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ABSTRACT

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This paper discusses some of the important details of tire tread design, and presents some test results showing how tread design parameters can delay the build-up of hydrodynamic pressure in the tire footprint area and improve braking and cornering traction on wet or flooded pavement surfaces. It is also shown how even minor differences in pavement texture can be of extreme importance in providing good traction under wet conditions, and a proposed technique for measuring surface roughness and predicting the wet friction level of a given pavement texture is discussed. The paper concludes with a brief summary of current research on tire hydroplaning.

INTRODUCTION

The main area of interest at the Landing and Impact Branch at Langley Research Center is in the landing and ground handling problems of aircraft. Recent studies have been concentrated on the problems of wet runway braking and directional control, and on tire hydroplaning. While the mode of operation of aircraft differs greatly from normal automobile operations, much of what has been learned of the actions and interactions in the tire-to-ground interface under low friction conditions can be extended generally to all pneumatic tires. It is the purpose of this paper to present the results of

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some limited wet runway testing of automobile tires, and to discuss some trends indicated by far more detailed testing of aircraft tires.

RESEARCH FACILITY

All tests to be described were conducted at the landing loads track, shown schematically in figure 1. A complete description of the operations and capabilities of the track is contained in references 1 and 2, but for the benefit of those who may not be familiar with this facility, a brief description of the track and its operation follows. The test carriage is catapulted to speeds in excess of 120 miles per hour by a water-jet catapult, shown on the left in figure 1, which, through a seven-inch diameter nozzle, expels a jet of water under the influence of air at pressures up to 3,260 psi. This jet is received by a bucket on the back of the carriage, turned down and around through approximately 180 degrees, and discharged rearward. The catapult develops a maximum thrust of 350,000 pounds which is sufficient to accelerate the 100,000 pound test carriage to top speeds in about three seconds, in a distance of 300 to 400 feet. Following acceleration, the carriage coasts freely for about 1,200 feet through the test section before contacting the arresting gears which stop the carriage in the 600 feet of track between the arresting cable engagement and the storage shed. The test section may be any desired type of landing surface such as concrete, asphalt, ice, carrier deck, etc., and the surface wetness conditions may be carefully controlled. Incorporated in the design of the main test carriage is a drop frame to which the test landing gear or other fixture is attached. Static loads in excess of 20,000 pounds may be applied to the gear, and sinking speeds at ground contact up to 20 feet per second may be achieved by proper positioning of drop height. Close control of all principal landing contact parameters thus permits a detailed investigation of many different landing impact and ground handling problems.

Paralleling the main test track, as indicated in figure 1, is a water tank which, together with a smaller, specially designed carriage, is used on occasion for high speed hydrodynamic research. This tank and small carriage have been modified as shown in figure 2, for special studies of smaller aircraft tires and automobile tires. An aircraft landing gear shock shrut is pressurized through a large accumulator to provide a constant vertical load on the tire. Provisions have been made on the fixture for the installation of a braking system, and for yawing the fixture up to about 10 degrees. In the bottom of the tank, a carefully leveled concrete test strip about 200 feet long and two feet wide was installed. Incorporated in one end of this test strip was a glass plate which had formerly been used for underwater photography of hydrodynamic models. A close-up view of this plate and the test fixture is shown in figure 3. High speed motion picture cameras and flash-equipped still cameras were installed beneath the glass to take pictures of the tire as it passed overhead. This technique permitted a detailed study of the changing flow patterns in the tire footprint area under various conditions of forward speed, water depth, and tire tread pattern. The results of some of these studies of automobile tires are presented in the following section of this paper.

PRESENTATION AND DISCUSSION OF RESULTS

Tread Pattern Effects on Wet Runway Cornering Force

The test fixture shown in figures 2 and 3 was used to explore the effect of various parameters on the free-rolling cornering force developed by automobile tires, and to provide additional data on the effects of hydroplaning on cornering force. According to reference 3, tire hydroplaning occurs when the hydrodynamic pressure developed in the tire-ground contact area equals or slightly exceeds the average tire-ground bearing pressure, thus forcing the tire off the pavement surface and resulting in large losses in directional control and braking ability, and possible wheel spin-down. Assuming that the average tire-ground bearing pressure is equal to the tire inflation pressure, reference 3 states that the hydroplaning speed of smooth tires on a smooth surface covered with some finite water depth may be predicted with fair accuracy by the simple relationship

$$V_p = 10.3 \sqrt{p}$$

where V_p = hydroplaning speed in miles per hour, and p = tire inflation pressure in pounds per square inch.

The level concrete runway previously described had an extremely smooth, steel-troweled surface over part of its length, and it was observed that due to surface tension, the minimum standing water depth averaged about 0.04 inch. Since this depth was reasonable and easily maintained, it was used for the first series of tests. In this investigation, the fixture was held at a fixed yaw angle of six degrees relative to the forward motion of the carriage, and the strut pressure accumulator charged with sufficient pressure to provide a constant 835 pound vertical load on the tire. Tire inflation pressure was held constant at 27 psi, and each tire was tested at nominal forward velocities of 20, 40, 50, 60 and 80 miles per hour. In the vicinity of the glass plate, a green sea-marker dye was added to the water to provide better photographic contrast between areas of the tire footprint in contact with the plate and areas supported by the water. All tires tested were standard size 6.50 x 13 automobile tires.

Four tires of widely different tread design were used to explore the effects of tire tread pattern on cornering force and hydroplaning in the shallow water depth of 0.04 inch. The first tire tested was a specially-molded smooth tire, which had a tread-rubber thickness equal to a new tire, but with no tread pattern. Photographs of this tire taken through the glass plate installed in the runway surface are shown in figure 4. For comparative purposes, figure 4(a) shows the tire at rest on the glass plate under full vertical load while the other photographs in this figure are arranged in order of increasing test velocity, with direction of motion being from left to right in each photograph. The ratio ω/ω_o indicated on figure 4 and subsequent figures is the ratio of the instantaneous wheel rotational velocity to the equivalent, dry runway rotational velocity, so that a ratio of less than one indicates some degree of wheel spin-down. The first evidences of tire hydroplaning, termed partial hydroplaning, can be observed in figure 4(c) where a barely discernible light streak through the center of the tire and evidence of water flow at the trailing edge of the footprint indicate that a small portion of the footprint has lost contact with the glass surface. This effect becomes more pronounced in figure 4(d) as the forward speed nears the predicted hydroplaning speed of 53.8 miles per hour. In figure 4(e), at slightly above the hydroplaning speed, it can be seen that although a significant portion of the tire is still in contact with the surface, wheel spin-down (ω/ω_o = .864) has begun, with probable loss of directional control. The higher speed of figure 4(f) results in a very pronounced water channel through the center of the tire, a characteristic of automobile tires which is due to the more highly loaded shoulders of the tire.

The effect of tire grooving was explored by using a tire similar in all respects to the smooth tire just described, but with four straight, uniformly-spaced, circumferential grooves about 1/4 inch wide and 1/4 inch deep cut into the tread. Examination of the series of photographs in figure 5 will show how these grooves offer good escape paths for the water trapped between the tire and ground, and thus permit a delay in the significant build-up of hydrodynamic pressures to a speed well above the predicted hydroplaning speed. At all speeds the grooves allow the rapid passage of water as shown by the heavy flow through the grooves at the trailing edge of the footprint. It will also be noted that the effective groove width changes considerably through the tire footprint due to the "squeezing" action of the tire.

Since the outside edges or shoulders of an automobile tire are the most heavily loaded, and are the last portions of the tire footprint to leave the surface, it was felt that grooves in this area might provide further escape paths for the water and offer improved high speed cornering forces. This was done as is shown in figure 6 where narrow lateral cuts were made at 1/2 inch intervals in the shoulder rib of a tire similar to the 4-groove tire. These cuts or slots did, in fact, prove quite beneficial as evidenced by the flow patterns of figure 6, and by the absence of wheel spin-down even at the highest speed tested, figure 6(f).

For comparative purposes, a tire having a typical production tread pattern was also tested, with the results shown in figure 7. This tread pattern proved to be quite effective up to the highest speed tested, as shown by absence of wheel spin-down, figure 7(f), and no observed light areas in the contact patch.

A summary of the cornering force coefficients measured on smooth, wet concrete for the four tires tested is shown in figure 8, where cornering force coefficient as used here is the ratio of measured side load to vertical load. Cornering force values measured for the 4-groove tire rolling dry on the same smooth concrete surface are included for comparison. The results show how the performance of any tire is degraded by the presence of even small amounts of water, although the benefits of a good tread pattern are evident. The good performance demonstrated by the production-type tire is probably due to the presence of "siping," or small knife cuts in the tread, since the flow patterns exhibited in figure 7 suggest relatively inefficient water escape paths through the zig-zag grooves as opposed to straight grooves. Considering the data shown in figure 8, it seems the predicted dynamic hydroplaning speed is not the only controlling factor in the shallow water depth tested, at least on the smooth concrete surface. In discussing the various factors affecting tire hydroplaning, reference 3 stated that in water depths greater than the groove depth in a tire, the grooves become "choked." The tire would then act as a smooth tire, and the hydroplaning speed equation would again apply.

This was demonstrated in this investigation, by repeating the same series of tests just described, but with the water depth held constant at 0.4 inch. The results of the deep water tests are summarized in figure 9, for the four tires tested. It will be noted that all of the tires lose cornering power and undergo wheel spin-down very close to the hydroplaning speed predicted by the method of reference 3. Thus it seems that the occurrence of true dynamic hydroplaning, and thus the accuracy of the equation $V_p = 10.3 \sqrt{p}$ in predicting its speed of occurrence, depends to a large degree upon the water depth. The apparent increase in cornering force experienced in excess of hydroplaning speed by some of the tires is only a component of increasing fluid drag and is not a true measure of lateral tire-to-ground friction.

Examples of the flow patterns observed in the deeper water are shown in figure 10, for the 4-groove tire, and figure 11, for the typical production tire. The apparent inconsistencies in degree of spin-down (ω/ω_o) noted in figure 10(e) and 10(f) and figure 11(e) and 11(f) are explained by the limited length of the test surface. At the higher forward speeds, there was insufficient time for complete wheel spin-down to occur, although examination of the records showed that tire-to-ground friction values dropped to near zero as soon as the tire entered the deep water. These figures emphasize the fact that, in automobile operation, a good tread pattern may provide an adequate margin of safety on normally wet pavements, but that hydroplaning may be a hazard to any tire operating in large, deep puddles, particularly since the loss of traction is almost instantaneous when deep water is encountered.

While no braking tests were performed with these automobile tires, previous experience with the braking of aircraft tires (ref. 4) strengthens the belief that the same factors which influence cornering force, i. e., tread pattern, water depth, tire pressure, etc., will predominantly influence wet pavement braking effectiveness.

Effect of Pavement Texture on Wet Friction Coefficients

As previously stated, the level concrete test surface was provided with an extremely smooth, steel-troweled surface finish. In order to explore the effects of surface texture on cornering force, a portion of this surface was sandblasted to provide a somewhat rougher finish. Even this slight amount of roughening had a marked effect as shown in figure 12 where measured cornering force coefficients are compared for the smooth and 4-groove tires on the roughened concrete and on the smooth concrete. Since the pavement which was roughened by sandblasting provided very little in the way of drainage channels, the great improvement noted for this surface must be due in some manner to the asperities caused by the sandblasting. It seems logical that this gain might be due to the action of the asperities in breaking up the viscous film of water found at the surface, especially since large improvements in cornering forces are noted even at very low speeds, where the dynamic pressure of the water is insignificant.

This argument gives credence, then, to the existence of two types of hydroplaning: that is, dynamic, or true, tire hydroplaning, where very low friction coefficients result when the tire is lifted off the pavement by hydrodynamic pressures in the tire footprint, and viscous "hydroplaning" which occurs only on a smooth surface, and gives very low friction coefficients even at very low speeds. The results shown in figure 12 suggest that viscous hydroplaning may be combated either with improved tread designs or with good pavement designs. However, good tread design should not be relied upon to the exclusion of good pavement design, since all too often tires are used until they become smooth.

While it has been demonstrated that minor changes in pavement texture can offer greatly improved tire performance, it is at the same time acknowledged that such changes or differences in pavement texture are very difficult to describe quantitatively and in meaningful terms. A method has been suggested by Joyner of the Landing and Impact Branch (ref. 5) which might be used to provide a measure, simply and quickly, of the average asperity height of a given pavement surface, and give an idea of the probable friction levels to be expected of that surface when wet. The apparatus is pictured in figure 13, and essentially consists of a known volume of cup grease applied to the pavement as shown. Two parallel strips of masking tape are applied to the surface a known distance apart, and the known volume of grease contained in the tube is expelled by the plunger onto this area. A squeegee, made of rubber which is similar in hardness to tire carcass rubber, is then used to work the grease into the surface between the lines of tape. Care is taken to assure that no large accumulations of grease remain around the larger asperities, and that the grease is applied as uniformly as possible. When the grease has been uniformly distributed over the area as far as it will go, the resulting area thus covered is measured, and when the initial volume is divided by this area, the number resulting may be taken as an average asperity height over the surface.

This method should be statistical in nature, with a number of samples of a single surface being taken and averaged. As a check on the method, measurements were taken of several test surfaces at the landing loads track during the course of an extended series of aircraft tire braking tests. Figure 14 shows a correlation of the average braking friction coefficients developed by the aircraft tire at three forward velocities with the average surface texture depth measurements obtained by the grease technique. The results of figure 14 show that roughening the surface provides large increases in friction coefficient until the texture approaches the average texture depth measured for the small aggregate asphalt surface. For textures rougher than this, the effect seems to be negligible for low speeds and only moderately effective for higher speeds. Correlation such as this gives some confidence in this method, although a vastly greater number of sample surfaces should be measured and checked.

Possible Methods of Improving Wet Surface Traction

The foregoing results suggest several methods by which wet pavement traction may be improved. The texture of the pavement itself has been shown to be of vital importance and it has been shown that undesirable effects can be minimized by providing asperities to puncture the viscous fluid film in order to prevent the occurrence of viscous "hydroplaning." The need for adequate drainage channels from the tire-ground contact area to improve cornering force has been proved, and such channels might be provided in the pavement design through grooving or some other technique. Any pavement should be designed with adequate surface drainage to prevent accumulation of water to substantial depths.

It has been shown that an effective tread design can do much to improve wet pavement performance, and it is equally true that a good tread design must be maintained in good condition. Tests at the track, reference 6, have shown that an aircraft tire which is about 80 percent worn behaves much as a smooth tire, and in fact, that normal tread deformation is enough to close such shallow grooves completely. It is supposed that the same trend would be noted on automobile tires.

A method for improving wet pavement traction which may have limited application for automobiles but shows some promise for aircraft is the removal of water from in front of the tire through the use of air jets, as shown in figure 15. These tests, reported in detail in references 5 and 7, have shown remarkable improvements in wet pavement braking and cornering force. Some of the tests were conducted on an automobile tire on the concrete surface described in the first section of this paper, with the results shown in figure 16. It can be seen that the cornering force coefficient is greatly increased by the use of air jets, even in relatively deep water, and the results on the smooth surface indicate that the air jet may also help to break up the viscous fluid film.

CONCLUDING REMARKS

The purpose of this paper is to show how wet pavements can degrade the braking and cornering performance of automobile tires, to discuss some of the mechanisms which cause this degradation, and to explore ways in which such losses in performance can be lessened or eliminated. A simple formula for conservatively predicting the hydroplaning speed of a pneumatic tire has been demonstrated to be accurate for automobile tires on a smooth surface covered with water to depths on the order of 0.4 inch. It has also been shown that the combined effects of partial dynamic hydroplaning and viscous hydroplaning associated with films of water on the order of 0.04 inch thick can cause significant losses in cornering power at speeds well under the predicted hydroplaning speed. The importance of pavement texture has been demonstrated, and a simple method proposed which gives promise as a way to classify the degree of slipperiness of wet pavements.

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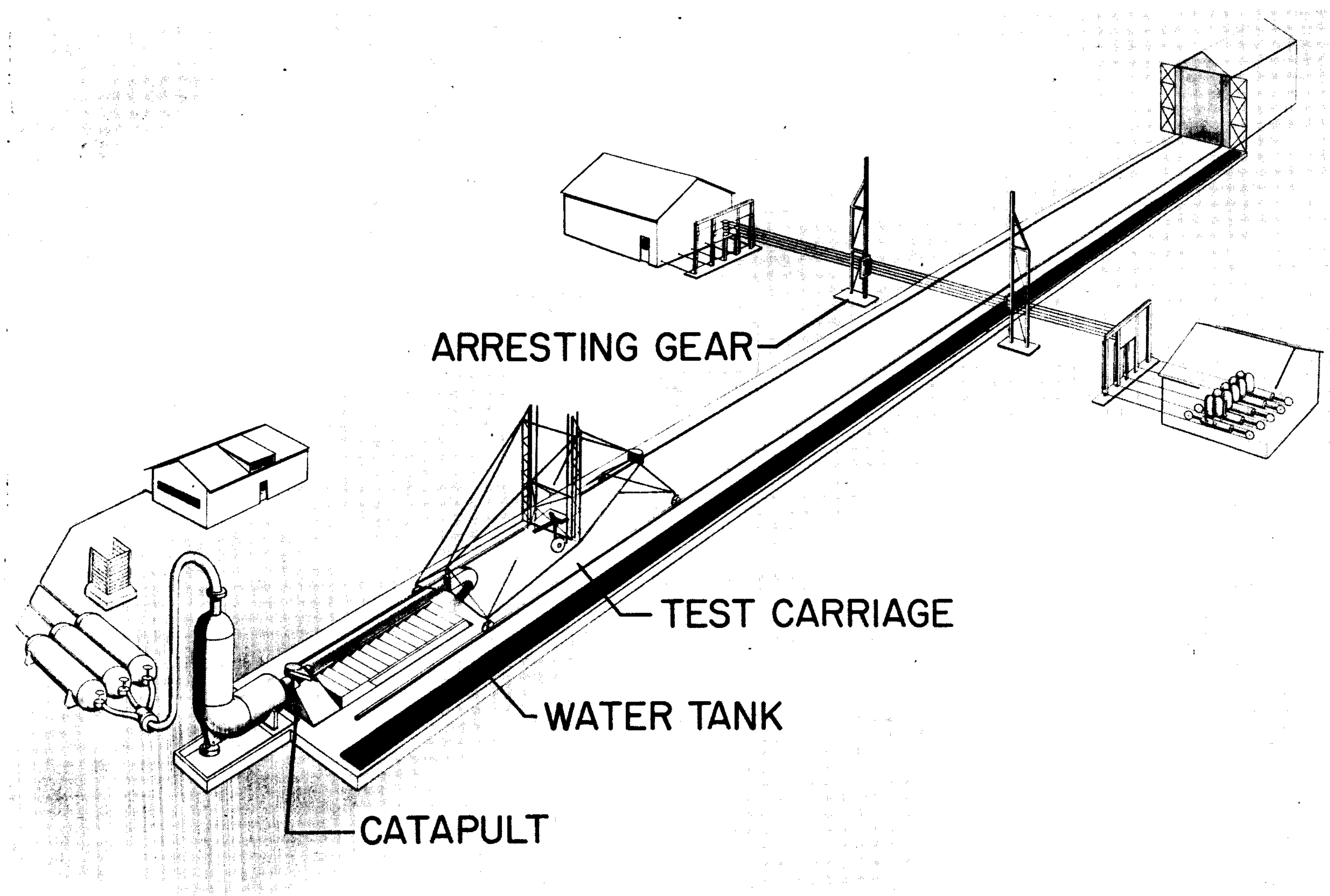


Figure 1.- Schematic of Langley landing-loads track.

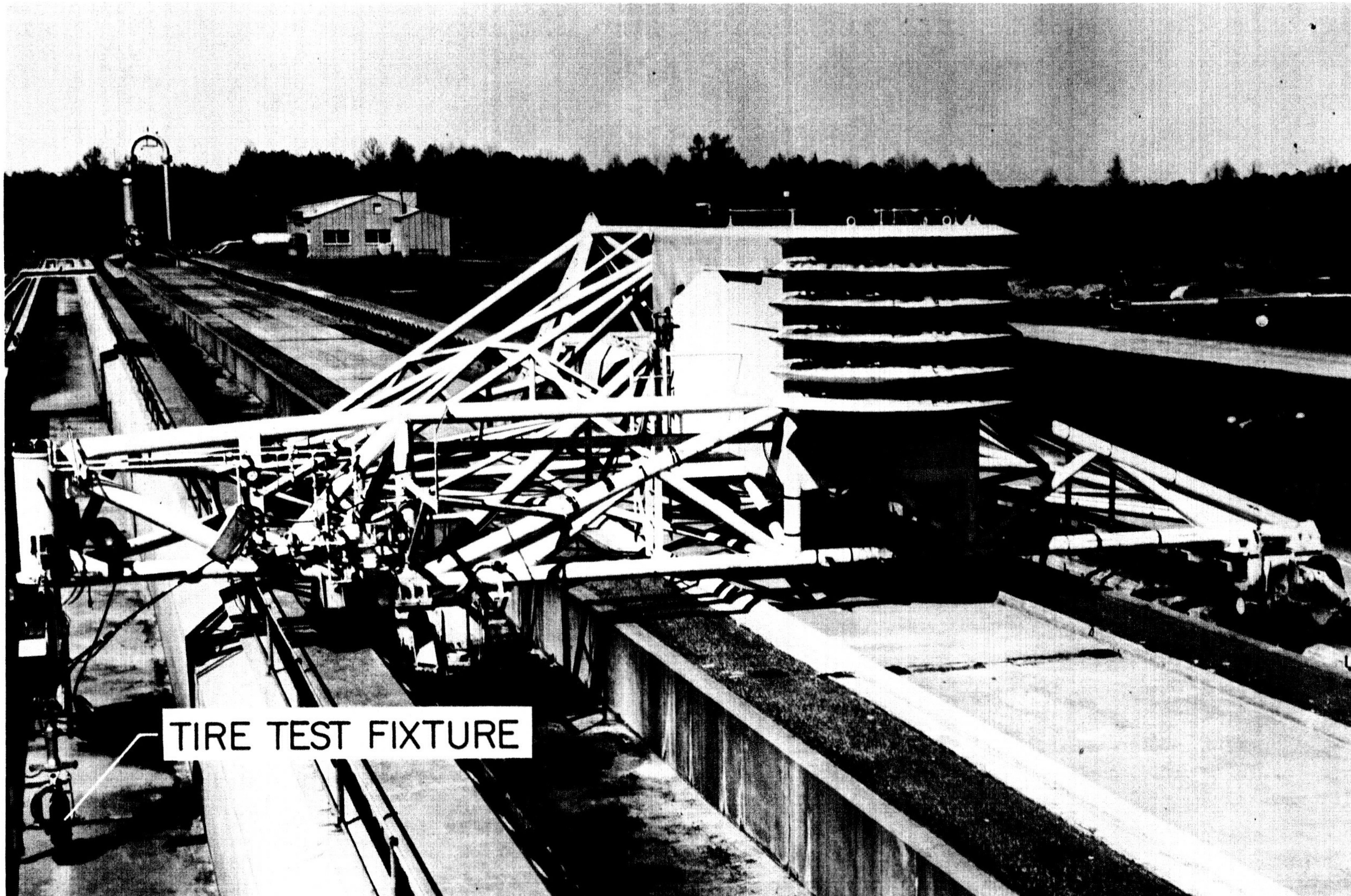


Figure 2.- Small test carriage fitted with tire test fixture.

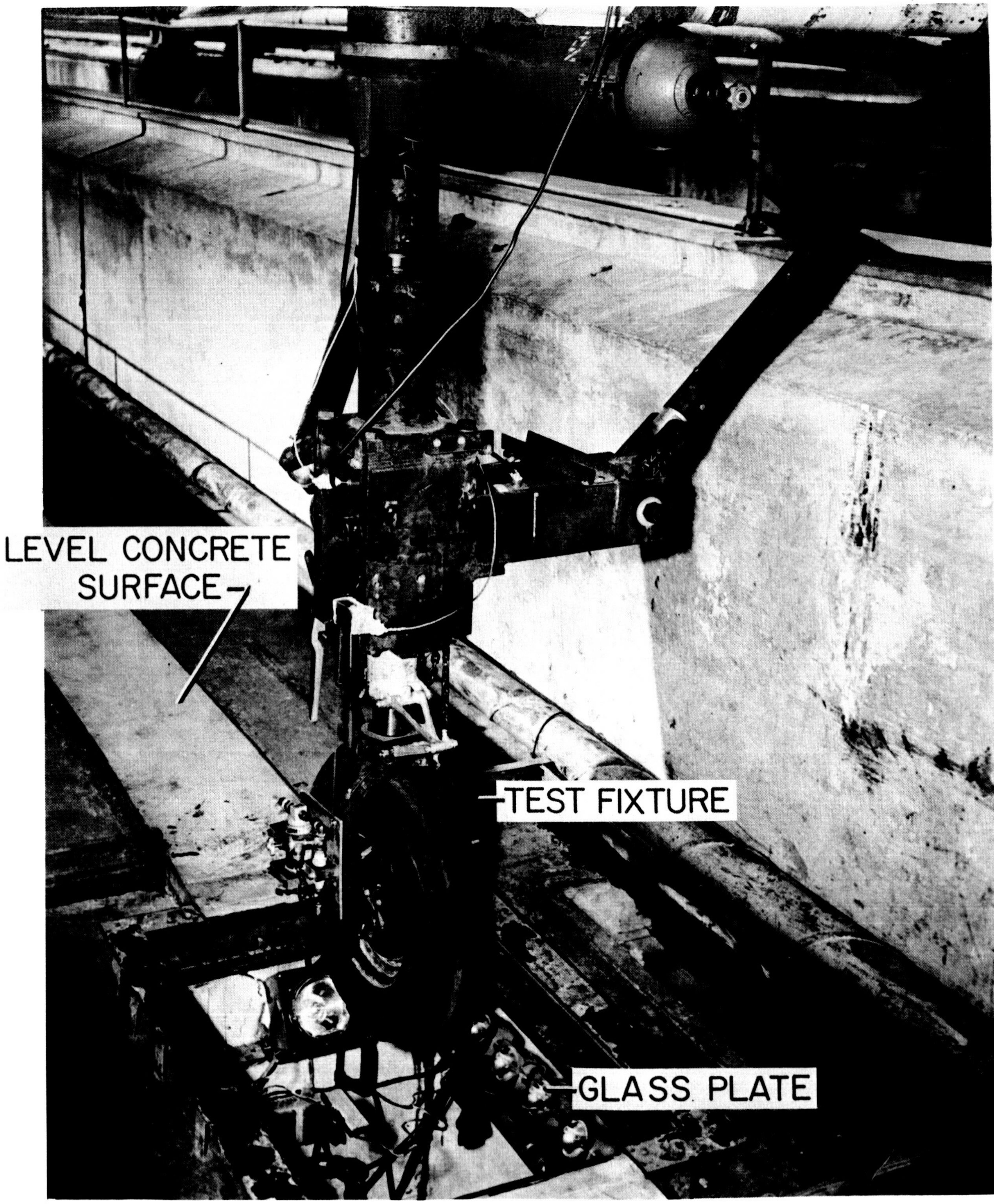
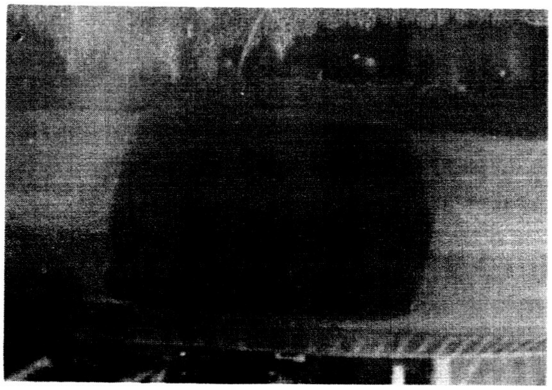
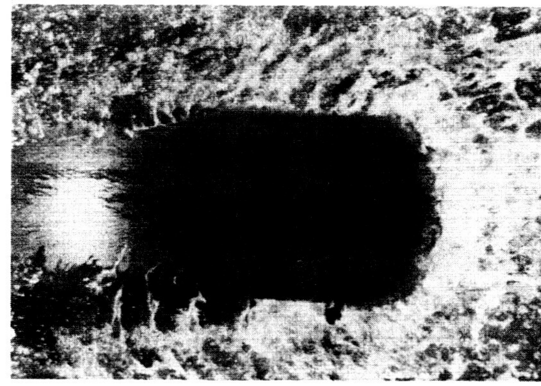


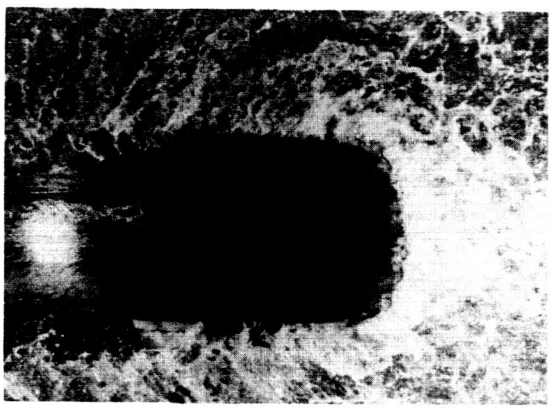
Figure 3.- Close-up view of test fixture with automobile tire installed.



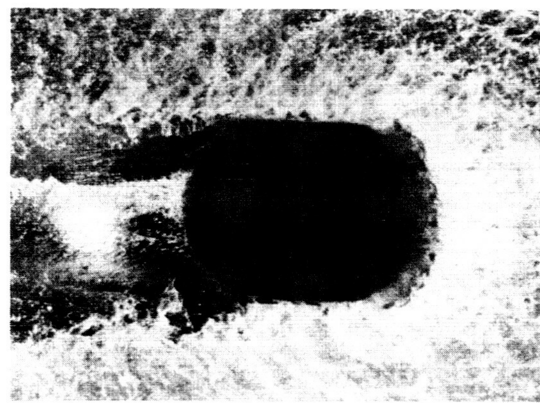
(a) Tire at rest.



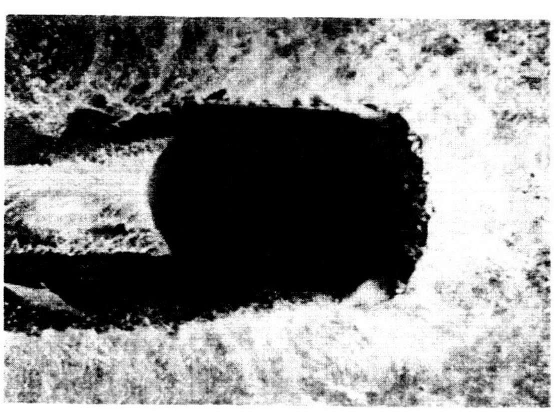
(b) V_G = 20.3 mph, ω/ω_o = 1.



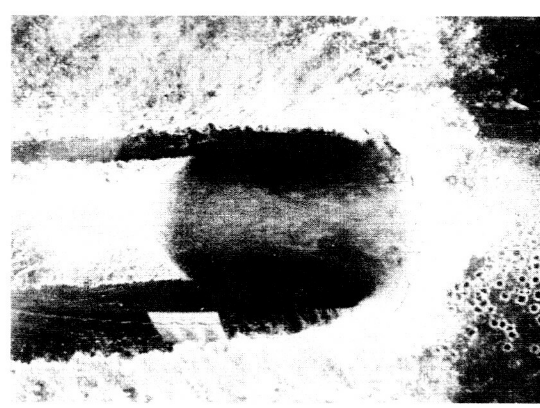
(c) V_G = 37.4 mph, ω/ω_o = 1.



(d) V_G = 49.1 mph, ω/ω_o = 1.

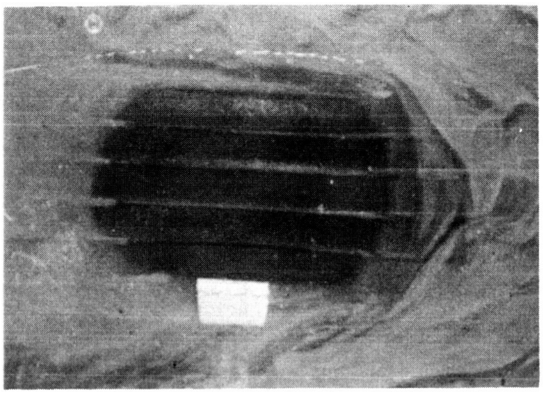


(e) V_G = 56.4 mph, ω/ω_o = 0.864.

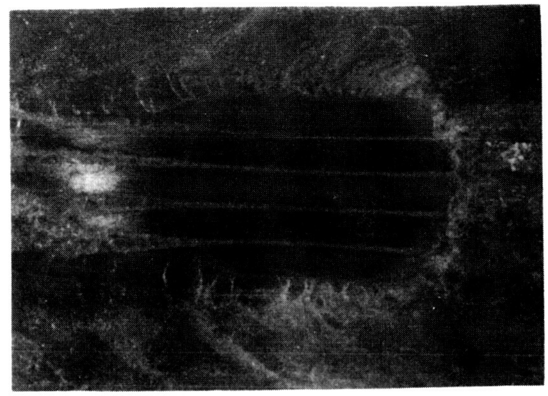


(f) V_G = 76.7 mph, ω/ω_o = 0.735.

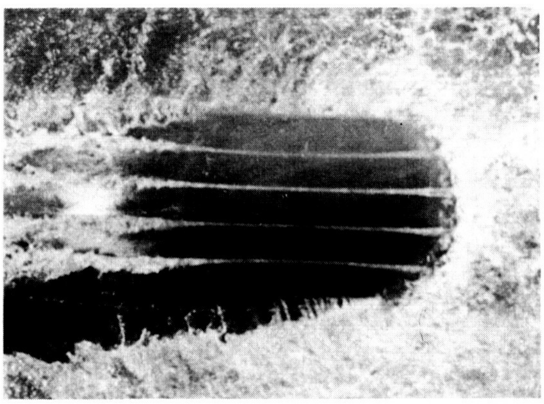
Figure 4.- Photographs of smooth tire taken through glass plate. Vertical load = 835 pounds. Water depth = 0.04 inch. Yaw angle = 6°. Direction of travel left to right.



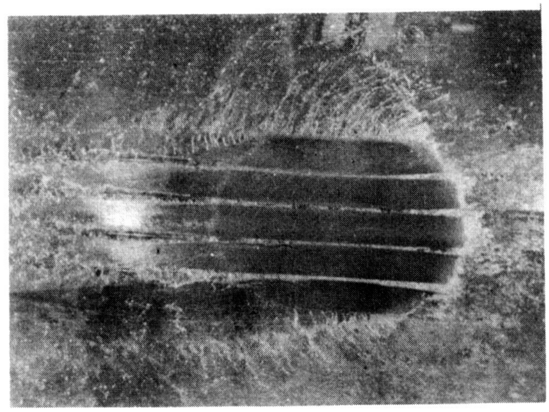
(a) Tire at rest.



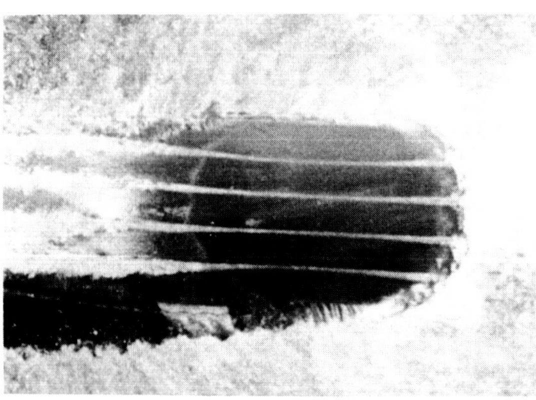
(b) $V_G = 22.4$ mph, $\omega/\omega_o = 1$.



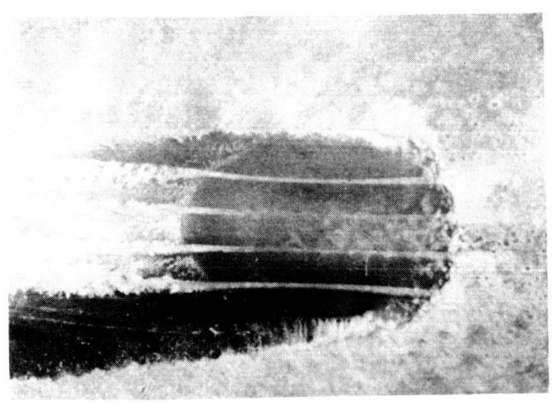
(c) $V_G = 41.5$ mph, $\omega/\omega_o = 1$.



(d) $V_G = 53.9$ mph, $\omega/\omega_o = 1$.

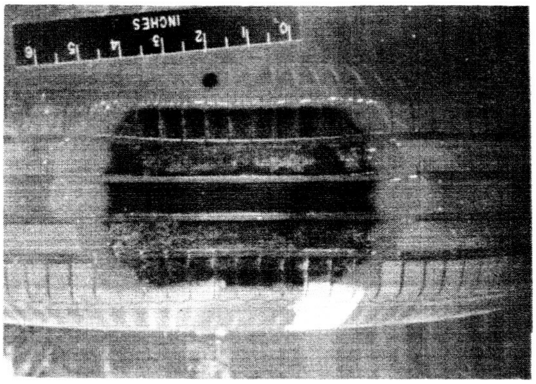


(e) $V_G = 63.2$ mph, $\omega/\omega_o = 1$.

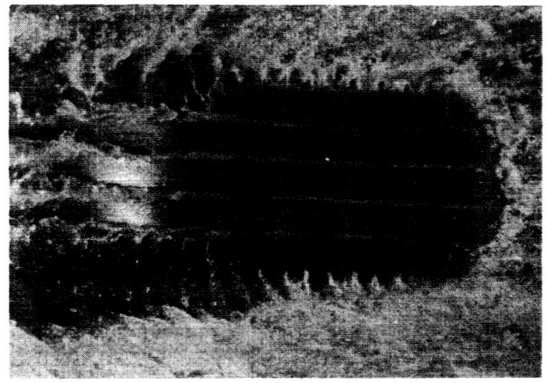


(f) $V_G = 86.1$ mph, $\omega/\omega_o = 0.814$.

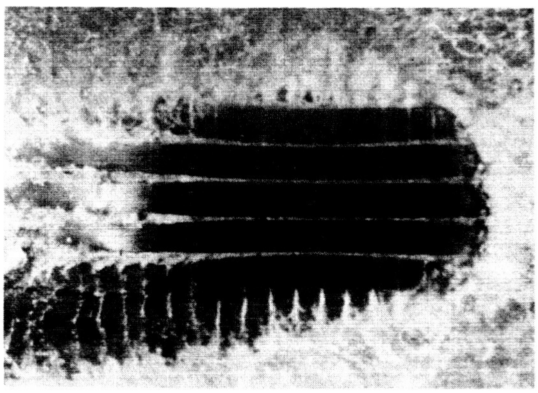
Figure 5.- Photographs of 4-groove tire taken through glass plate. Vertical load = 835 pounds. Water depth = 0.04 inch. Yaw angle = 6^o. Direction of motion left to right.



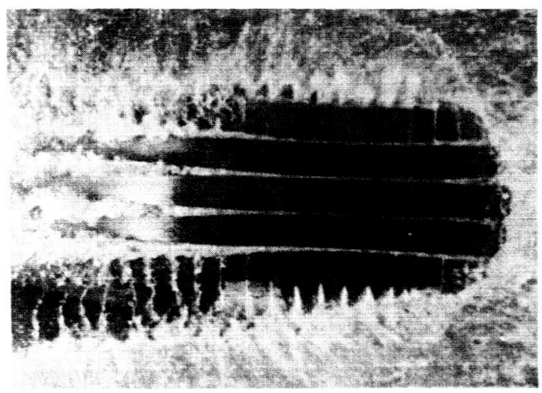
(a) Tire at rest.



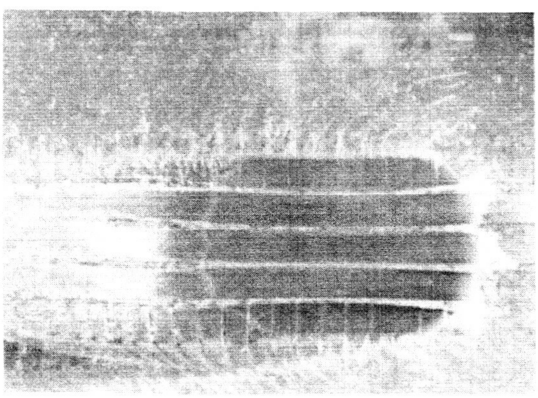
(b) V_G = 18.0 mph, ω/ω_o = 1.



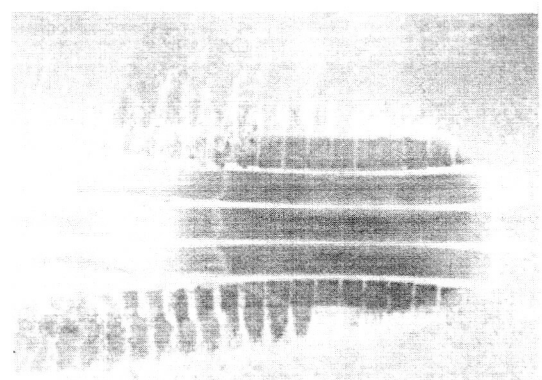
(c) V_G = 40.8 mph, ω/ω_o = 1.



(d) V_G = 51.2 mph, ω/ω_o = 1.

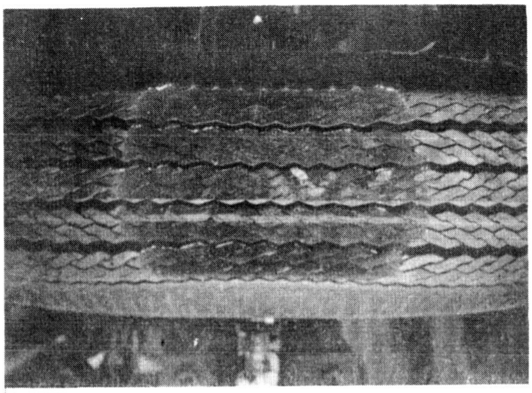


(e) V_G = 59.2 mph, ω/ω_o = 1.

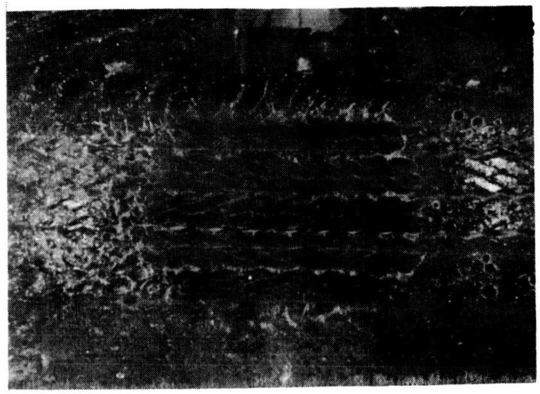


(f) V_G = 82.8 mph, ω/ω_o = 1.

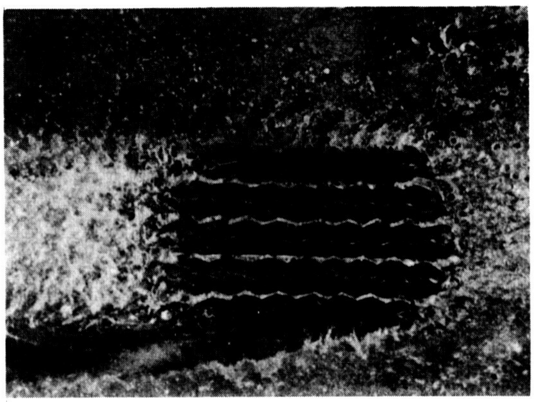
Figure 6.- Photographs of 4-groove tire with slotted shoulder rib taken through glass plate. Vertical load = 835 pounds. Water depth = 0.04 inch. Yaw angle = 6°. Direction of motion left to right.



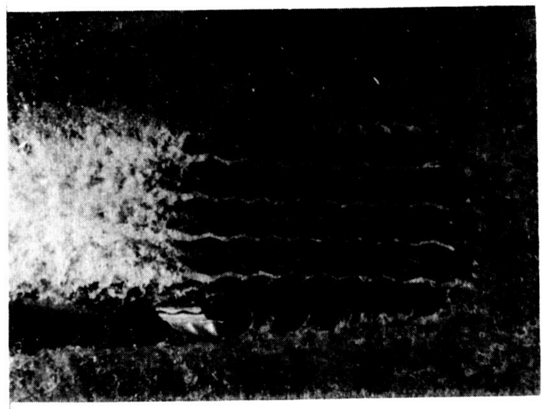
(a) Tire at rest.



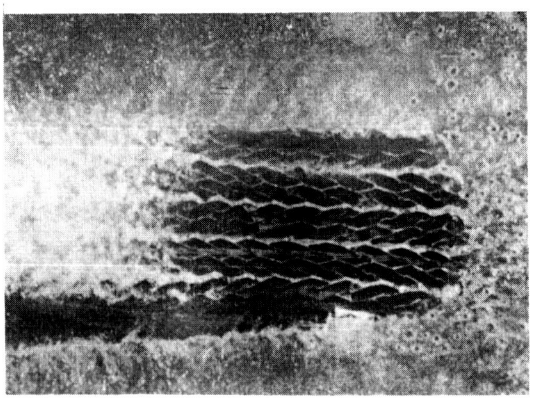
(b) $V_G = 19.8$ mph, $\omega/\omega_o = 1$.



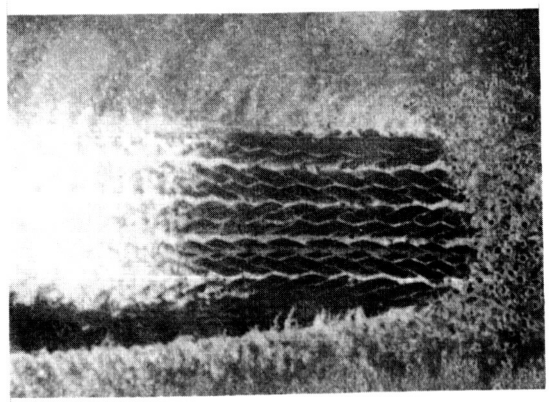
(c) $V_G = 36.2$ mph, $\omega/\omega_o = 1$.



(d) $V_G = 52.1$ mph, $\omega/\omega_o = 1$.



(e) $V_G = 59.9$ mph, $\omega/\omega_o = 1$.



(f) $V_G = 75.3$ mph, $\omega/\omega_o = 1$.

Figure 7.- Photographs of typical production-type tire taken through glass plate. Vertical load = 835 pounds. Water depth = 0.04 inch. Yaw angle = 6°. Direction of motion left to right.

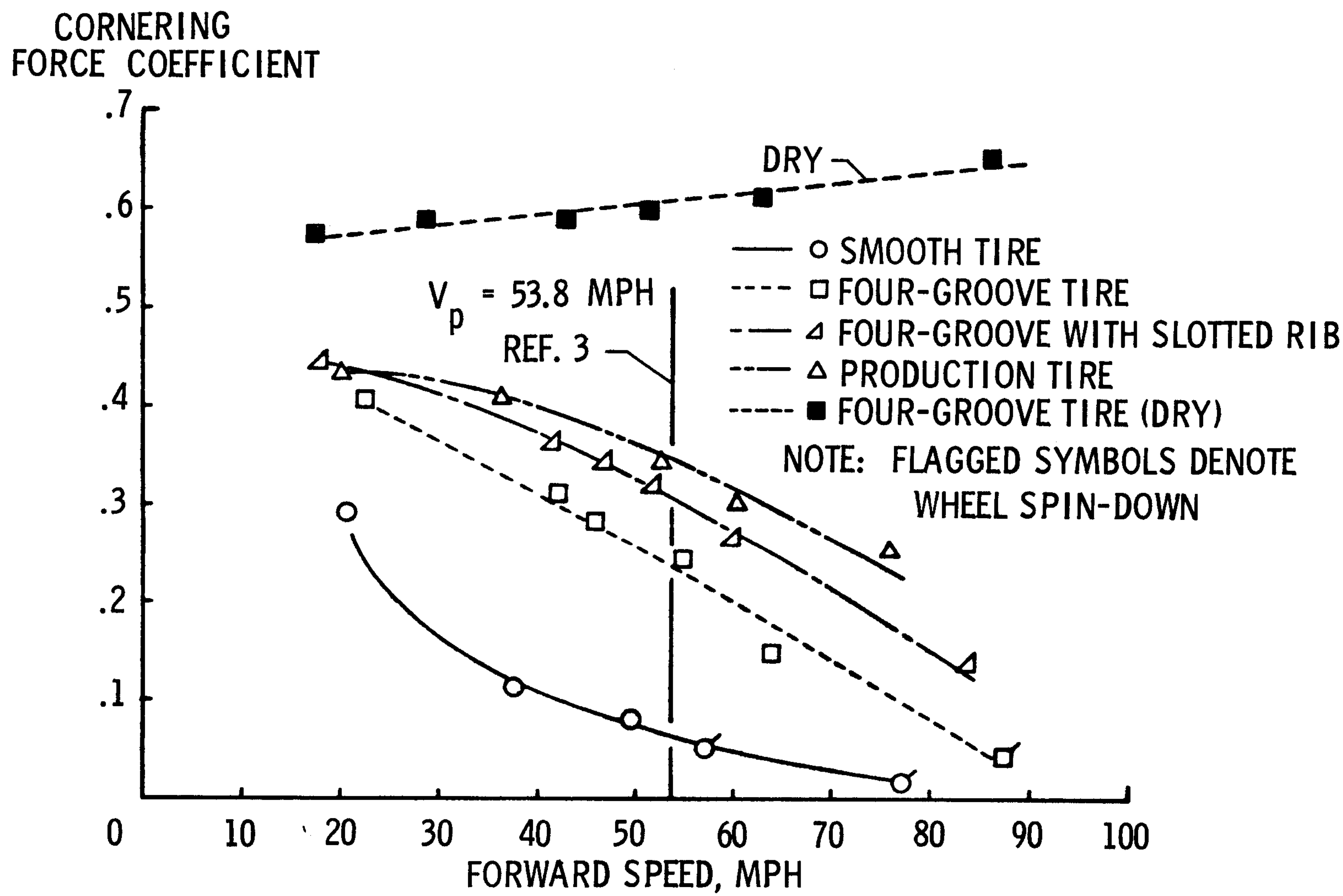


Figure 8.- Cornering force coefficients developed by the four tires tested. Smooth concrete surface, water depth = 0.04 inch. Vertical load = 835 pounds. Tire pressure = 27 psi. Yaw angle = 6°.

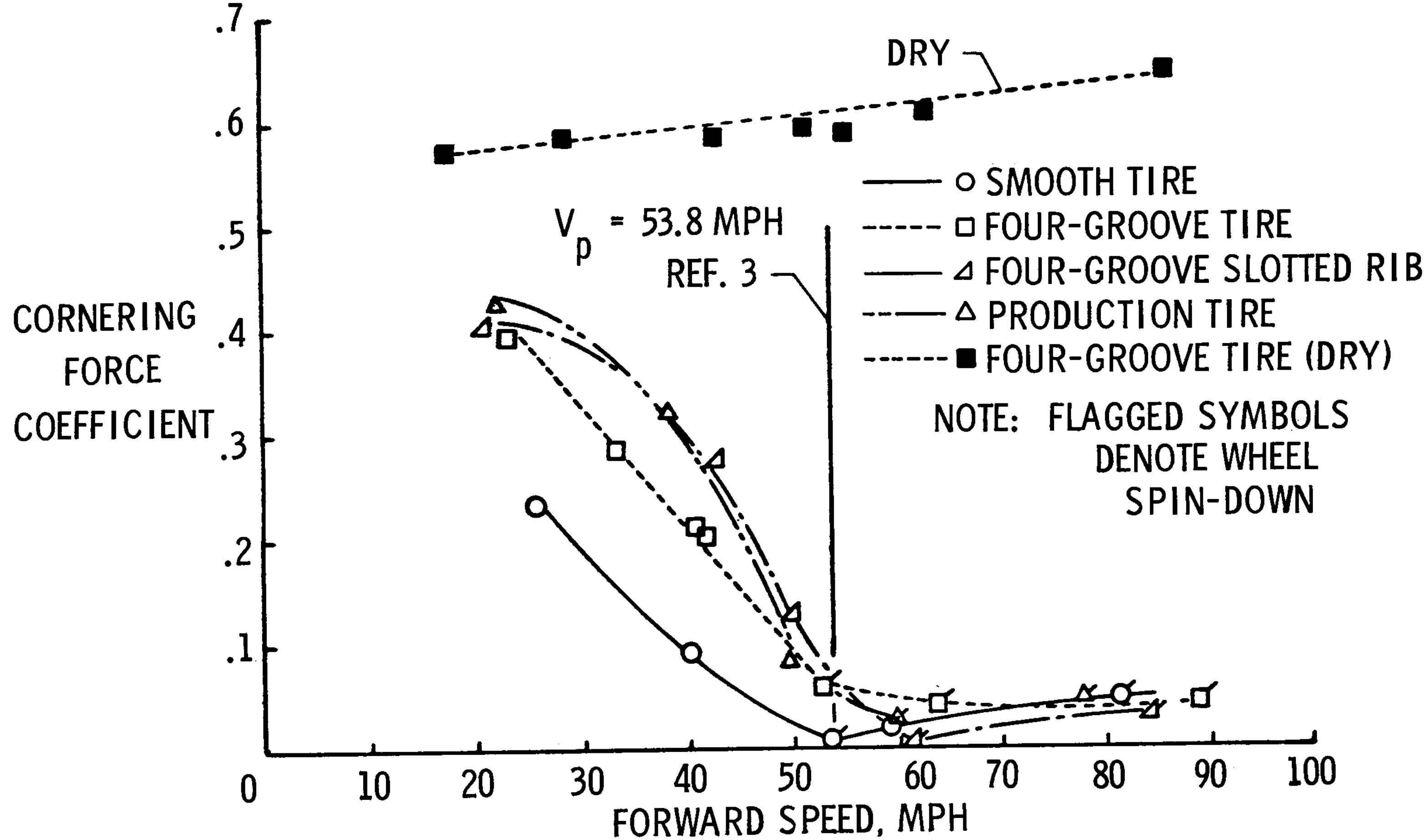
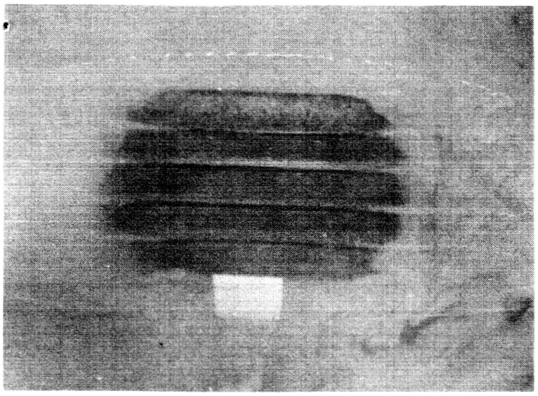
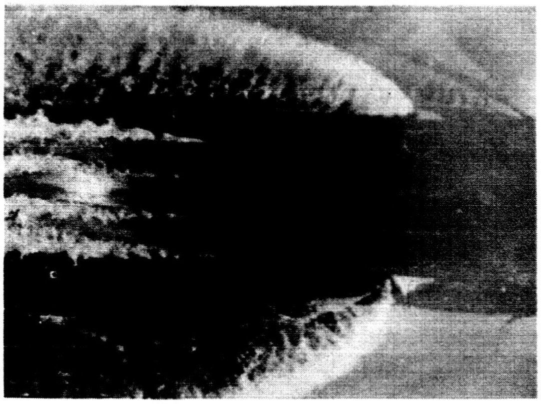


Figure 9.- Cornering force coefficients developed by the four tires tested. Smooth concrete surface, water depth = 0.4 inch. Vertical load = 835 pounds. Tire pressure = 27 psi. Yaw angle = 6°.

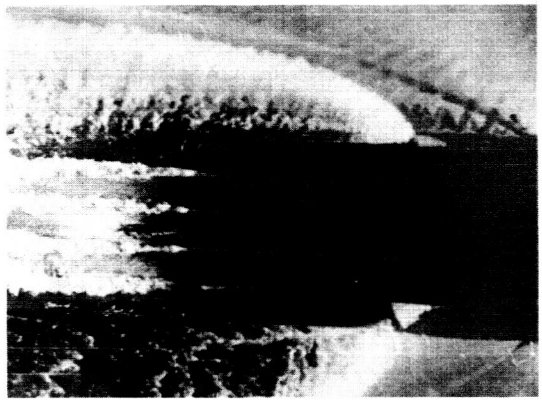


(a) Tire at rest.

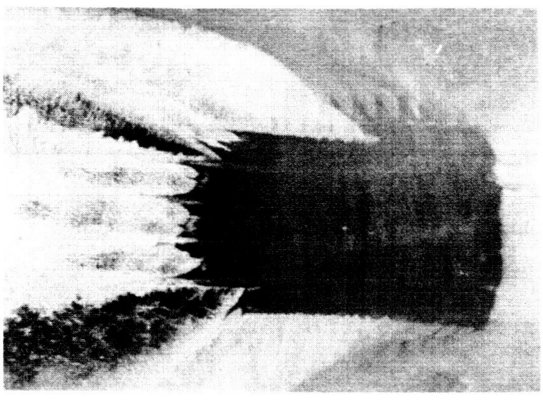
(b) $V_G = 22.8$ mph, $\omega/\omega_o = 1$.



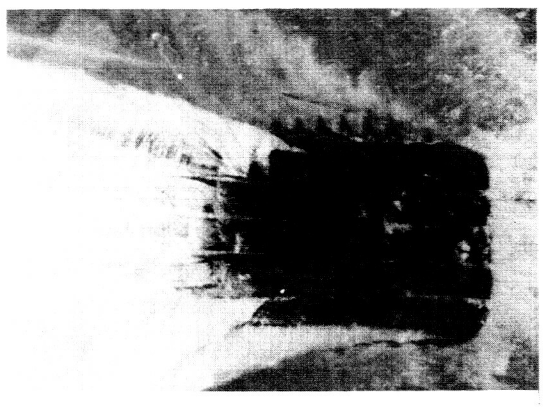
(c) $V_G = 40.7$ mph, $\omega/\omega_o = 1$.



(d) $V_G = 41.4$ mph, $\omega/\omega_o = 1$.

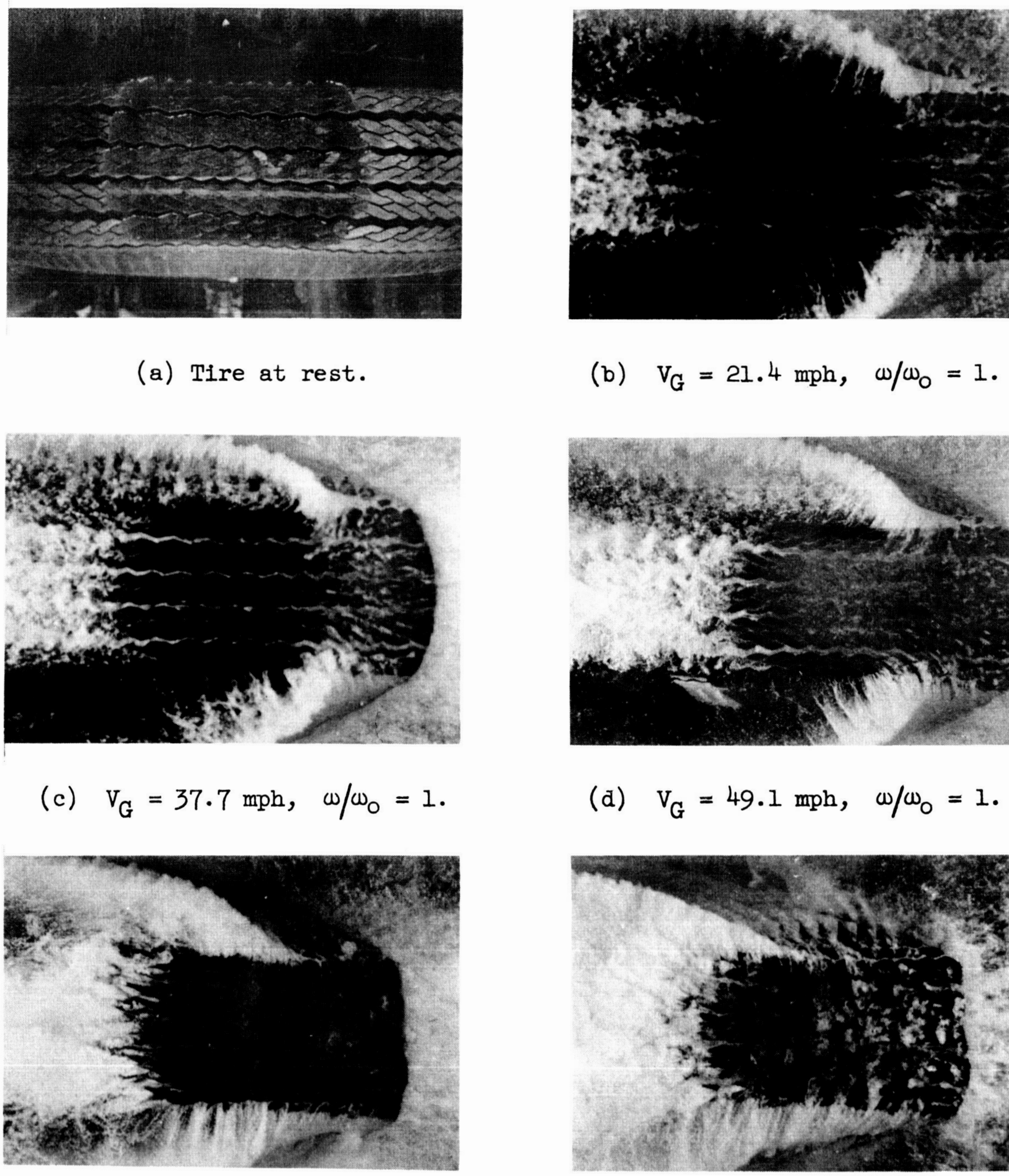


(e) $V_G = 62.6$ mph, $\omega/\omega_o = 0.193$.



(f) $V_G = 87.8$ mph, $\omega/\omega_o = 0.400$.

Figure 10.- Photographs of 4-groove tire taken through glass plate. Water depth = 0.4 inch. Vertical load = 835 pounds. Yaw angle = 6°. Direction of motion left to right.



(a) Tire at rest.

(b) V_G = 21.4 mph, ω/ω_o = 1.

(c) V_G = 37.7 mph, ω/ω_o = 1.

(d) V_G = 49.1 mph, ω/ω_o = 1.

(e) V_G = 59.2 mph, ω/ω_o = 0.245.

(f) V_G = 77.3 mph, ω/ω_o = 0.425.

Figure 11.- Photographs of typical production-type tire taken through glass plate. Water depth = 0.4 inch. Vertical load = 835 pounds. Yaw angle = 6°. Direction of motion left to right.

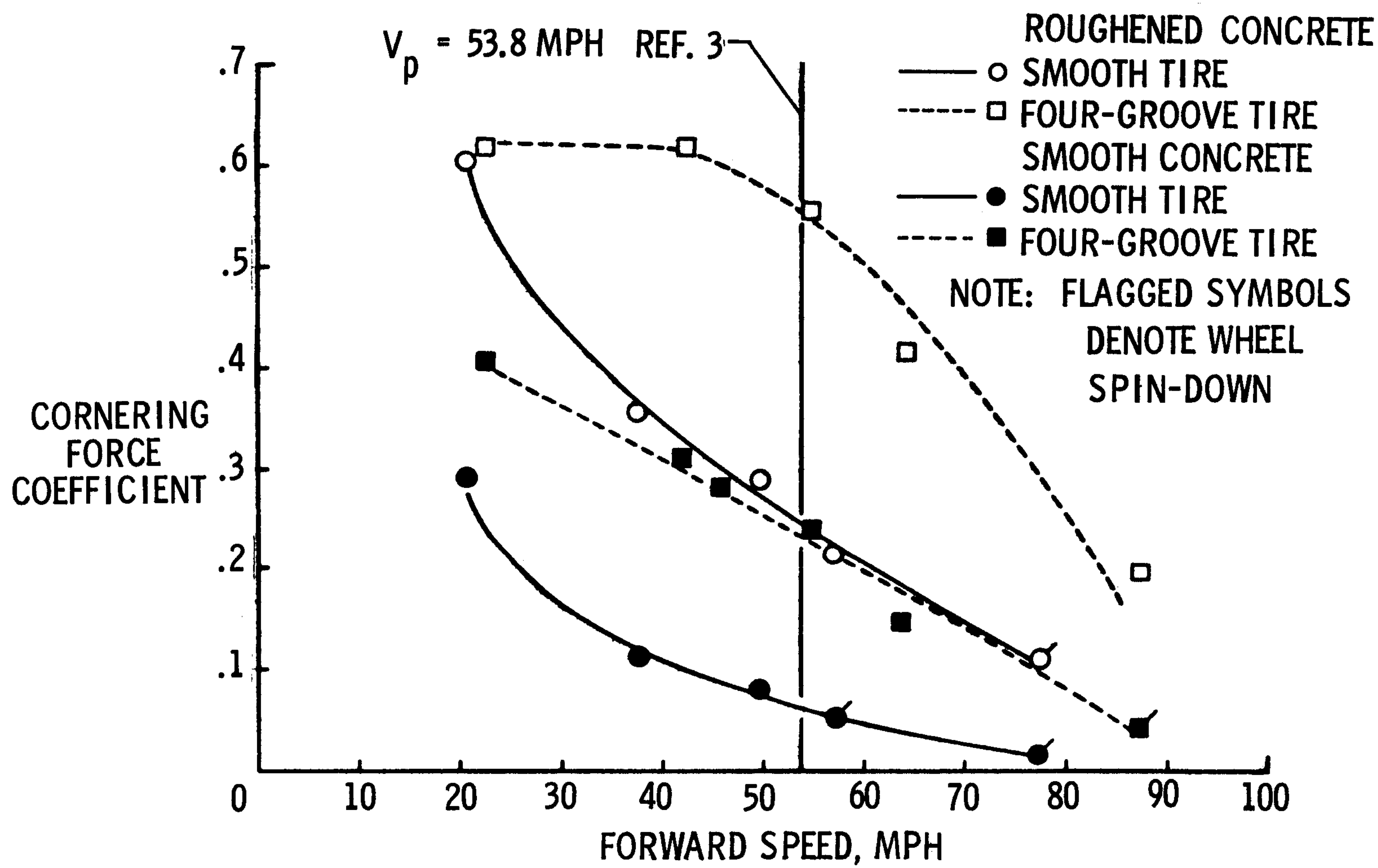


Figure 12.- Effect of pavement texture and tread design on cornering force. Water depth = 0.04 inch. Vertical load = 835 pounds. Tire pressure = 27 psi. Yaw angle = 6°.

Figure 13.- Illustration of apparatus used in grease application technique for measuring runway surface texture depth.

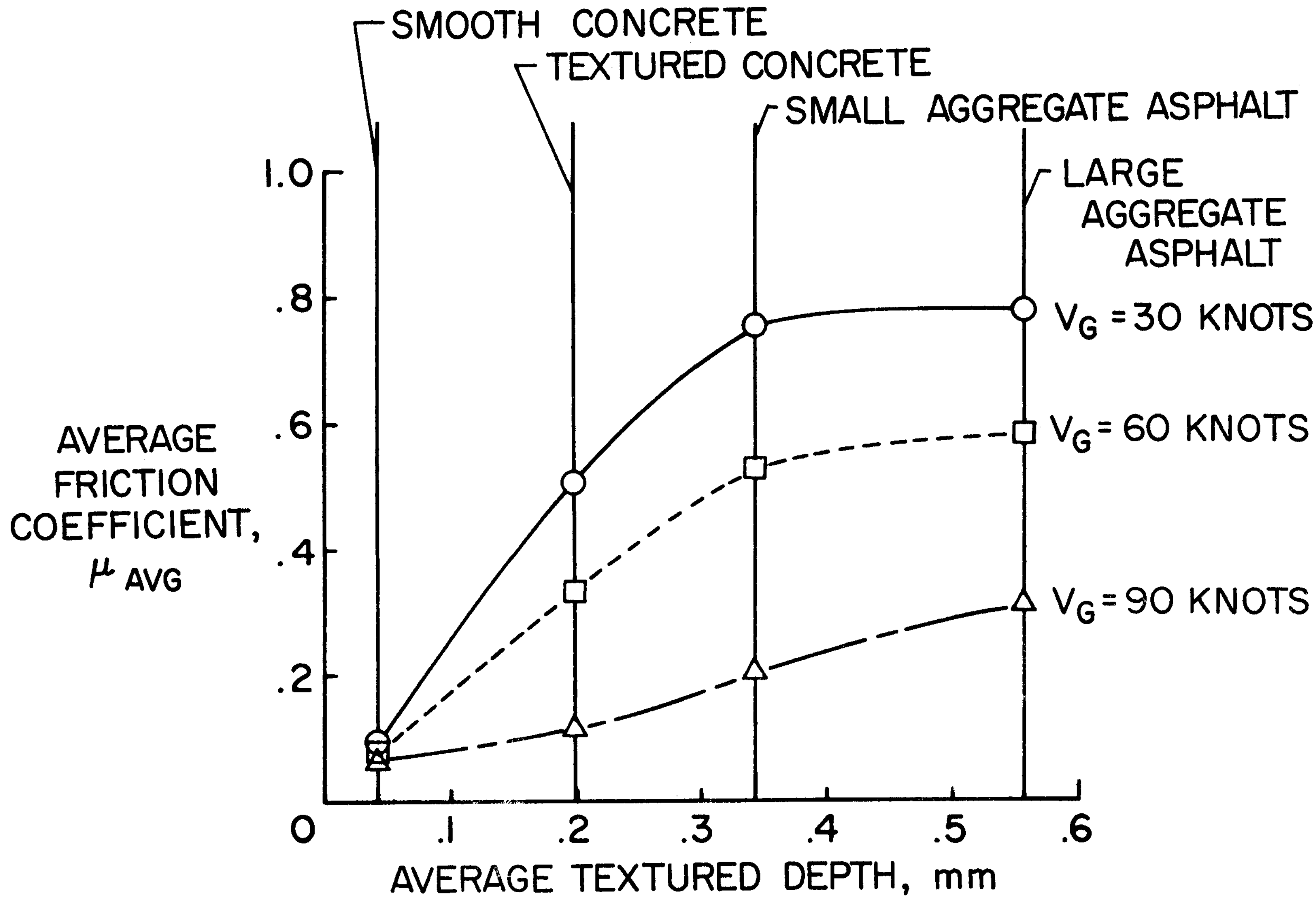


Figure 14.- Effect of measured surface roughness on average braking friction coefficient developed by a smooth aircraft tire. Water depth = 0.1-0.2 inch. Vertical load = 12,000 pounds. Tire pressure = 140 psi.

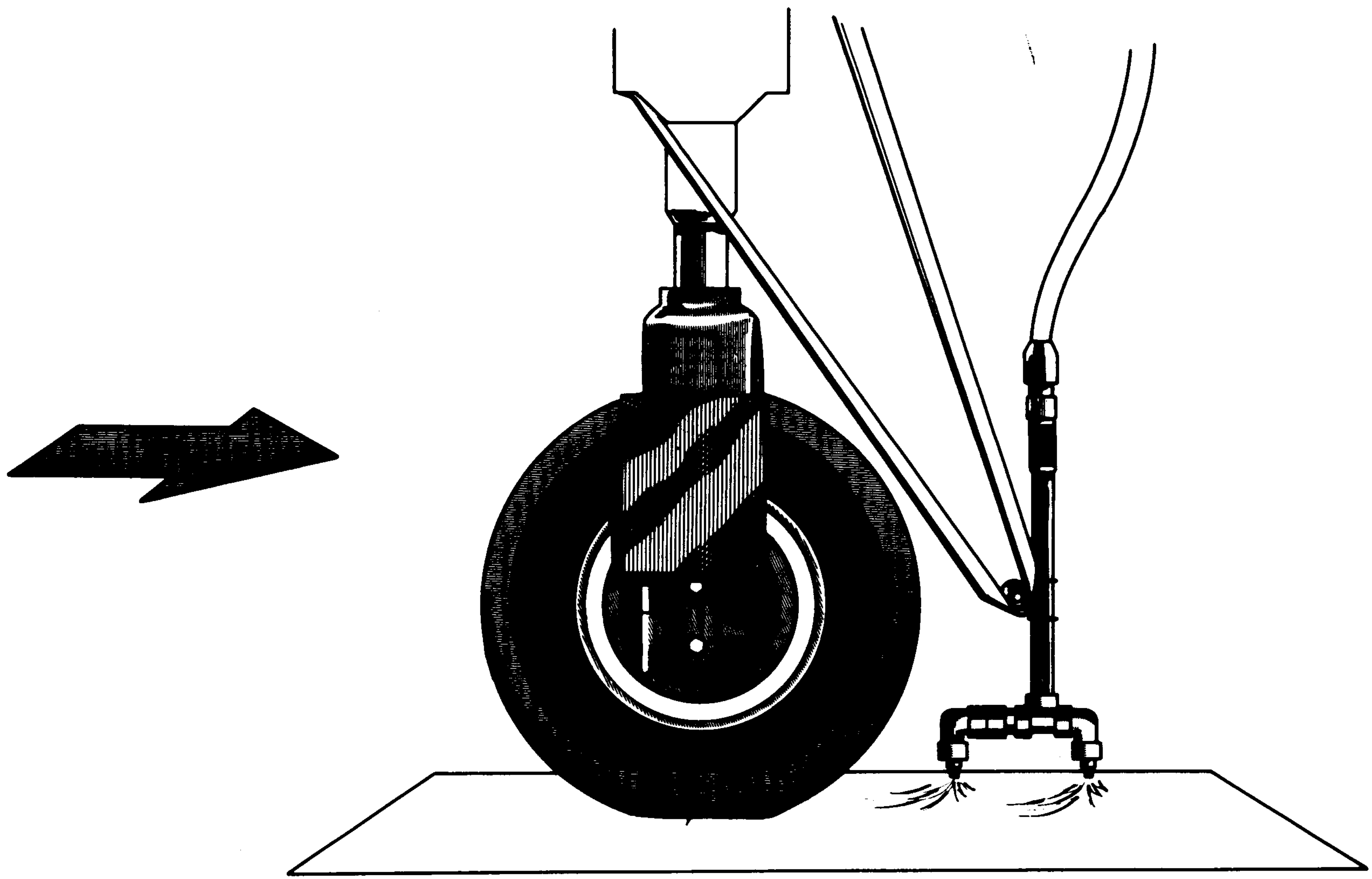


Figure 15.- Schematic of air jet arrangement on automobile tire tests. Airflow at jet nozzle ≈ 2.7 lb/sec. Nozzle pressure ≈ 390 psi.

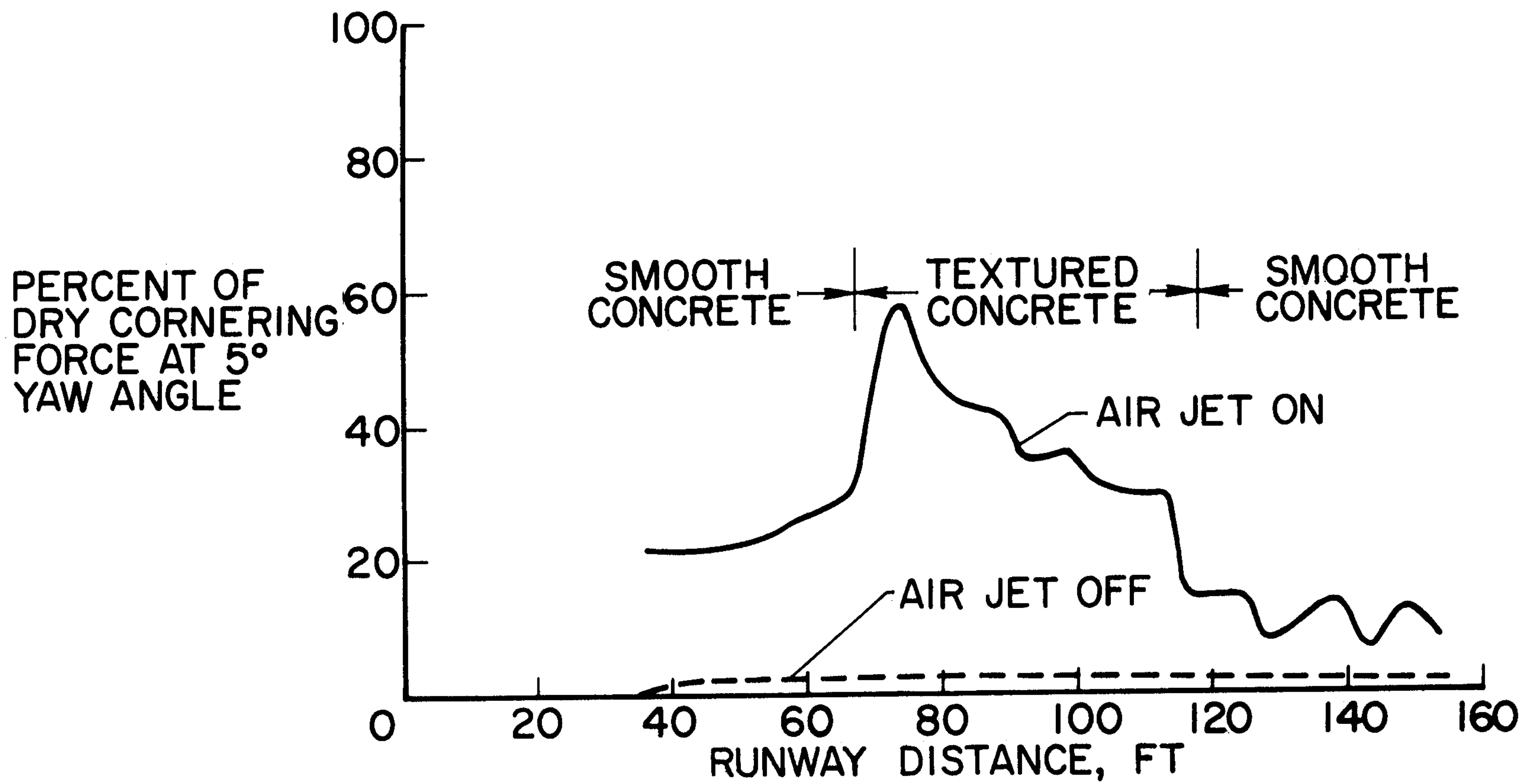


Figure 16.- Effect of air jet on cornering force developed by an automobile tire. Water depth = 0.3 inch. V_G = 88.5 mph. Vertical load = 835 pounds. Tire pressure = 27 psi.

NASA-Langley, 1965