects of runway texture and tyre pressure on this critical depth. The method used was to measure the height of the aquaplaning tyre above the runway surface and the report discusses briefly the probe devised for this purpose. Attempts have been made to obtain criteria for runway surface texture and to correlate these with the aquaplaning characteristics of the runway.

The height of the aquaplaning tyre above the runway surface is proposed as an important "characteristic" of the phenomenon which can be used as a measure of runway and tyre performance. Measurements made have yielded some information on tyre distortions during aquaplaning, which assists in the description and understanding of the phenomenon.

INTRODUCTION

The phenomenon of pneumatic tyre aquaplaning must now be familiar to everyone employed in the aircraft and vehicle operating fields. The importance of the research and the relevance of the problem is brought into focus periodically by accidents in which aircraft overrun or lose directional control whilst landing in heavy rain or on a flooded runway.

It would appear that two basic requirements have to be present to produce aquaplaning conditions:

(i) A speed above a certain critical aquaplaning speed

(ii) A certain minimum depth of standing water on the runway or pavement.

Previous research notably by NASA in the United States has produced the now familiar simple formula $V_c = 9\sqrt{p}$, where V_c is expressed in knots and p is tyre pressure in psi, for the estimation of the critical aquaplaning speed for a vehicle. This formula has been shown to be quite accurate generally, although it now appears that this basic planing speed varies slightly with deflexion, loading, and tyre design (ref. 1).

From a practical point of view, education of the automobile driver and an awareness of the problem could go someway toward reducing aquaplaning accidents on the highways. However, there is very little that a pilot can do about his speed on the runway – this to all intents and purposes is fixed.

The Ministry of Technology research programme at Cranfield sprang from a requirement for a system to warn landing pilots that aquaplaning conditions were present so that if considered advisable, a short standoff period for standing water drainage or, in the worst case, a diversion could be initiated.

To meet the requirement for an indicator of standing water on a runway, the Ministry of Technology issued a contract to Inertia Switch Limited for a water depth gauge for use on runways. This first appeared in prototype form in 1963 and has since been installed under development at Gatwick, London. The indicator was also installed on the landing research runway at NASA Wallops Station for the Joint NASA-British Ministry of Technology Skid Correlation Study. The system measures water depth at selected points on the runway and records this information remotely in the airport control tower. To use this device, it is obviously necessary to know precisely at what water depth aquaplaning is likely to occur, and it was to meet this requirement that the Cranfield aquaplaning research programme was initiated by the Ministry of Technology.

It was thought at the outset that runway texture might affect the critical water depth required for aquaplaning; thus, to have this variable present in the trials, a special test area was constructed on the main runway at Cranfield.

This area measuring 200 by 60 feet was composed of six different types of surfaces covering a large range of surface texture and generally being representative of standard runway surfaces in use in the U.K. at the time. (See figs. 1 to 6.)

The specific object of the trials then was to determine the minimum depth of water required for aquaplaning on the six surfaces and to observe the effect of any variation in tyre pressure on this minimum depth; the answers obtained could then be used as a danger datum for the water depth indicator.

EXPERIMENTAL PHILOSOPHY

An aquaplaning tyre appears to have two unique measurable characteristics: its distortion, or shape, and the minimum height above or the minimum separation between it and the pavement surface, which will be referred to as the aquaplaning height. These two dependent variables appear to be functions of normal load, tyre pressure, tyre design (tread and mechanical properties), ground speed, water depth, and pavement surface texture. Wheel rotational speed may also exert a small influence on these two characteristic parameters.

In the programme at Cranfield attempts were to be made to measure the aquaplaning height and also to obtain some idea of the tyre shape when aquaplaning. To study the effect of all the previously mentioned controllable parameters on these two, although desirable, was considered to be excessive for the present programme, and to achieve the stated aims, it was decided to measure the variation of aquaplaning height and tyre shape with water depth for the six different surfaces available at Cranfield at two tyre pressures.

To obtain the values of the minimum water depth to support aquaplaning, it would then be required to observe the relationship between aquaplaning height and water depth for a given surface and pick off the depth at which this aquaplaning height became zero, that is, when the tyre achieved ground contact. This technique had already been used by Gray at the Royal Aircraft Establishment, Farnborough, with some success using plasticine strips as a measuring device (ref. 2).

It was also considered that this information together with any data on tyre deformation would provide additional understanding of the mechanism of aquaplaning.

THE AQUAPLANING HEIGHT INDICATOR

After a series of attempts at using mechanical devices operated by contact with the tyre, it was eventually decided to develop an electrical probe to measure the clearance between runway surface and tyre. The reasons for abandoning the use of mechanical devices were many, the chief ones being the restrictive effects of such devices on the water under the tyre and the difficulties of separating tyre effects from those of the local water under pressure. These devices also required an involved resetting procedure between runs and therefore limited the number of runs possible per aircraft sortie.

Following considerable development the sensor shown in figure 7(a) was produced and this has since functioned successfully, measuring aquaplaning heights with an excellent degree of consistency.

The sensor consists of 36 individual probes, each capable of measuring the height of the particular area of tyre immediately above it. The basic principle of the probe lies in the measurement of the conducting power of the column of water immediately surrounding it. Any interfering body reduces the height of the column and hence the conducting power; thus, there is a drop in output current between centre pole and surrounding earth plate. A charged guard ring surrounding the centre pole ensures that the probe is sensitive only to restrictions vertically above it; there is no sideways looking. This guard ring also improves the range of the probe.

For processing and recording purposes the probes have been grouped into units of six. One probe in each unit is connected in parallel and has its own individual electronic circuit, being completely independent of the other probes in the unit. There are, therefore, six electronic channels. Test tyre dimension and the spacing of the probes at 1-inch intervals result in only four or five probes being affected by the tyre traversal; thus, no two probes in the same channel can be affected.

The output voltages from each of the six channels are conditioned and stored on magnetic tape from which they can be played back at leisure on an oscilloscope and analysed.

The resulting outputs give a time history of the aquaplaning height at four or five points on the cross section of the tyre. Since these are all measured from a flat surface this also conveys the tyre distortion and provides a three-dimensional picture of the tyre foot print.

Laboratory tests have been carried out to determine environmental effects on the sensitivity of the probes. Since the basic principle relies on the water conductivity, temperature and contamination were found to influence the sensitivity, as was expected.

It was found after intensive laboratory work that the effect of both temperature and contamination on the sensitivity of the probes was to increase the output signal for any given aquaplaning height by a constant multiplying factor. Thus the measuring of the output signal for any fixed aquaplaning height would supply this multiplying factor for any given water condition. The laboratory calibration curve could then always be used to analyse the results once the water factor had been evaluated. This water factor was obtained in situ during the trials, immediately prior to each run.

A micrometer system was devised to enable accurate calibration to be achieved. This was conducted in the laboratory and was found to be repeatable to within 0.005 inch in height measurement.

TEST TECHNIQUE

The aircraft used in the trials was a Hawker Siddeley Hunter F.6 jet fighter, the mainwheels equipped with standard Goodyear 29×16, 14 ply tyre having seven circumferential grooves. Average operating all up weight of the aircraft was 18 000 pounds.

The range of ground speeds required in the ponds was such that a touch-and-go procedure was necessary, using the throttle to adjust to the required pond entry speed. Constant centre-of-gravity position and fully down elevator ensured an aircraft attitude consistent with small aerodynamic lift and a reasonably constant wheel loading.

The aircraft was fitted with wheel speed generators, the output being recorded on paper by a Hussenot A13 type recorder. It was discovered after some time that wheel speed prior to entry gave values of ground speed accurate to within 1 knot once the system had been calibrated using a take-off camera.

The aquaplaning height indicator was installed with precision in the test area, great care being taken to ensure that it was at the same level as the runway surface to within 0.01 inch. The discrepancy in level between surface and each individual probe was measured with a micrometer system to 0.001 inch (fig. 7(b)).

Water depth was measured on the hypotenuse of a 20° wedge. Such a method, although less accurate than the needle micrometer type device used by Road Research Laboratory, avoided any local texture effects and gave the water depth from the peaks of the asperities. In calm weather it was possible to measure the water depth to an accuracy of 0.025 inch. This method of water depth measurement, however, became impracticable at depths below 0.1 inch. The needle type method was rejected for use at these low depths since it was thought that the texture variations on the surfaces to be tested, being of the same order as the water depths, would prevent any reasonable useable value being obtained.

The water spray patterns were photographed and their behaviour with variations of speed, water depth, and tyre pressure studied.

Prior to each run, one probe in each channel was covered with a bridge 0.1 inch above it as a reference. The magnitude of the output signal, when compared with that achieved in the laboratory calibration, provided the water constant for that run.

Analysis was simple and involved playing back the tape to obtain a visual signal on a storage oscilloscope. This could then be photographed, traced, or analysed on the tube itself. By using the calibration curve and the water correction factor the traces of output voltage against time for each channel could then be converted into aquaplaning height-time curves which were also tyre profiles. The use of a long strip of Secomastic along the sensor enabled the tyre passage to be located with respect to the individual channels and so fix the position of each trace in the tyre cross section.

SURFACE TEXTURE MEASUREMENTS

Attempts were made during the trials to obtain some numerical rating to describe the texture and the drainage characteristics of the test surfaces in order to observe whether there existed any correlation between these and the aquaplaning characteristics of the surfaces. Three methods were used to obtain some measure of the surface characteristics:

(1) Sand-Patch Method

The sand-patch method devised by the Road Research Laboratory is intended to obtain the mean depth of the asperities. This is done by working a known volume of sand into the surface texture to form a circular patch in which all the indentations in the surface are filled. From the known volume and the measured area of the patch a mean asperity depth may be calculated.

(2) Outflow Meter

An outflow meter as described by Moore (ref. 3) was constructed and used to measure the channel drainage characteristics of the surface. The meter consists basically of a loaded open cylinder sitting on a rubber ring base. The cylinder is set on the surface and filled with water. The time taken for the water to fall from one fixed level to another through the drainage between rubber base and the surface is recorded and used directly as a measure of the surface characteristics.

(3) Impression Method

Plasticine blocks were squeezed into the surfaces to obtain casts of the texture. Magnified shadow images of the cross-sectional profiles were then projected onto a paper screen and drawn. A straight line was drawn over the tops of the asperities and the drainage area per inch length under this line was measured.

RESULTS

Aquaplaning Height

Figure 8 shows the curves obtained for aquaplaning height of the tyre against water depth for a tyre pressure of 120 psi. The speed used throughout these tests was 140 knots ground speed, equal to 1.47 V_c.

The intercepts with the horizontal axis give the critical water depth for aquaplaning for the various surfaces. The Marshall asphalt surface gave identical results to the lightly brushed pavement concrete, and the grooved concrete gave identical results to the grooved asphalt. These facts seem to indicate that the microtexture of the surface has little or no effect on the aquaplaning characteristics of a surface.

The grooved surface proved to be the least prone to aquaplaning, requiring some 0.12 inch of water to support the tyre clear of the runway; the scored concrete followed, with the lightly brushed pavement quality concrete and Marshall asphalt decidedly the worse. It is worthwhile noting that on the very lightly brushed concrete under these test conditions, it required less than 0.05 inch of water to cause aquaplaning, and runs in slightly less than 0.1 inch showed all the characteristics, including spin-down and suppression of the bow wave, as well as an indicated separation from the surface.

Figure 8 shows that the grooved and scored surface characteristics actually cross and this caused some concern for a time. It was noted, however, that tests carried out by Moore (ref. 3) in an aquaplaning study involving the experimental measurements on the sinkage of flat plates onto surfaces of different texture show similar characteristics for similar surfaces. One can consider the flow of water from beneath the tyre (fig. 9) to be composed of a bulk flow between the tyre undersurface and a point just clear of the surface, a boundary flow in the region immediately adjacent to the asperity peaks, and a channel flow in the asperity troughs. With the tyre some distance from the surface, the greater openness of the texture at the peaks of the asperities for the scored concrete (fig. 10) allows the boundary flow to be much larger than for the grooved surface. When the tyre approaches the surface, however, the predominating flow is the channel flow and the measured drainage area per inch is larger for the grooved surface. The square grooves also have superior discharge characteristics to the triangular ones.

It is also interesting to note that for both concrete and asphalt, the curves of aquaplaning height against water depth with and without grooves have the same shapes with a near constant displacement of aquaplaning height. This apparently common influence of the grooving can be attributed directly to the increased water drainage in the grooves themselves. In this context, tests on a surface having grooves of different dimensions could prove interesting and illuminating.

Effect of Tyre Pressure Variation

Figure 11 shows plots of aquaplaning height against water depth for two surfaces at two tyre pressures, 200 psi and 120 psi, with all other conditions constant. It can be seen that the softer tyre aquaplanes considerably higher in the water, and thus is more prone to aquaplaning on a given surface. The reduction of pressure will, of course, also reduce the aquaplaning speed so that the two conditions really represent two different ratios of speed to aquaplaning speed $\frac{V}{V_c}$. Whether this is the influencing parameter as opposed to pure shape difference of the softer tyre will not be known until tests can be carried out at two different speeds giving the same two ratios at equal tyre pressures. It is worthwhile noting here that the figures quoted in the previous section for critical aquaplaning depth for the various surfaces are pessimistic. The normal aircraft would be more likely to touch down in the region of 1.1 V_c than 1.47 V_c, and therefore, as can be seen from figure 11, the critical depth for the lightly brushed concrete and Marshall asphalt would be slightly less than 0.1 inch. This value, although extremely possible to envisage on a runway, is far less frightening than the previous figure of 0.05 inch.

To justify the interpolation of these curves and to show that no strange occurrences were taking place at their lower ends, a further experiment was devised to verify the results obtained. In steady headwind conditions of about 15 knots the water in the ponds tends to heap at the downwind end giving a longitudinal water profile which could be measured and recorded as shown in figure 12. Tests conducted over a period of time showed that in the right conditions this profile remained constant. The aircraft was then taxied at the appropriate speed into the deep end, spin-down occurring at the entry point. By observing the time elapsed before spin-up commenced, one could pinpoint the location of spin-up in the pond and hence read off the water level at this point. This test was only possible when the critical depths were 0.1 inch or above owing to the difficulty in depth measurement below 0.1 inch. The results obtained for these surfaces, however, showed close agreement with the values obtained by extrapolation.

Wheel Spin-Down

Figure 13 shows the variation of spin-down rate with water depth for two surfaces, the lightly brushed concrete and the grooved concrete, both at tyre pressures of 120 psi.

The rate of spin-down for the grooved concrete is seen to be considerably higher than for the lightly brushed pavement concrete. Since the rate of spin-down is proportional to the hydrodynamic spin-down moment, this is obviously less for the pavement concrete. The main difference between the two is the depth to which the tyre has sunk in the water and the aquaplaning height (fig. 14). Thus these two factors must have produced either a reduction in hydrodynamic force or a large change in its orientation.

It is seen also that for a given surface the spin-down rate and hence the spin-down moment both decrease with decreasing water depth, the main difference again being a reduction of both sinkage depth and aquaplaning height. It is interesting to note that the curve of spin-down rate for the grooved concrete starts reducing rapidly with water depth from 0.2 inch. This value at which the gradient changes coincides with the value of the critical water depth under these conditions.

Observations on the Mechanism of Aquaplaning

The longitudinal shape of that portion of the tyre influenced by the water shows a forward wedge region where the tyre elements have a velocity relative to the water generating the hydrodynamic force. Behind this area and about the instantaneous centre is a region where the tyre and water velocity vectors are in the same direction. In this region it is difficult to envisage a hydrodynamic force, although cross sections of the tyre here indicate a large pressure beneath it, distorting it as shown in figure 15. The pressures in this region appear to be decidedly more of a viscous nature, and theorists may feel that this demonstrates the type of distortion which would arise from the classic parabolic viscous pressure distribution generated beneath a flat plate. Tests have shown that a large amount of water from under the tyre is displaced in the sideways direction and the presence of this transverse pressure gradient across the tyre would generate this flow.

Such a viscous pressure would tend to increase as the gap between tyre and surface decreases and this is borne out by comparing the distortions of the tyres shown in figure 15. The tyre planing in the lower depth has a far larger distortion of the centre portion indicating an increase in viscous pressure in this region.

This increase of viscous pressure in what is termed the "squeeze film region" suggests a decrease in the hydrodynamic force as the water depth is decreased. Figure 15 shows that the depth of sinkage into the water reduces with water depth and this together with the marked reduction in spin-down moments tends to confirm this reduction in hydrodynamic force and increase in viscous pressure force as the level of water is reduced, the tyre walls approaching closer to the surface in order to generate the increased viscous pressure.

Thus it would appear that the information obtained from these tests tends to support the now generally accepted theory that the aquaplaning tyre is supported partly by hydrodynamic force and partly by viscous forces in the "squeeze film region." This mechanism has been proposed recently by a number of people. There does, however, appear to be an interchange between the two forces and in small depths of water the viscous force appears to become predominant.

Surface Texture Correlation

Figure 16 shows a plot of critical water depth for three types of surfaces against their value of texture obtained using the outflow meter. Here again there was no distinguishable difference between the grooved asphalt and grooved concrete, the large volume of drainage in the grooves presumably masking the differences in microtexture.

It was found that the sand-patch method was extremely difficult to use on the grooved surfaces, the sand tending to run out along the grooves making the true area covered extremely difficult to evaluate.

The third method used, obtaining casts of the surface and measuring channel area per inch, proved to be possible only for the surfaces with large drainage channels, that is, the scored and grooved surfaces.

It may be added also that very little consistency was achieved with any of these texture measurements on any particular one of the surfaces, this being more a reflection on the consistency of the surfaces than the measuring equipment. The values used are average values from a large sample which showed a great deal of scatter. It would appear that texture measurements on such surfaces may require some form of statistical analysis.

As a result of these limitations only two points were obtainable for the sand-patch and the casting methods, whereas three were obtained from the outflow meter values. Figure 16 shows a rapid improvement with any reasonable texture followed by small gains due to variations in the form of drainage. A similar type of curve has been obtained by NASA in a correlation of friction coefficient and surface texture obtained in a similar manner to the sand-patch method but using grease instead of sand (ref. 4). Further tests are required on other surfaces to confirm the form of this correlation. The casts of the scored and grooved surfaces gave average values for channel cross-sectional area per inch as 0.013 square inch and 0.016 square inch. These figures support the theory that the grooved surface is superior to the scored surface with regard to critical water depth.

CONCLUDING REMARKS

Critical water depths have been obtained for a Hunter F.6 aircraft at two tyre pressures and on six surfaces. The critical water depth required for aquaplaning varies considerably with surface texture and tyre pressure at a given speed. Aquaplaning has been shown to be possible on lightly brushed concrete pavements at water depths of less than 0.1 inch. Grooving appears to improve the characteristics of a runway considerably, increasing the critical aquaplaning depth by as much as a factor of 5. The predominant factors in the grooving seem to be channel drainage area per inch and also the shape of the channel cross section. Data on tyre deformation appear to indicate that the aquaplaning tyre is supported partly by hydrodynamic and partly by viscous forces, with the viscous pressure force predominating at low water depths.

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3. Moore, Desmond F.: Drainage Criteria for Runway Surface Roughness. J. Roy. Aeronaut. Soc., vol. 69, May 1965, pp. 337-342.
4. Horne, Walter B.; and Joyner, Upshur T.: Traction of Pneumatic Tires on Wet Runways. Conference on Aircraft Operating Problems, NASA SP-83, 1965, pp. 9-17.

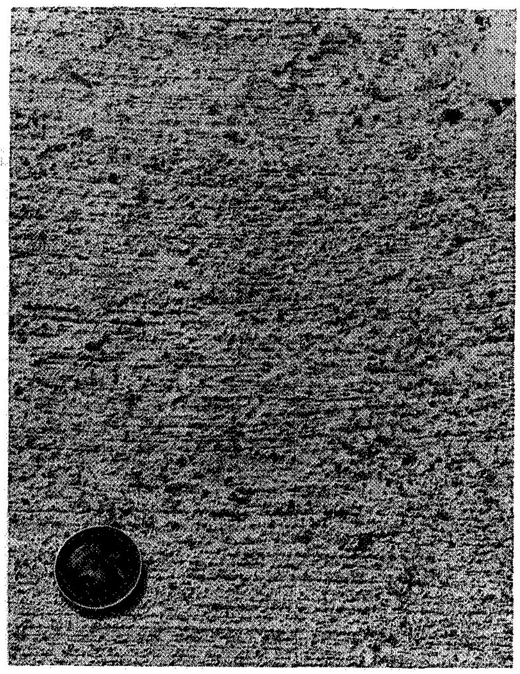

Figure 1.- Lightly brushed concrete.

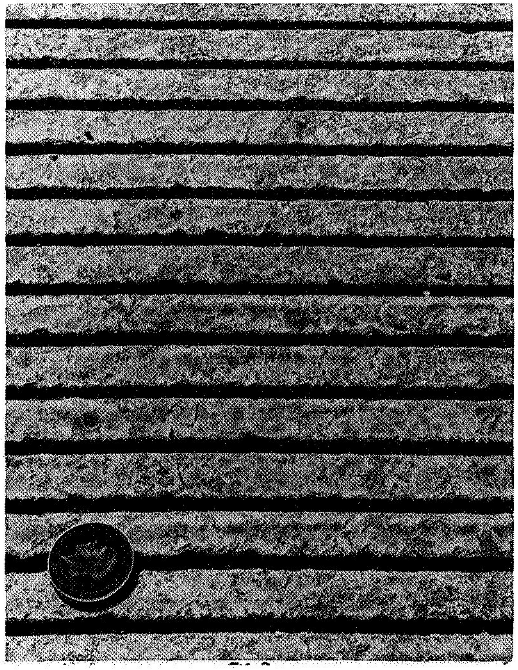

Figure 2.- Grooved concrete.

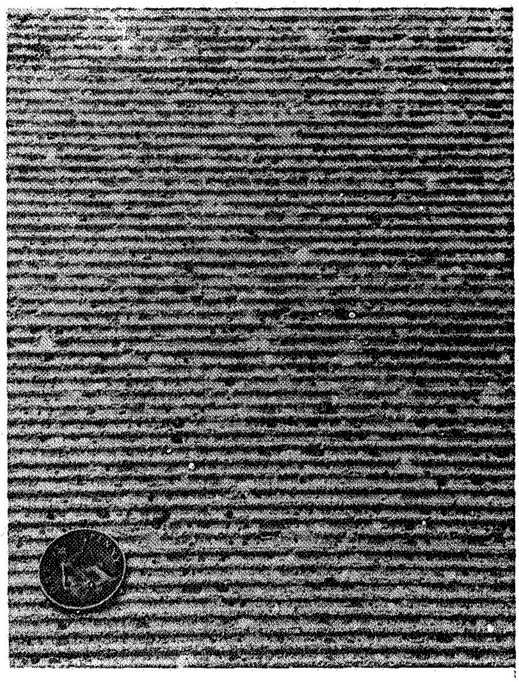

Figure 3.- Scored concrete.

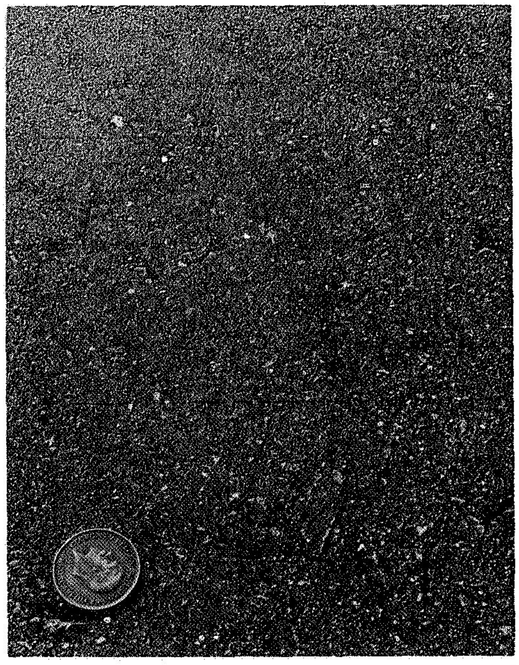

Figure 4.- Marshall asphalt.

Figure 5.- Grooved asphalt.

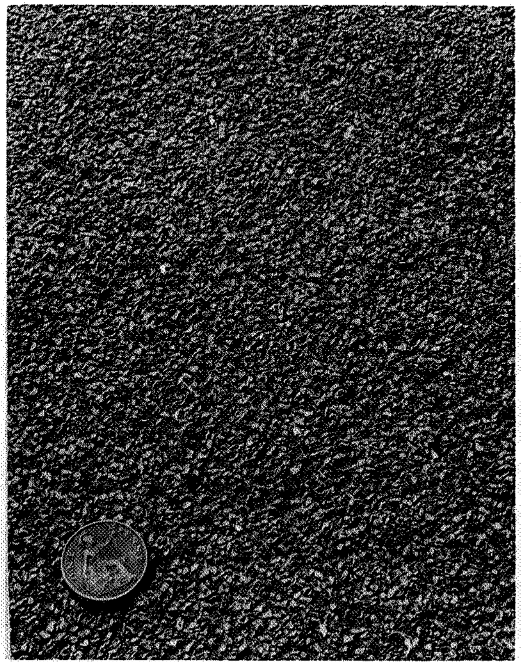

Figure 6.- Asphalt dressing.

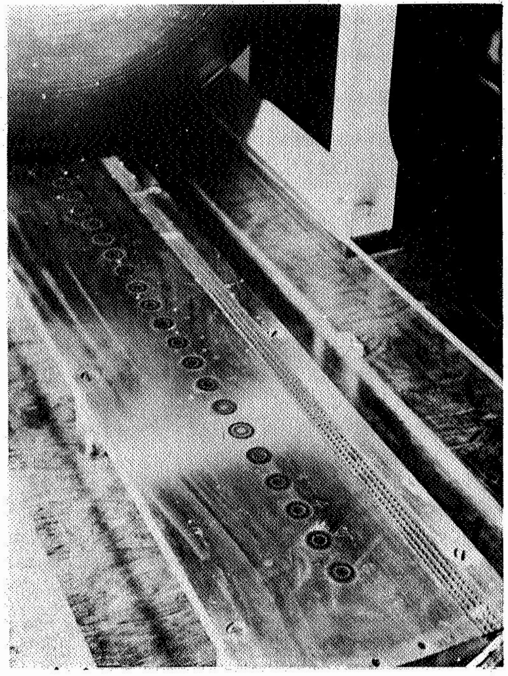

Figure 7(a).- Sensor used to measure aquaplaning height.

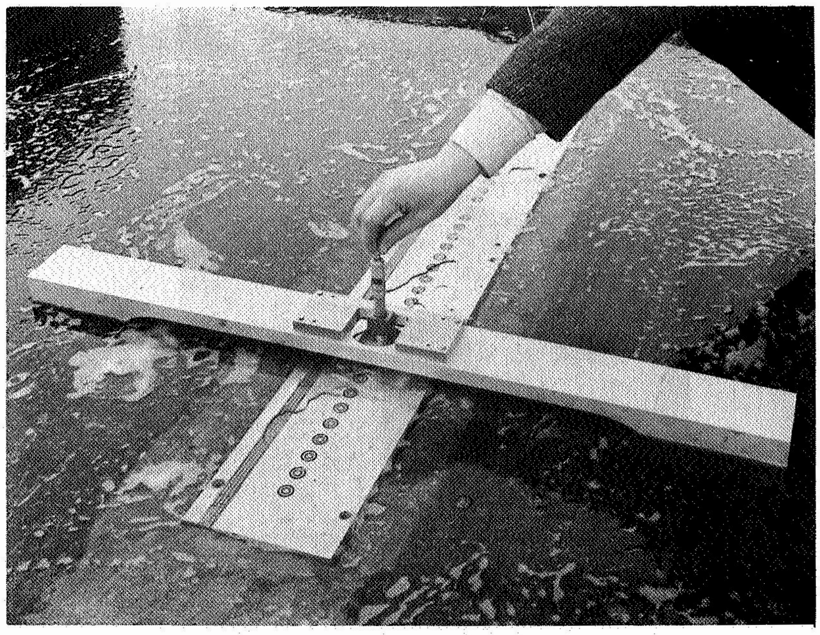

Figure 7(b).- Micrometer system used to measure discrepancy in level between surface and each probe.

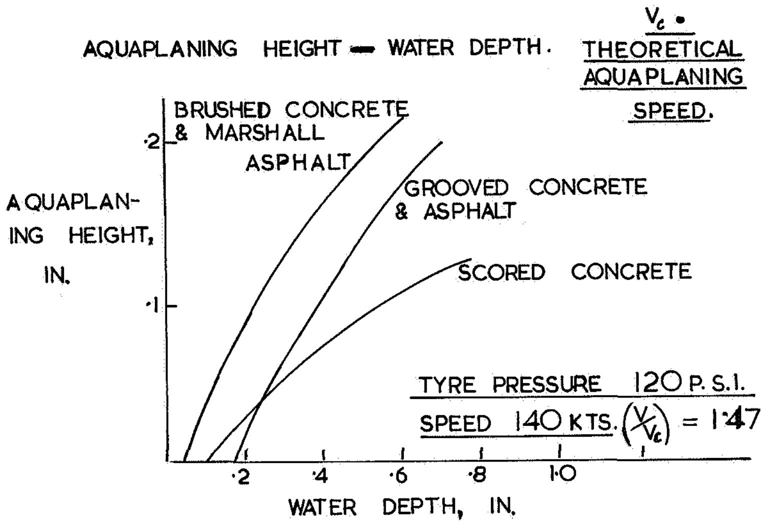

Figure 8.- Aquaplaning characteristics of test surfaces.

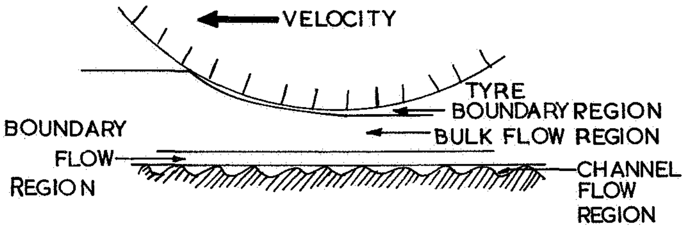

Figure 9.- Flow regions under tyre.

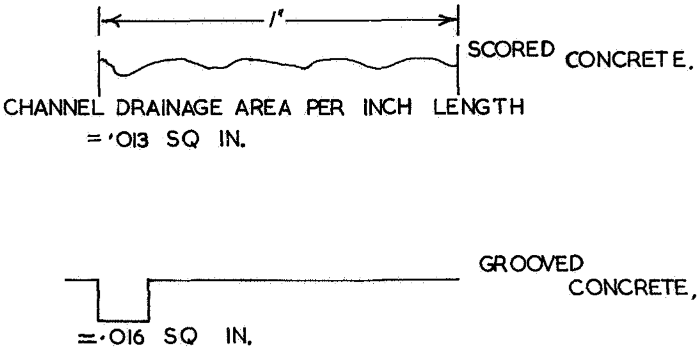

Figure 10.- Magnified profiles of two surface textures showing channel drainage per inch length.

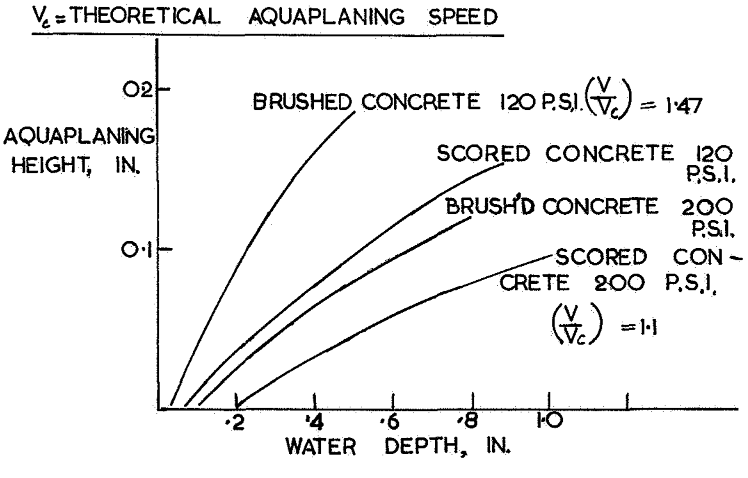

Figure 11.- Effect of tyre pressure on aquaplaning characteristics.

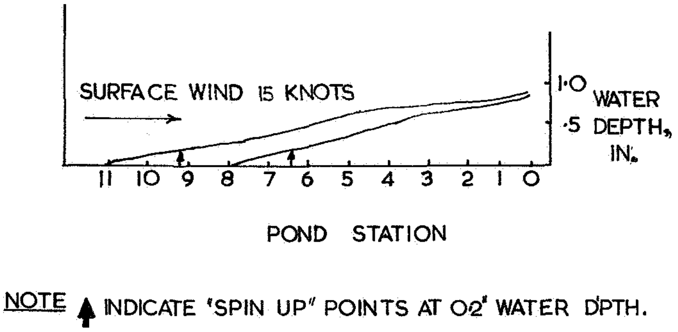

Figure 12.- Longitudinal water depth profiles in heaped ponds.

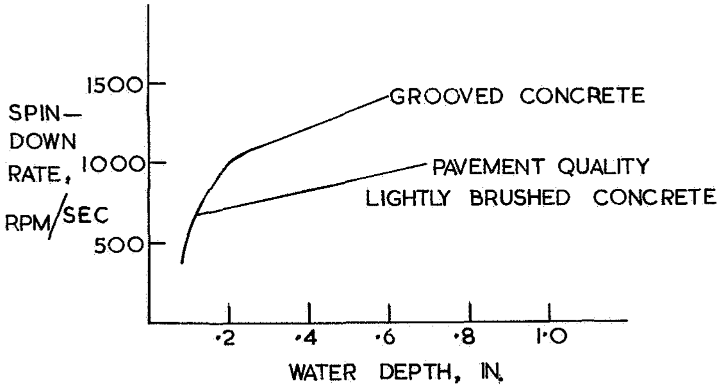

Figure 13.- Effects of surface texture on spin-down rate.

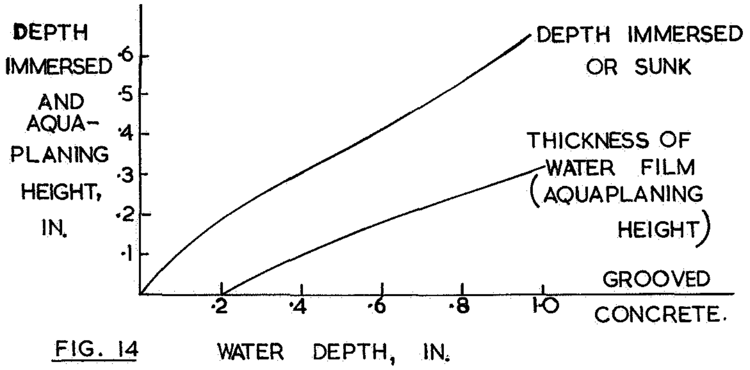

FIG. 14

(BOTH CURVES ON FIGS. 14 & 15 SHOW CLOSEST APPROACH TO RUNWAY SURFACE.)

Figure 14.- Water layer characteristics.

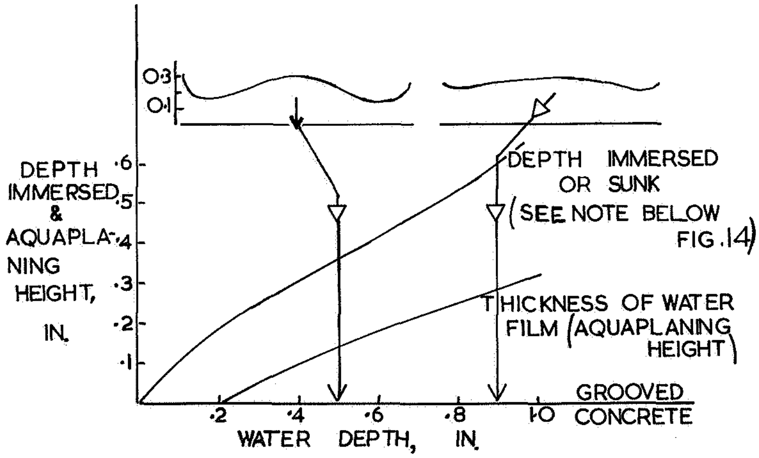

Figure 15.- Tyre distortion at points of closest approach to ground.

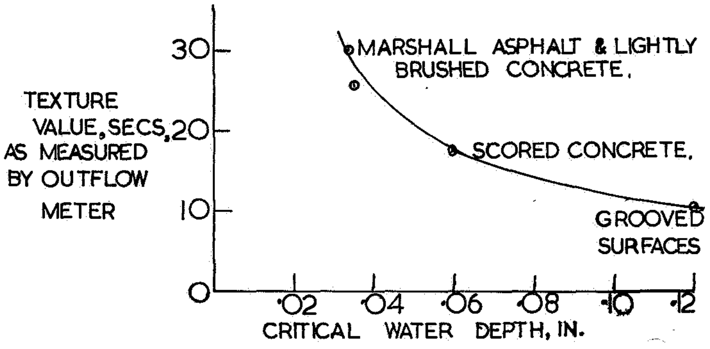

Figure 16.- Critical water depth-surface texture characteristics correlation.