AUTOMOBILE TIRE HYDROPLANING - A STUDY OF WHEEL SPIN-DOWN AND OTHER VARIABLES.

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16. Abstract

A study of the wet weather characteristics of five different pavements and ten different tires is presented. The pavements studied were a portland cement concrete, a seal coat surface treatment, a hot mix asphalt, a jennite surface and a longitudinally grooved portland cement concrete. The tires studied were several bias ply tires with different tread depths, a wide tire with full tread, a test standard tire, a smooth fiberglass belted tire and a full tread steel belted radial. In this study, wheel spin-down was used as the criterion for the detection of hydroplaning and the variables considered were tire tread depth, tire inflation pressure, water depth and wheel load. A sloping trough 800 ft. long, 30 in. wide and 4 in. deep was used in obtaining the data. The results indicate that the seal coat surface treatment requires a considerably higher ground speed to cause spin-down than do the other pavements tested. It was also observed that no single critical speed, necessary for wheel spin-down to occur, exists for the range of variables selected, but it is recommended that there be a reduction of speed to 50 mph for any section of highway on which water can accumulate to 0.1 inch or more during wet weather periods.

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Page 30

wrong: $d = 3.38 \times 10^{3} \dfrac{T^{0.11} L^{0.43} I^{0.59}}{S^{0.42}}$

<u>correct</u>: $d = 3.38 \times 10^{-3} \dfrac{T^{0.11} L^{0.43} I^{0.59}}{S^{0.42}}$

wrong: d = Water depth in inches

<u>correct</u>: d = Average water depth above top of texture in inches

wrong: S = Cross slope in in./ft.

<u>correct</u>: S = Cross slope in ft./ft.

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DISCLAIMER

ABSTRACT

A study of the wet weather characteristics of five different pavements and ten different tires is presented. The pavements studied were a portland cement concrete, a seal coat surface treatment, a hot mix asphalt, a jennite surface and a longitudinally grooved portland cement concrete. The tires studied were several bias ply tires with different tread depths, a wide tire with full tread, a test standard tire, a smooth fiberglass belted tire and a full tread steel belted radial. In this study, wheel spin-down was used as the criterion for the detection of hydroplaning and the variables considered were tire tread depth, tire inflation pressure, water depth and wheel load. A sloping trough 800 ft. long, 30 in. wide and 4 in. deep was used in obtaining the data. The results indicate that the seal coat surface treatment requires a considerably higher ground speed to cause spin-down than do the other pavements tested. It was also observed that no single critical speed, necessary for wheel spin-down to occur, exists for the range of variables selected, but it is recommended that there be a reduction of speed to 50 mph for any section of highway on which water can accumulate to 0.1 inch or more during wet weather periods.

Key Words: highways, pavements, hydroplaning, spin-down, surface texture, water depth, tire inflation pressure, tire tread depth, grooved pavements.

SUMMARY

Vehicles operating on wet pavements suffer impairment of their steering and braking capabilities. Tests have shown that this condition deteriorates as the vehicle speed increases, and at a critical ground speed the vehicular wheel is separated from the pavement by a layer of fluid and is said to be hydroplaning. When this occurs the steering ability of the vehicle is completely lost and the braking capability is greatly diminished.

The spin-down (reduction in wheel speed) of a wheel is an indication of a loss in the tire-ground frictional force and is regarded as a manifestation of hydroplaning. Spin-down occurs when the hydrodynamic lift effects combine to cause a moment which opposes the normal rolling action of the tire caused by the drag forces. As ground speed increases, the tire footprint becomes detached from the pavement which decreases the ground friction on the tire. This report uses wheel spin-down as a criterion for evaluating the wet weather properties of several pavements and considers the effects of water depth, tire inflation pressure, tire tread depth and wheel load on the vehicle speed necessary to cause spin-down. The study was performed by conducting full-scale tests in a hydroplaning trough 800 ft. long, 30 in. wide and 4 in. deep. Water depths up to 0.8 in. can be maintained in the trough.

The most significant findings based on the assumption that spin-down greater than 10% causes a sufficient reduction in the frictional coefficient so that vehicle stability is affected may be stated as follows:

1. A high macrotexture pavement which allows water to escape from under the tire requires a considerably higher ground

speed to cause spin-down than a low macrotexture pavement. Consequently, a safer condition is created.

2. Decreasing the tire inflation pressure normally has the effect of lowering the ground speed at which a certain amount of spin-down occurs. Thus, a less safe condition is created.
3. Increasing the width of a tire causes a decrease in the ground speed required to produce spin-down.
4. An increase in the water depth causes a decrease in the speed at which spin-down takes place.
5. A reduction in tire tread depth causes a decrease in the speed at which spin-down takes place.

IMPLEMENTATION

Hydroplaning is the culmination of conditions leading to loss of tire pavement friction on the highway. The primary causes are water on the pavement surface and high vehicle speeds. Since this end point in available friction deterioration can be absolute, meaning total loss of contact with the road surface and thus total loss of control, it must be systematically avoided. The findings of this study concerning the influences of the road, the automobile and the driver can be implemented in the following ways.

1. By adopting the objective that pavement cross slopes, surface textures and drainage path lengths will be designed, constructed and maintained so that significant water depths on roadway surfaces will be extremely rare occurrences. Figure 67 shows appropriate combinations of these interacting factors for a suggested design rainfall of one inch per hour, an intensity that will not be exceeded 99.95% the time in Texas.
2. By using the anti-hydroplaning criteria presented as a justification for the resurfacing of highways which have rutted water holding wheel paths, insufficient cross slope (due to poor construction practice or to substrate movement) or insufficient surface texture.
3. By using the findings of this study concerning proper vehicle maintenance and driver performance in public information documents, films and training schools. These findings include:
    a. The need to maintain high tire pressures.

b. The need to maintain deep tire tread depths.

c. The need to reduce vehicle speed.

d. The way to determine visually whether a hazardous highway surface condition exists.

4. By the use of specific data which determines critical hydroplaning speeds to justify wet weather speed limits as interim measures at sites determined to be hazardous during rainfall.

I. INTRODUCTION

As a vehicle travels along the highway, the friction required to perform maneuvers is developed at the tire-pavement interface. The friction developed will depend on such things as the pavement texture, tire configuration, area of the contact zone, tread design, speed and tire pressure. If this area is contaminated, the friction developed at the interface will be decreased. If the contaminant is water, the possibility of hydroplaning exists.

Hydroplaning is caused by the build up of fluid pressures within the tire-pavement contact zone, and hydroplaning is considered to exist when the hydrodynamic uplift equals the downward force exerted on the wheel. At this point the tire is completely supported by the water layer. When in this condition, the tire has lost all contact with the pavement surface and thus has lost the tractive force necessary to perform normal or emergency driving maneuvers.

This study has chosen to use wheel spin-down as the indicator of tire hydroplaning. Spin-down is a term describing the loss of angular velocity of a wheel traveling over a flooded pavement as the speed of the vehicle remains constant or increases. Wheel spin-down is caused by the build up of hydrodynamic pressure in the forward portion of the tire-pavement contact area. This force acts to oppose the normal rotating action of the tire and can build up to a point to cause the tire to stop rotation completely. It has been assumed that once spin-down has been initiated some loss of tire-pavement contact has occurred. Once a portion of the contact is lost, the friction developed between the tire and the pavement is decreased and a potentially dangerous situation exists.

The factors being considered in this study are water depth, pavement texture (primarily macrotexture), vehicle speed, wheel load, tire inflation pressure, tire configuration and tire tread depth. By adjusting each of the variables, the effect each has on the speed at which a certain amount of spin-down occurs can be observed.

Up to this time most research in this area has been done by the aircraft industry at the high speeds involved with take-off and touch-down. Because of this, the research has been done using aircraft tires which have very different characteristics from automobile tires. It is the objective of this study to observe what occurs at lower speeds, wheel load and tire inflation pressure.

II. REVIEW OF THE LITERATURE

Theoretical and experimental studies have been made by a number of researchers. The works more nearly associated with the research investigation presented in this report and reviewed during the course of the study are listed in references 1-52.

Saal (42) initially studied the problem in 1935 and developed a model based on two planes approaching each other in a fluid. He assumed the tire contact area to be elliptical and used Reynold's equation to obtain his results. Moore (40) used squeeze film theory to analyze the problem and concluded that the molecular mechanism of viscosity that would be encountered between tire and wet pavement requires further study. Also, he feels that the Reynolds-Stefan equation is inadequate to describe this phenomenon.

Horne and Dreher (27) derived an equation to predict the critical speed at which total hydroplaning begins. This equation assumes the load on the tire to be in equilibrium with the dynamic pressure in front of the tire and neglects the effects of fluid depth. For an experimentally determined lift coefficient of 0.7, Horne develops the equation

$$V_{cr} = 10.35 \sqrt{p} \qquad (1)$$

where

V_{cr} = total hydroplaning speed in statute mph, and

p = tire inflation pressure in psi.

This equation is limited to smooth tires or commercially treaded tires whose tread depth is less than the water film thickness. Reference 27 indicates that the results predicted by Eq. 1 are in reasonable agreement with experimental data obtained for a variety of tires subjected to different loads and inflation pressures.

Gengenbach (19) developed an empirical equation which includes the thickness of the water film and his correlation with test results showed that the total hydroplaning speed was significantly affected by the water film thickness. This contradicted the equation developed by Horne (27). Gengenbach's equation, like Horne's (27) assumed that the wheel load and dynamic pressure were in equilibrium but used the cross section of the water film under the tire contact patch perpendicular to the surface velocity as the area for the force calculation. The area was multiplied by a lift coefficient and the equation to predict the total hydroplaning speed was derived as

$$V = 508 \sqrt{\frac{Q}{B\ t\ C_L}}$$

where

V = total hydroplaning speed in km/hour,

Q = wheel load in KP(1KP = 2.2 lb.),

B = maximum width of contact patch in mm,

t = thickness of water film in mm, and

C_L = lift coefficient determined empirically for a particular tire.

Gengenbach concludes that grooving of the tires considerably reduces the lift coefficient and thus increases the critical hydroplaning speed. In his work, tire designs with mainly circumferential grooves achieved C_L reductions of nearly 50% whereas designs with grooves primarily oriented in the lateral direction achieved reductions down to 25% of the smooth tires.

Martin (35) explains the tire hydroplaning phenomenon from the standpoint of theoretical hydrodynamics and then compares theoretical and experimental results. From the study it is concluded that for moderate water depths and grooved tires, the lift coefficient for incipient hydroplaning does not vary appreciably. Also, an inviscid fluid may be assumed except for the case of smooth tires and/or thin films of water.

Dugoff and Ehrlich (13) studied the hydroplaning problem through scale model laboratory experiments and employed dimensional analysis principles to interpret their results. The tests were conducted for smooth tires of rectangular cross-section at various loads and water depths. The authors interpret Eq. 1 presented in ref. 27 in terms of dimensional analysis principles and indicate that neither fluid gravity forces nor viscosity forces had an appreciable influence on the full-scale tests that were used in the comparison of Eq. 1 and presented in ref. 27. Further, the authors of ref. (13) recommend that the effects of configurational and tread changes to tires and the partial hydroplaning problems be studied.

Wray and Jurkat (50) derived an empirical equation relating critical hydroplaning speed, water film thickness and nominal contact patch bearing pressure for 8" diameter polyurethane model tires having four different widths and a smooth surface. The results obtained using their equation were compared to those obtained by Horne's equation (Eq. 1). They noted that Horne's equation was bracketed by lines of constant water film thickness having nearly the same slope. This implies that by selecting a certain water depth, Horne's NASA equation can be duplicated with experimental data from the model wheel.

A vast amount of research concerning friction characteristics and effects of the pavement texture and material has been conducted by British researchers (1,2,4,17,18,22,23,36). Allbert (1) discusses the effects of tire design parameters on hydroplaning and concludes that the most important is the geometric design of the tread pattern. Allbert, Walker and Maycock (2), after investigating various tires and pavement surfaces, conclude that the coefficient of friction for a slipping tire is significantly decreased with an increase in speed on fine-textured surfaces and to a lesser extent on coarse-textured surfaces. Further, the tread pattern did not play as significant a role on the coarse-textured surfaces. This implies that tread wear would have a minor effect on coarse-textured surfaces. Gough and Badger (22) discuss the effect of tread design on various surfaces and the hydroplaning of heavy vehicles fitted with smooth tires which are traveling on flooded road surfaces. Their findings on pavement surfaces are similar to those presented in ref. 2. Martin (36) discusses treatments to existing concrete and asphalt surfaces in order to improve their skidding resistance. The materials and methods which may be used in future construction are also described and illustrated.

A large amount of research concerning the variables associated with hydroplaning and particularly pavement texture has also been conducted by American investigators (5,11,14,28,30,33,34,43,51,52). Beaton, Zube and Skog (5) conducted studies on the effect of pavement grooving to reduce wet weather accidents. Their results indicate that pavement grooving parallel to the centerline enhances the wet weather behavior of concrete pavements and the friction value is raised. DeVinney (11) investigated the effects of the tread design and compound, tire construction and road surface on the hydroplaning problem. He concluded that the vehicle operating speed is the most significant single factor affecting wet skid resistance. Also, a coarse textured surface has the greatest effect on decreasing the significance of speed; tread design, tread compound, tire construction, surface and temperature all play a role with the effects on skid resistance. Horne (28) from his investigation of tires and pavements concluded that tires having smooth or badly worn treads, and pavements that are worn from heavy traffic or possess too little surface texture, are hazardous. Yager (51) discusses the types of tire traction losses on wet roads and the effects of pavement surface contaminants, surface texture, tire tread design and ground speed on pneumatic tire braking and steering capability. From his study, the author concludes that pavement grooving, both transversely and longitudinally, is an effective means for reducing all known phenomena associated with low tire-surface friction. In addition, badly worn tires indicated a significant reduction in the vehicular braking and steering characteristics when compared with new full tread tires.

III. SELECTION OF PARAMETERS

Pavements

Five pavements have been selected for this study. The first pavement studied was a burlap drag finish concrete surface with an average surface texture of 0.018 in. as measured by the silicone putty method. This pavement was considered to be typical or similar to concrete pavements presently in use. The second pavement tested was a seal coat surface treatment with rounded river gravel, stone size between -5/8 in. and + No. 4 sieve used as cover stone. The average texture of this surface was 0.146 in. measured by the silicone putty method. This high texture composed of fairly loosely bound aggregate is obviously impractical for use on high speed roadways but was chosen simply to show the effect of increasing the macrotexture. A hot mix asphalt was used as the third pavement. An average texture of 0.033 in. was measured by the silicone putty method. This pavement was chosen as one that was similar to those presently in use. The fourth pavement tested was a clay filled coal-tar emulsion surface (Jennite). This surface had a texture of 0.020 in. as measured by the silicone putty method. This surface was chosen because it was felt that it was similar to a bleeding asphalt pavement or a worn wheel rut. The fifth and final surface tested was the initial burlap drag finish portland cement concrete modified by longitudinal grooves 0.125 in. deep by 0.125 in. wide on 1.0 in. centers. This surface was chosen because of the increased use of grooving on public highways. The surface texture was 0.047 as measured by the silicone putty method.

It should be noted that by measuring the texture by use of the silicone putty method only the macro-texture is indicated. It is impossible to show the magnitude of the micro-texture when using this method. This is shown by the fact that pavement four, the jennite surface, has a higher texture than the concrete pavement, surface one. The concrete pavement has a very gritty feeling texture while the jennite is smooth. It is felt that microtexture plays an important part in the reduction of hydroplaning but no quantitive measure of its effect was made in this study. It is possible however to make inferences from the data obtained.

Water Depths

Various water depths, measured from the top of the surface asperities, were considered and values were selected so that the influence of this variable could be evaluated. The water depths studied on the concrete surface varied from 0.12 to 0.70 in. This is a very wide range, with the upper limit being rather impractical, but studied to see just how much effect the water depth had on spin-down and if there was a point past which it had no effect. The depths selected for the seal coat surface varied from 0.25 in. to 0.70 in. This range was considered because when using water depths below 0.25 in. on this particular surface it was extremely difficult to obtain any data, the main reason being that the speeds necessary to cause spin-down at the lower water depths were not achievable with the test vehicle. On the third and fourth surfaces the water depth was varied from 0.12 to 0.40 in. On the fifth surface the water depth was varied from 0.18 in. to 0.40 in. It was found that this is a more realistic range of water depths and that there were ample data produced using these values.

Tire Inflation Pressures

Tire inflation pressures varying from 18 psi to 36 psi in 6 psi increments were selected for evaluation on all five pavements. This range of values was not only representative of pressures found in the tires of most ground vehicles, but also provides an adequate variation or range for studying the effect of the variable. Pressures higher than 36 psi were not selected because the tow vehicle was unable to attain speeds high enough to produce meaningful data.

Wheel Load

Wheel loads of 800 lb. and 1,085 lb. were selected for evaluation on the concrete pavement. The load of 1,085 lb. was used as the basic test weight. This was done because of its specification as the ASTM skid trailer standard. The 800 lb. load was used on tires No. 7 and 8 tested on the concrete surface. This weight was chosen because it provided enough variation to observe the effect of this parameter. Only the 1,085 lb. load was used when testing the other four surfaces since no appreciable variation in the results was observed in the evaluation of the concrete pavement when the 800 lb. was used.

Tires

Ten tires were selected for the study. They included:

1.	Manufacturer A	7.75-14 Bias Ply - Full Tread Depth
2.	Manufacturer A	7.75-14 Bias Ply - 1/2 Tread Depth
3.	Manufacturer A	7.75-14 Bias Ply - Smooth
4.	Manufacturer B	F70-14 Wide Tire - Full Tread Depth
5.	Manufacturer C	7.75-14 Bias Ply - Full Tread Depth
6.	ASTM E-17 Traction Standard	7.50-14 - Full Tread Depth
7.	Manufacturer D	7.75-14 Bias Ply - Full Tread Depth
8.	Manufacturer E	7.75-14 Bias Ply - Smooth

9. Manufacturer E F78-14 Glass Belted - Smooth
10. Manufacturer F 195-14 Steel Belted Radial - Full Tread Depth

It was felt that this wide range of tires would provide an adequate evaluation of the effects of tire geometry, stiffness and tread depth.

IV. EXPERIMENTATION

The tests were conducted in a sloped trough (0.88'/100') 800 ft. long, 30 in. wide and 4 in. deep which is shown in Figure 1. The construction procedures and specifications for this facility can be found in reference 46. Because of its configuration and water supply, there was no difficulty encountered in obtaining water depths of 0.7 in. above the pavement asperities. Even though a perfectly level surface was desired, variations in the trough existed. Therefore, in order to better interpret the data, water depths were taken at several points in the trough as shown in Figure 2. The variation of water depths was most pronounced for the seal coat surface.

It is difficult to obtain constant conditions when performing tests in the open. Therefore, the data contain the influence of temperature and varying winds. Experimentation was halted whenever wind speed was greater than 15 mph. It was felt that this would cause variations in the water depth that would affect the data. It has been observed that wind speed below this point did not affect the data.

The tow vehicle and instrumented test trailer are shown in Figure 3 and a photograph of a typical test is shown in Figure 4. As can be seen from these photographs, the tow vehicle is positioned so as to straddle the trough while the test trailer is offset so that the left tire of the trailer is positioned in the trough. The ground speed from the fifth wheel and the speed of the test wheel in the trough are sensed by identical tachometer generators. The output from the generators is fed into a Hewlett-Packard 320 recorder which contains its own amplifier circuits. The two wheel speeds are simultaneously recorded as analog traces on a strip chart. From this chart the two ground speeds can be compared and the percent spin-down calculated. The fifth wheel or vehicle speed is also displayed to the driver on a digital voltmeter.

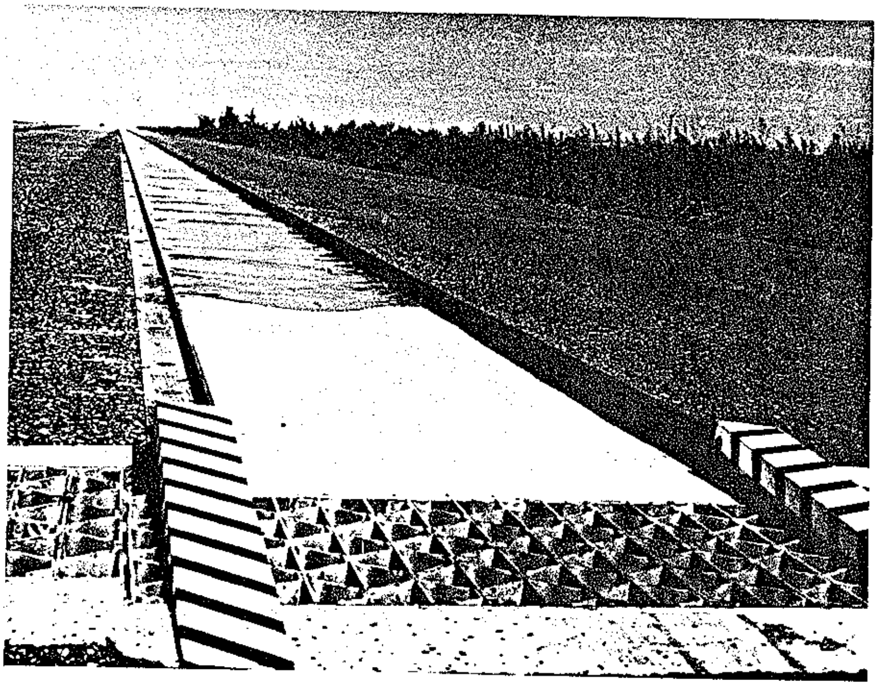

Figure 1. The Hydroplaning Trough.

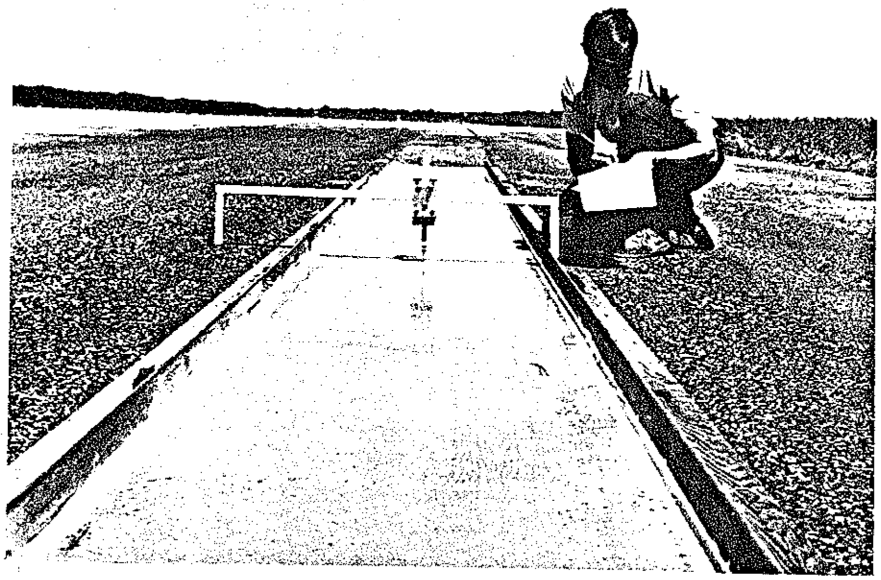

Figure 2. Typical Water Depth Reading Taken Before Test on Hydroplaning Trough.

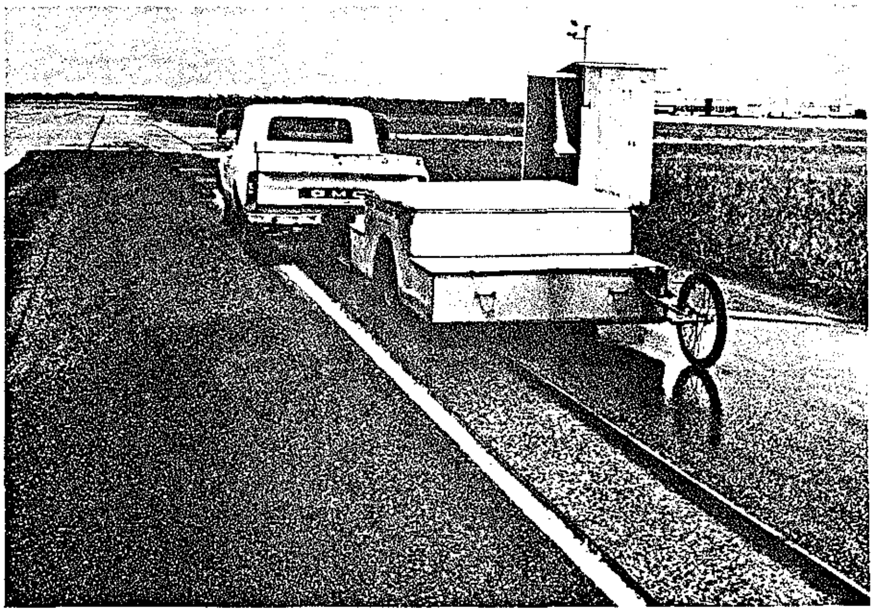

Figure 3. Tow Truck and Instrumented Test Trailer.

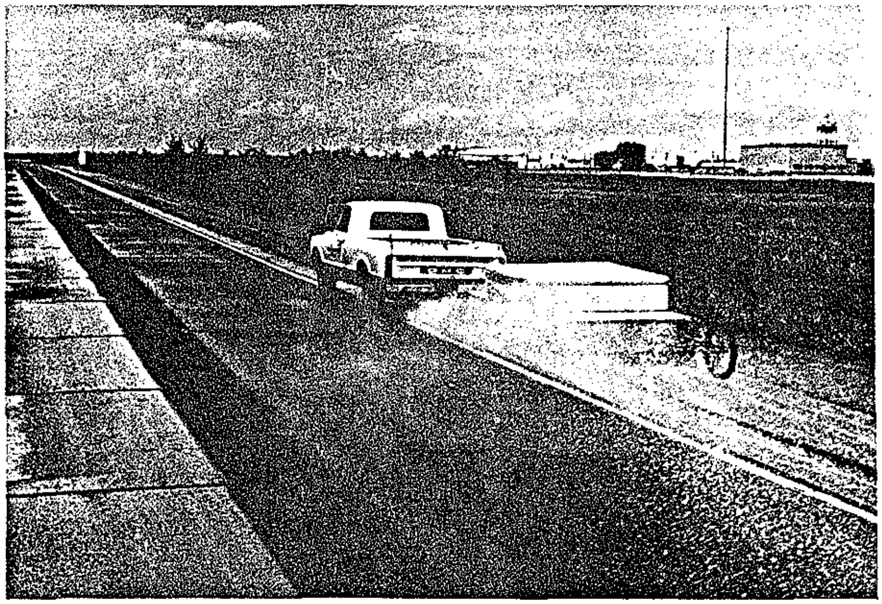

Figure 4. Typical Test Run on Hydroplaning Trough.

V. DISCUSSION OF RESULTS

As defined by Horne (27), the critical hydroplaning speed is that speed at which the hydrodynamic uplift force is in equilibrium with the load carried by the tire. At this speed the tire is being supported completely by the layer of water. However, this is not the speed at which spin-down is initiated. In fact, spin-down can be initiated at speeds considerably below the critical hydroplaning speed. According to Reference 27, in tests run on tandem wheels spin-down was initiated at speeds that were 70% the value of the predicted hydroplaning speed. In a later report (12), Horne restates this conclusion and also states that total spin-down (wheel stops rotating) can take place between 80% and 120% of the predicted hydroplaning speed. These data were obtained from the tests run on aircraft tires

However, it is dangerous to use spin-down as the only criterion for the determination of hydroplaning. As pointed out by Horne (12), as speed is increased above the critical hydroplaning speed there is less tire-fluid exposure time due to increased speed and a more uniform hydrodynamic pressure exists in the contact zone. Rather than having the center of force in the forward portion of the contact zone, it has moved toward the center of the zone, thus shortening the moment arm and reducing the amount of spin-down. A similar situation exists for the water skier. As he is being pulled in the water, the force is being exerted closer to the tips of the skis, however, as he comes to a plane, the uplift force is positioned towards the middle of the skis. Therefore, one should not be trapped into the fallacy that if there is no spin-down there is no hydroplaning. Spin-down is only one indication of the hydroplaning phenomenon. Other things such as coefficient of friction and appearance or disappearance of the bow wave should also be considered when determining the hydroplaning speed.

For the experimentation conducted on the hydroplaning trough, wheel spin-down was the only criterion used to indicate loss of tire-pavement contact. Because of this, it was decided to evaluate the pavements studied and discuss the effects of the variables on the basis of percent spin-down. Percent spin-down means the amount the test wheel relative ground speed has been reduced in relation to the vehicle ground speed.

The data are presented as a plot of vehicle ground speed vs. percent spin-down at a specific water depth showing the plots at the various tire inflation pressures tested. This method of presentation lends itself to the development of further comparisons of data when desired. Several examples of additional comparisons are included in the report.

Figures 5 thru 24 are examples of these plots. These figures display wheel spin-down characteristics for various tires, surfaces, tire pressures, water depths, tread depths and vehicle speeds. One of the most notable trends is the effect of tire inflation pressure. As the inflation pressure is increased, the speed required to cause a certain amount of spin-down is also increased. Figure 5, for example, shows that by increasing the inflation pressure by 6 psi, the speed required to cause 10% spin-down is increased about 4 mph. However, decreasing the tire pressure does not necessarily decrease the speed at which a given amount of spin-down will occur. As can be seen in Figures 5, 10 and 11, there was no significant spin-down obtained at 18 psi for speeds up to 64 mph. It must be remembered, however, that wheel spin-down is only an indication of hydroplaning or tire-pavement contact loss. One explanation for the lack of spin-down is that as the inflation pressure is decreased, the contact area is enlarged. With this enlarged zone, the water pressure profile across the tire is less uniform and the spin-down torque is decreased to the point where partial hydroplaning can occur without spin-down. Also, once the tire is completely supported by the water layer the same water pressure profile is more uniform which can cause a decrease or disappearance of spin-down. Figures 19 thru 23 offer some good examples of the danger of relying solely on spin-down as an indication of hydroplaning. Figures 19, 20, 21 and 23 at 18 psi, and Figure 22 at 24 psi all show % spin-down progressively increasing with increasing speed. However, in these particular cases, as the speeds continued to be increased, spin-down dropped to values usually less than 5%. The phenomenon of decreasing spin-down with increasing speed is also shown in Figures 12 and 17. This was normally observed for an inflation pressure of 18 psi, but was also noticed occasionally at pressures of 24 and 30 psi. It is therefore unjustified to assume that if a tire has not spun-down it has not lost some pavement contact in the lower range of inflation pressures. In such cases, it may be helpful to perform skid tests at varying speeds to determine at what speed the coefficient of friction reaches minimum value.

Figures 5 thru 24 exhibit another interesting point. It should be noticed that each family of curves for a certain tire and water depth are approximately parallel. This was true in all instances. In fact, the curves for the same tire, even as the water depth was varied, showed a similar slope. This would indicate that each tire has its own "hydroplaning characteristics". For example, the steeper the curves the less sensitive the tire is to increases in speed. The closer grouped the curves the less sensitive the tire is to inflation pressure changes.

Figures 25 and 39 are plots of tire inflation pressure vs. ground speeds at 10%, 32% and 60% spin-down. These plots are compared to the equation for critical hydroplaning velocity presented by Horne in reference 27 (i.e. $V_{CR} = 10.35 \sqrt{P}$) where P = tire inflation pressure in psi. Figures 25, 27, 28, 31 thru 36 and 39 show comparisons of tires with full tread depths with Horne's equation. In all cases, the experimental plots are approximately parallel with each other, but not necessarily parallel with plots of other tires. This again indicates the possibility that the tires may possess individual characteristics which may affect the speeds at which they hydroplane. These full tread depth tires require comparatively high speeds to cause spin-down. Therefore, simply because a plot is to the right of the NASA equation does not mean that the tire is definitely hydroplaning. It simply means that the speed required to cause a certain amount of spin-down is higher due to the tires' construction and that there has been at least a partial loss of pavement contact.

Figures 26, 29, 37 and 38 compare the results obtained for a smooth or worn tire with Horne's equation. For these plots, even when total spin-down was compared to the equation, the speeds were far below those perdicted. It should be noticed that the slopes differ from that of the NASA equation. Also, it has been observed that the slopes are affected by the test surfaces. However, the slopes of these plots do not seem to be affected by the water depths at which the tests were run. The water depth did affect the positioning of these plots, that is, it affected the speed at which a certain amount of spin-down would take place. But, as stated by Horne (27), the speeds for even 10% spin-down are within 70% of the speeds predicted by the equation.

As can be seen from the above observations it would be extremely difficult to derive an equation for hydroplaning velocity that would fit all tires under varying conditions. Horne has done an exceptional job, even though as he admits, his equation is very limited. But the agreement of the data presented with his equation is quite encouraging.

Figures 40 thru 48 are plots of water depth vs. ground speed at which 10% spin-down occurred and are used to make various comparisons.

Figures 40 and 41 show the effect of varying the wheel load from 800 lbs. to 1085 lbs. The results for the smooth tire are plotted on Figure 40 and indicate that increases in the wheel load increases the speed necessary to cause 10% spin-down. However, the results for a tire with a full tread depth, plotted in Figure 41, indicate the reverse takes place. These data indicate that the hydroplaning speed is less dependent on wheel load than other variables. However, it should be made clear that only a limited amount of data were collected and this may not be true for other tire-tread depth-texture-wheel load combinations.

Figure 42 shows a comparison of tire No. 4, the F70-14 wide tire, with Tire No. 7, a 7.75-14 bias ply. The bias ply tire required higher speeds to cause the same amount of spin-down obtained with the wide tire. These results are in agreement with the findings of other researchers which indicate that the hydroplaning speed decreases as the tire width increases. In other words, the wider the tire, the lower the speed to cause a given amount of spin-down, all other things being equal. When a person water skis, it is much easier to hydroplane using an aquaplane rather than two skis or using two skis instead of a single ski. The more surface area available, or the larger the contact area, the easier it is to hydroplane. This same trend was observed on all pavements tested.

Figure 43 clearly demonstrates the effect of tire tread depth on spin-down. The data shown are for bias ply tires similar in all aspects except tread depth. As can be seen, the speeds to cause spin-down for the worn tires are considerably lower than for the fully treaded tire. In some cases the difference was as great as 11 mph. Since the tire tread grooves act as a channel for partial escape of the water trapped beneath the tire, this is a very important variable. When the tread is worn smooth, there is no drainage but through the channels in the pavement surface texture. A limit is reached beyond which even deep pavement textures cannot prevent hydroplaning at higher speeds. The maintenance of good tread depth extends this limit significantly.

A bias ply glass belted F78-14 smooth and a steel belted radial 195-14 full tread were tested only on the concrete surface (No. 1), the jennite surface (No. 4) and the grooved concrete surface (No. 5). The glass belted tire produced data similar to the other smooth tires tested. The radial tire produced usable data within the capability of the tow vehicle only on the jennite surface. This would tend to indicate that the radial tire is less susceptible to spin-down and therefore less susceptible to hydroplaning, but a definitive statement cannot be made until methods of measurement other than spin-down are available.

Figures 49 and 50 show that the data collected in previous years work could be repeated. Between 1972 and 1973, it was necessary to replace the jennite surface (No. 4) but no significant texture change was measured. Bias ply full tread and smooth tires were rerun in the repeatability checks and the results are shown in Figure 49. In preparation for grooving the trough, surfaces 2, 3 and 4 were then removed using a hydro-laser. Bias ply tires full tread and smooth were run again on the original burlap drag concrete (No. 1). Results are shown in Figure 50.

A comparison of the pavements tested is shown in Figures 51 thru 56. As stated previously, the textures for the five pavements tested were 0.018 in., 0.146 in., 0.033 in., 0.020 in. and 0.047 in., respectively as measured by the silicone putty method. As can be seen from Figure 51, the speeds to cause spin-down on the seal coat surface (No. 2) are much higher than for the concrete surface (No. 1). In fact, very scant data were obtained at depths below 0.70 in. for all tires tested on the seal coat surface. The speeds at which spin-down occurred on the concrete pavements are well below those traveled on high speed roadways. The data presented are those obtained from a bias ply tire with a full tread depth. Figure 52 is a similar comparison using the data obtained from the F70-14 wide tire with a full tread depth. Again, the speeds to cause spin-down on the seal coat surface were higher. The speed to cause spin-down at 0.70 in. water depth on the seal coat surface was higher than the speed to cause 10% spin-down at 0.40 in. on the concrete surface.

Figure 53 is a comparison of surface 1 (concrete) with surface 3 (hot mix asphalt). Even though the hot mix pavement was shown to have a higher texture than the concrete (0.033 in. as opposed to 0.018 in.), the speeds necessary to cause spin-down are lower on the hot mix pavement. The reason for this could be the fact that the hot mix pavement was rolled with a flat wheel steel roller. Because all of the texture depth is not inter-connected, it provides fewer escape paths for the water trapped beneath the tire. This situation may be compared to that of a waffle iron and the waffle. On the face of the iron, the depressions are interconnected while in the waffle the impressions are not. Both the face of the iron and the waffle would have about the same average texture depth if measured by methods used to acquire texture depths in this study.

By comparing surfaces 3 and 4 shown in Figure 54, it can be seen that the speeds to cause spin-down are higher for the hot mix surface. This result is to be expected. The jennite surface is relatively smooth with very little texture and offers poor drainage for trapped water. This surface could be considered similar to a bleeding asphalt pavement. It was observed, however, that the speeds to cause spin-down on the jennite surface were higher than expected in some cases. It is possible that the test tire was actually hydroplaning, thus making the pressure profile more uniform and decreasing the amount of spin-down observed. Further testing would have to be performed in order to determine the cause.

In deriving his equation, Horne neglected the effect of water depth on hydroplaning speed. In this way he implied that as long as the asperities are covered, hydroplaning will occur at a certain speed depending on the tire pressure. From the data collected here, it seems that the effect of water depth is more pronounced for some surfaces and tires than for others. Figure 46 shows that increasing the water depth on surface 4 (jennite) has little effect on the speed at which spin-down occurs. Increasing the water depth on surface 3 (hot mix asphalt) has the effect of decreasing the speed at 10% spin-down as much as 9 mph: (Figure 45). When comparing surfaces 1 and 3 (Figure 53) it can be seen that the water depth has about the same effect on both surfaces when the higher inflation pressures are concerned. But as the inflation pressures are decreased, the apparent effect of the water depth is decreased. However, there is no real consistency in this change.

In Figure 55, the two belted tires are compared on the three surfaces upon which they were tested. The difference in 10% spin-down at 24 psi was 13 mph for the grooved concrete surface but some of this difference is attributable to smooth vs. full tread depth.

Figure 56 effectively compares all five surfaces for one tire, the F70-14 wide tire full tread. The seal coat surface (No. 2) is superior to the other surfaces with the grooved concrete (No. 5), second highest texture, the next best. These data in conjunction with the information already discussed and presented in Figures 51 and 52 emphasize the importance of drainage efficiency at the tire pavement interface.

Figure 57 shows a comparison of the bias ply tires tested on surface 4. The speeds shown in these figures are for 10% spin-down, and are plotted against water depth. As can be seen, there is little agreement among the tires as water depth and tire pressure are varied. From the data presented, it appears that tire No. 7 yielded the best results in terms of speed at a given amount of spin-down. From these results it can be seen that even similar tires possess individual spin-down or hydroplaning characteristics. Since the configuration and composition of the tires are basically the same, the difference may be caused by the tread design. Unlike tire 5, both tires 1 and 7 have a basic 4 groove tread design. Tire 1 has a small, straight groove around the center of the tread pattern and a pattern of unconnected saw tooth cuts in the tread. This fact seems to be the difference. Tire 7 also has a 4 groove tread pattern but has a more extensive pattern of cuts which are deeper, wider and inter-connected. Not only do they form a continuous pattern, but they are connected to the main groove design allowing exit of water from the rib area which has the effect of easing the pressure build up beneath the tire. Tire 5, is a 6 groove tread design with no cuts in the ribs and only limited siping.

Figure 58 compares the two belted tires tested. These is a large variation between the data presented; however, the portion of this variation attributable to the difference in tread depth is not known. Tire No. 9 was a smooth glass belted bias ply and tire No. 10 full tread steel belted radial. The tread design on tire No. 10 has a basic 4 groove pattern without interconnections between the grooves.

Figures 59, 60 and 61 summarize data plotted on other figures in this report. In general, the degree of influence of the variables tested on the speed to cause spin-down, from most to least, is as follows: tread depth, tire inflation pressure, texture and water depth. It must be remembered that this is simply a general trend depending on the tire tested.

From the electronic instrumentation data, it was observed that if wheel spin-down occurred it began as soon as the tire came in contact with the water in the hydroplaning trough. In order for the spin-down to reach its maximum value, it is necessary for the spin-down moment to overcome the inertia of the rolling tire. Time is required to accomplish this. This time is indicated as distance on the read out equipment. For example, considering the seal coat surface and using tire No. 4 with an inflation pressure of 24 psi and a water depth of 0.7 in. (see Figure 10), it took approximately 80 ft. to reach a spin-down of 20% when entering the trough at 48 mph. However, when entry speed was increased to 58 mph it took 240 ft. of travel before a spin-down of 78% was attained; after 80 ft. the tachometer generator traces indicated a wheel spin-down of approximately 20%. The important point here is that the tire is influenced immediately when it comes in contact with the water.

Therefore, it can be concluded that partial loss of pavement contact or partial loss of traction occurs soon after the tire comes in contact with a flooded pavement. If the flooded portion of pavement is not long and the vehicle is not subjected to abnormal maneuvers, the tractive force may be regained before a hazardous condition develops. For a given vehicular ground speed that is high enough to cause wheel spin-down, it can said that the probability of a hazardous vehicle control condition developing increases with increasing length of the flooded pavement.

VI. APPLICABILITY TO
SAFE WET WEATHER SPEEDS

In legislative action, Section 167 of Senate Bill No. 183, 62nd Legislature, the State of Texas has given authority to the Highway Commission to set wet weather speed limits at specific places on Texas highways. Although by no means encompassing all the factors which could be considered in determining safe speeds, the current data on hydroplaning give indications of the speeds which result in a potentially marginal condition with regard to vehicle control. Hydroplaning is only <u>one</u> of the many factors which must be considered in determining safe speeds. It is limited to the case when a significant depth of water is encountered on the roadway due to an exceptionally high intensity rain or to poor drainage, puddles, wheel ruts, low cross slopes, etc.

In the discussion presented in this section, it is assumed that a 10% spin-down of a free rolling automobile wheel signifies the approach of a control problem due to either loss of stopping capability or loss in directional control. In this section the 10% spin-down speed will be called the "critical speed".

Figures 62 thru 65 show approximate curves which represent the data developed. The effects of pavement texture, tire pressure and tire type or condition are shown by these curves. Several tires are used to illustrate the various effects.

Bias ply tires 7 and 8 represent full tread depth and smooth tires respectively. Tire No. 4 is full tread depth with a wide tire configuration. Wheel load in all cases is 1085 lbs.

The influence of pavement texture on critical hydroplaning speed (as indicated by 10% spin-down) is significant as shown in Figure 62. An increase in critical speed of 13 mph, from 47 to 60 mph, is indicated at a water depth of 1/4 inch when the macrotexture is increased from 0.018 in. to 0.145 in. This difference apparently decreases slightly as water depth increases. Pavement texture effects are also illustrated in Figure 63 for tire No. 4, the wide tire.

The effect of tire pressure is illustrated by Figure 64. The tire pressures of 24 psi to 36 psi shown in this figure account for approximately 70% of the range of tire pressures observed in a study of 501 wet pavement accidents in Texas (25).

Figure 64 shows that at a water depth of 0.1 inch, the critical speed increases by approximately 10 mph (from 48 to 58 mph) as tire pressure increases from 24 to 36 psi. This difference becomes much smaller at greater water depths.

The effect of three different tires on critical speed is shown is Figure 65. Unlike the effects of texture and pressure, the differences between these tires increase as the water layer becomes thicker. At a water depth of 1/2 inch the critical speed varies from 43 to 51 mph. It is notable that the full tread depth wide tire falls between the bias ply smooth and bias ply full tread depth as related to critical speed.

Figure 66 is a consolidation of individual wheel tire pressure graphs as reported in reference (25). The 50 percentile pressure of 27 psi is used in Figures 29, 63 and 65.

From graphs presented in this report, it is obvious that there is no <u>one</u> critical speed that is appropriate for the range of pavements, tire pressures, water depths and tire parameters investigated.

Partial hydroplaning, and thus some loss of vehicle control, may result at speeds significantly below the posted speed limit on major rural highways in Texas. No critical speeds below 39 mph were found and a speed of 50 mph seems to be the approximated median value for all parameters investigated.

It is therefore suggested that a reduction of speed to 50 mph be considered on any section of highway where water can accumulate to depths of 0.1 inch or more during wet periods. Further improvements in the safety of these sections can be made if a high macrotexture surface is placed and maintained.

It has been conclusively shown by numerous tests that the hydroplaning phenomenon can occur for many tires and recommended tire pressures at speeds lower than current speed limits. It is possible, however to design highways so that hydroplaning will be an extremely rare occurrence. Ivey (53) has shown that high intensity rainfall is a rare occurrence in Texas, with a probability of experiencing over one inch per hour less than 0.05% of the time. The highway engineer has the prerogative, based on this study to choose an appropriate design rainfall. If this is done, the following is an example of what design criteria can be applied to make hydroplaning a remote possibility.

> Example: Assume that the design rainfall has been chosen as 1 in./hr. (This then means that less rainfall occurs 99.95% of the time.) Based on the fact that hydroplaning cannot occur at zero water depth, defined as that depth coincident with the tops of the pavement surface asperities, choose appropriate combinations of cross slopes and textures for various drainage path lengths which will give a zero water

depth at a rainfall intensity of 1 inch per hour. This has been done using the equation developed by Gallaway which was presented in nomograph form in Report 135-2F (54). This equation is:

$$d = 3.38 \times 10^3 \quad \frac{T^{0.11} \quad L^{0.43} \quad I^{0.59}}{S^{0.42}} \quad - T$$

Where

d = Water depth in inches

T = Texture depth in inches

L = Drainage path length in feet

I = Rainfall intensity in in./hr.

S = Cross slope in in./ft.

Figure 67 shows the results of these computations for drainage path lengths of 12 and 24 ft. If the cross slope is chosen as 3/16 of an inch per ft., it is required that 0.040 and 0.055 inches of texture be maintained for 12 and 24 ft. respectively if water depths are to be controlled to the asperity top level. Note that combinations of cross slope and texture that fall to the right of each curve would result in lower (negative) water depths and those combinations which fall to the left result in positive (unsafe) water depths.

Since all automobile tires, as presently designed, appear to be susceptible to hydroplaning at some combination of surface, water depth and speed, the vehicle operator must be aware of visual indications of potential hydroplaning conditions. Surface water on a highway can be detected by a driver and speed reduced appropriately. Some of the visual indications of dangerous water accumulations are as follows:

A. Puddling in low spots and wheel ruts appear as very shiney areas on the road surface.

B. The coarser the texture of the pavement, the less light reflected from the surface.

C. Traffic will indicate to the driver the water quantity on the road by the amount of spray produced by tires.

D. Traffic tire tracks tend to wipe the surface. The length of time these wiped tracks are visible, particularly in areas where drainage is crossing the road, is an indication of the amount of water present.

VII. CONCLUSIONS

The following general conclusions are based upon the data obtained from the tests performed at the Texas Transportation Institute's Research Annex and the assumption that 10% spin-down causes a sufficient reduction in the frictional coefficient so that vehicle stability is affected.

1. Wheel spin-down is normally initiated at a ground speed that falls within 70% of the critical hydroplaning speed predicted by Horne's NASA equation. Total spin-down (wheel stops rotating) may occur at speeds lower than those predicted by Horne.
2. As the tire tread becomes worn, the drainage provided by the tread becomes less efficient and the speed to cause a given amount of spin-down is decreased. Speeds to cause spin-down on worn tires are considerably less than for tires with a full tread depth.
3. Decreasing the tire inflation pressure has the effect of increasing the area of the contact zone. In the majority of cases, the larger the area of the contact zone, the lower the speed to cause spin-down.
4. Increasing the tire width has the effect of decreasing the critical speed.
5. An increase in water depth generally has the effect of decreasing the speed at which wheel spin-down is initiated.
6. An increase in the macrotexture of the pavement increases the speed at which spin-down occurs. The interconnection

of drainage channels in the pavement surface is an important factor in minimizing hydroplaning.

7. Even though a tire may not have reached the total hydroplaning speed, a hazardous condition may exist when the wheel has partially spun down and some tire-roadway surface friction has been lost.

8. Many factors must be considered in determining safe wet weather speeds. From a hydroplaning standpoint, it is suggested that a reduction of speed to 50 mph be considered on any section of highway where water can accumulate to depths of 0.1 inch.

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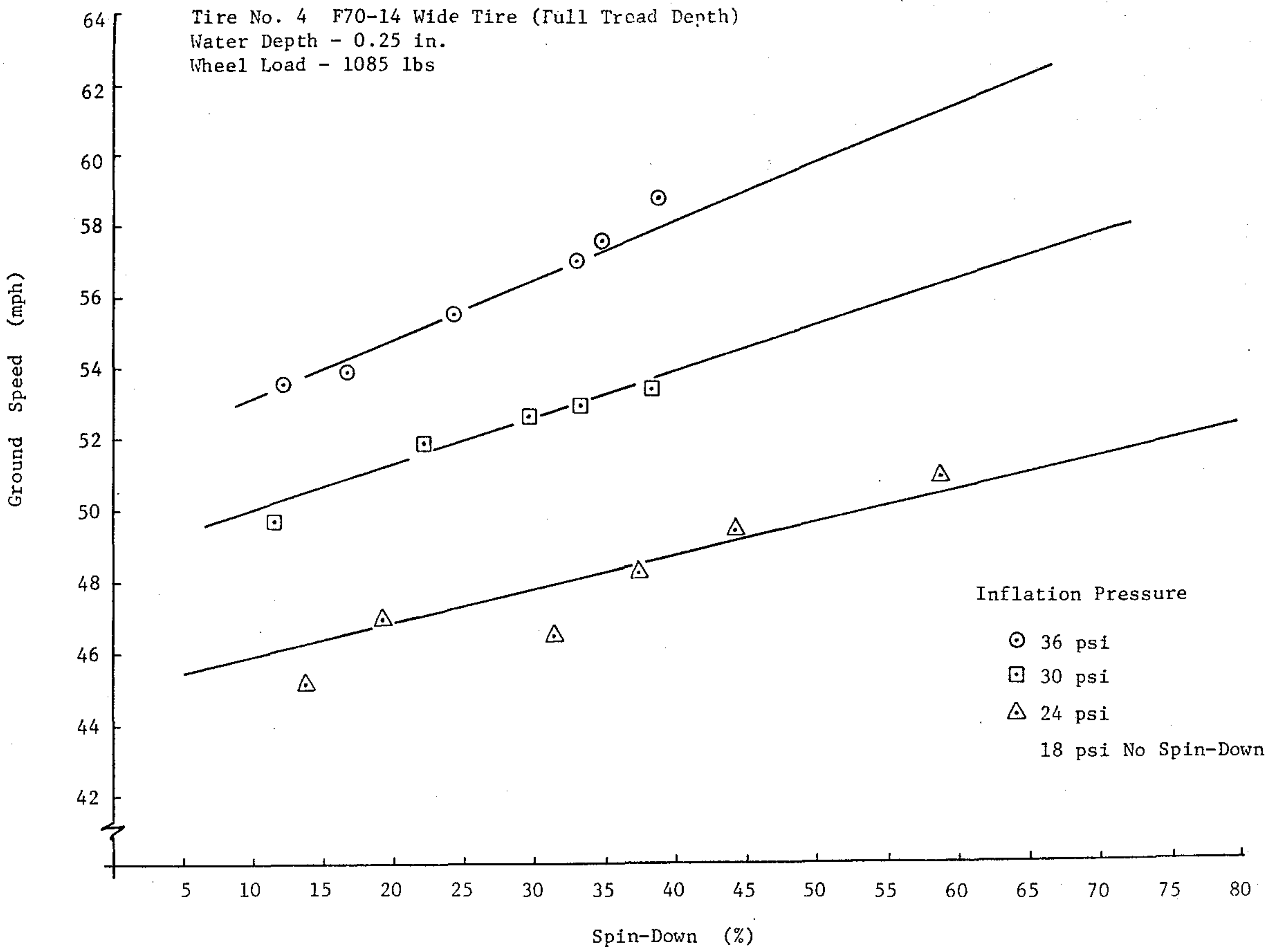

FIGURE 5. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT.

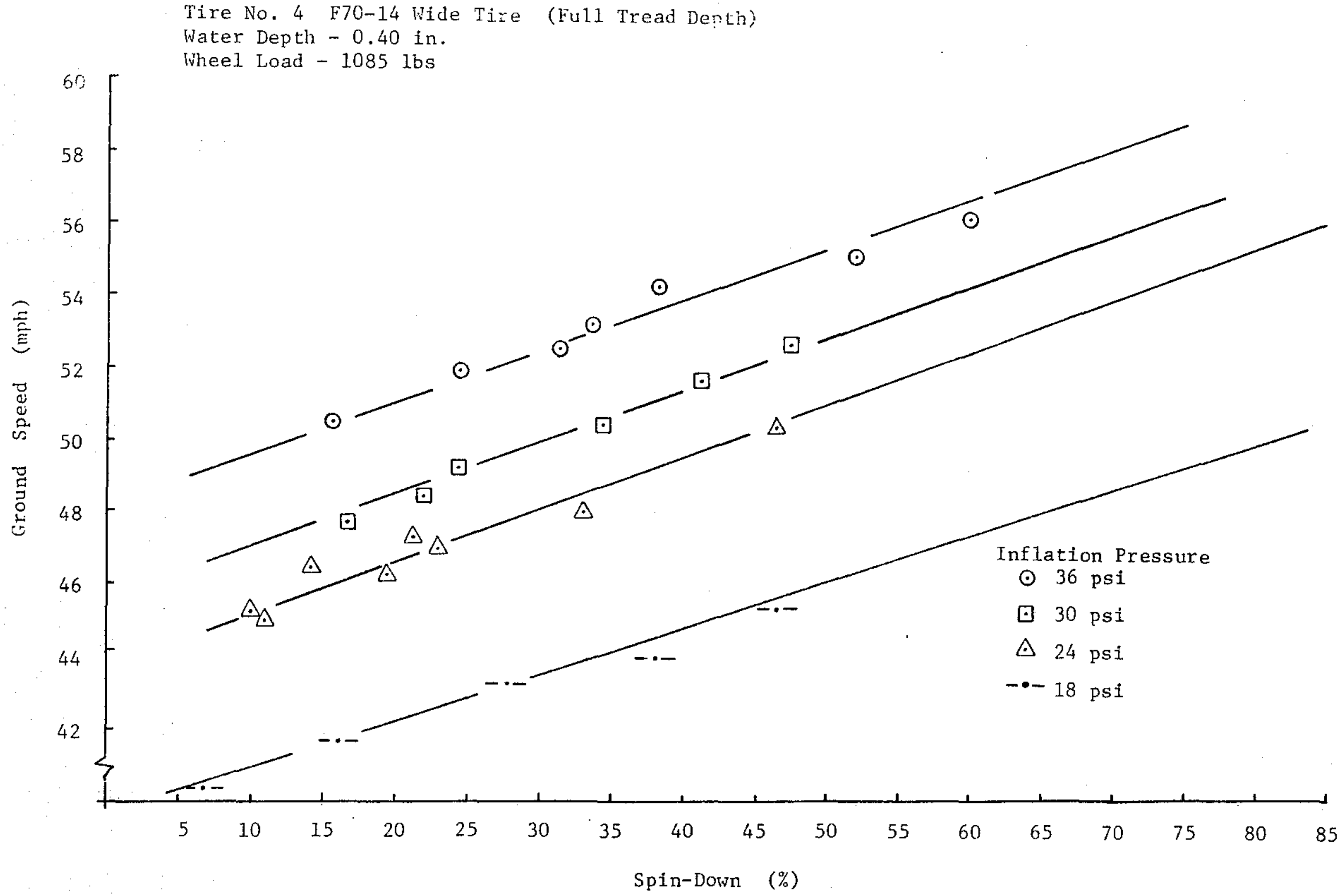

FIGURE 6. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT.

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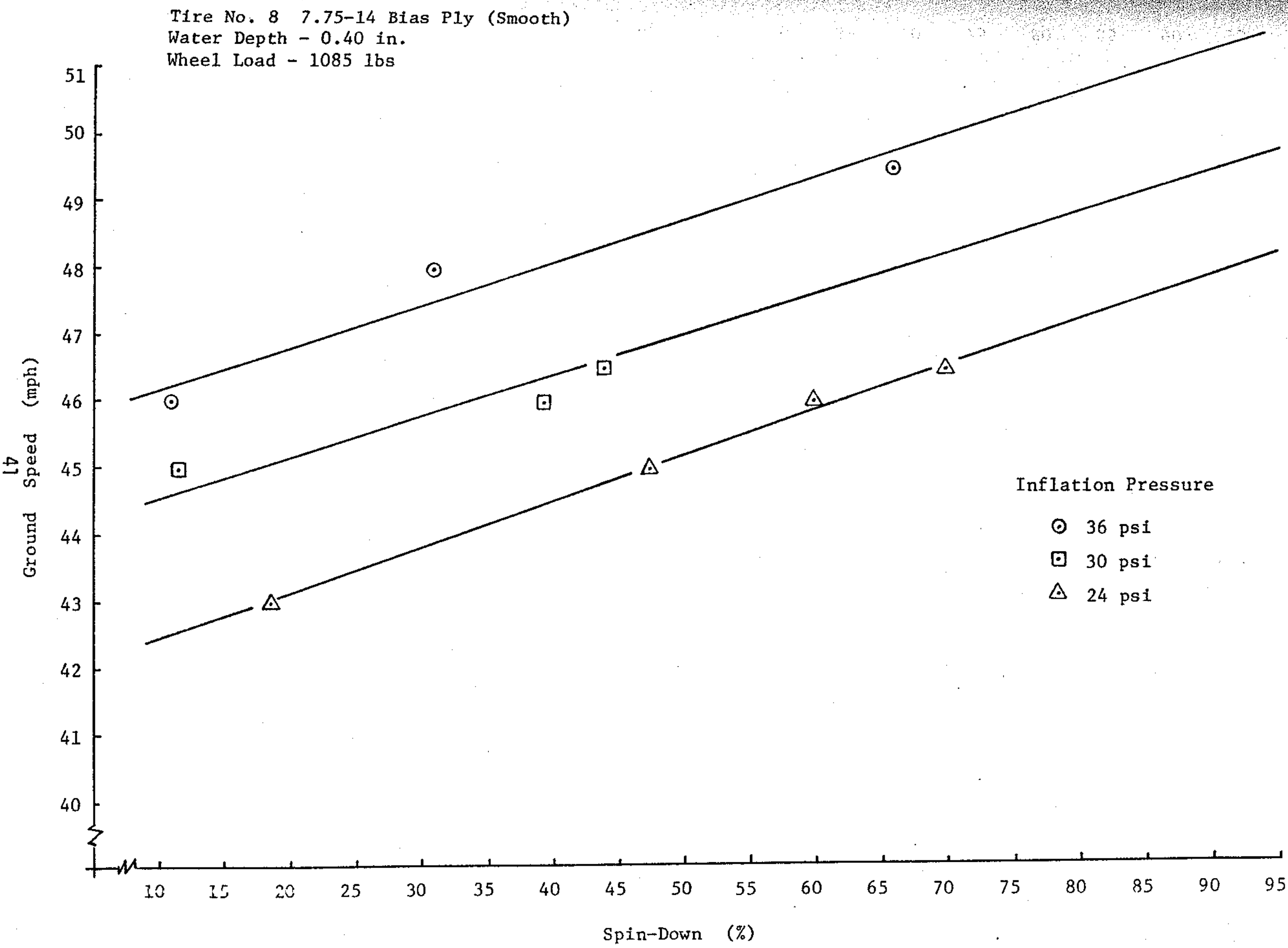
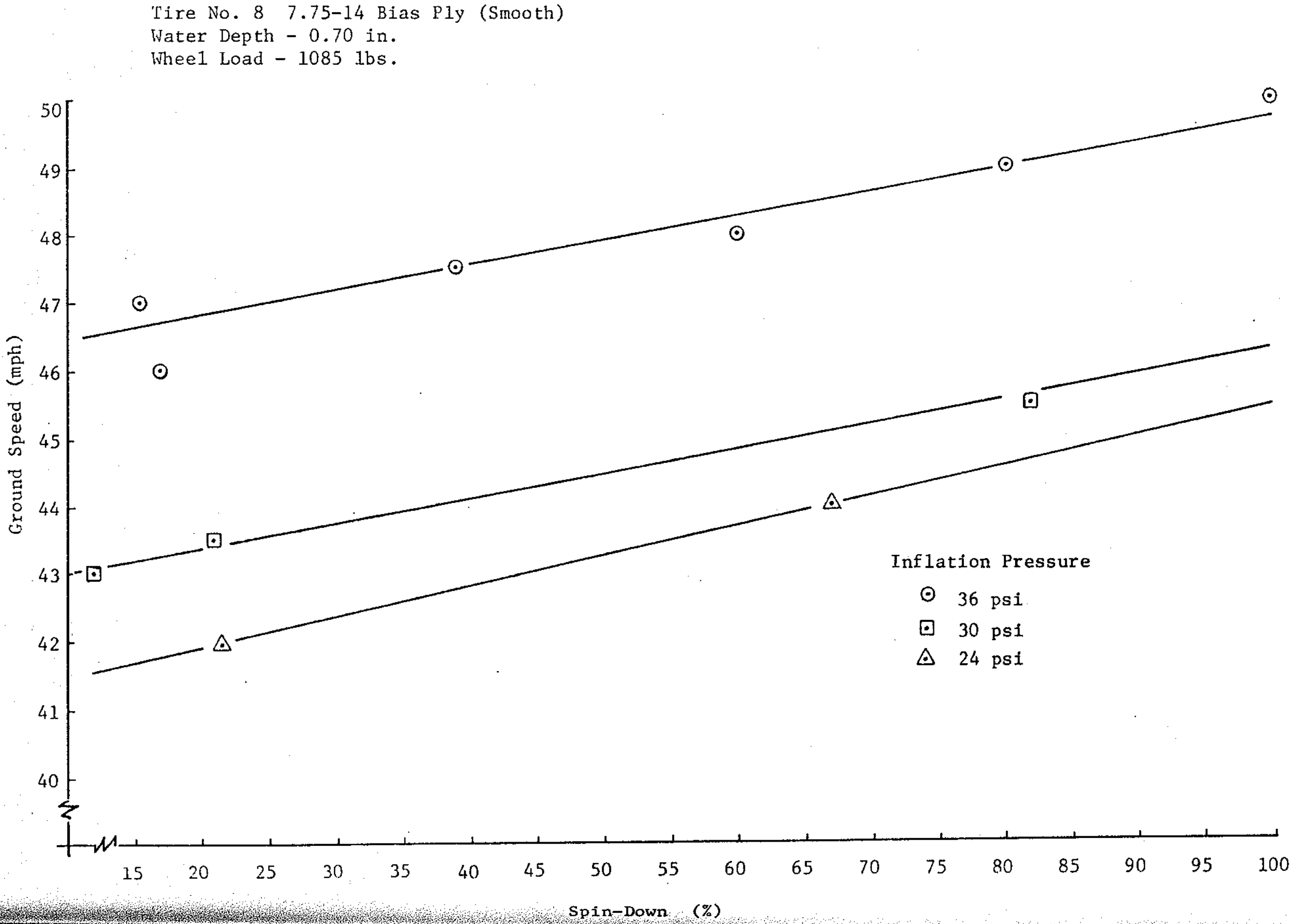


FIGURE 7. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR CONCRETE PAVEMENT.


Tire No. 8 7.75-14 Bias Ply (Smooth)
Water Depth - 0.70 in.
Wheel Load - 1085 lbs.
Ground Speed (mph)
50
49
48
47
46
45
44
43
42
41
40
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
Spin-Down (%)
Inflation Pressure
⊙ 36 psi
⊡ 30 psi
△ 24 psi

Tire No. 4 F70-14 Wide Tire (Full Tread Depth)
Water Depth - 0.40 in.
Wheel Load - 1085 lbs

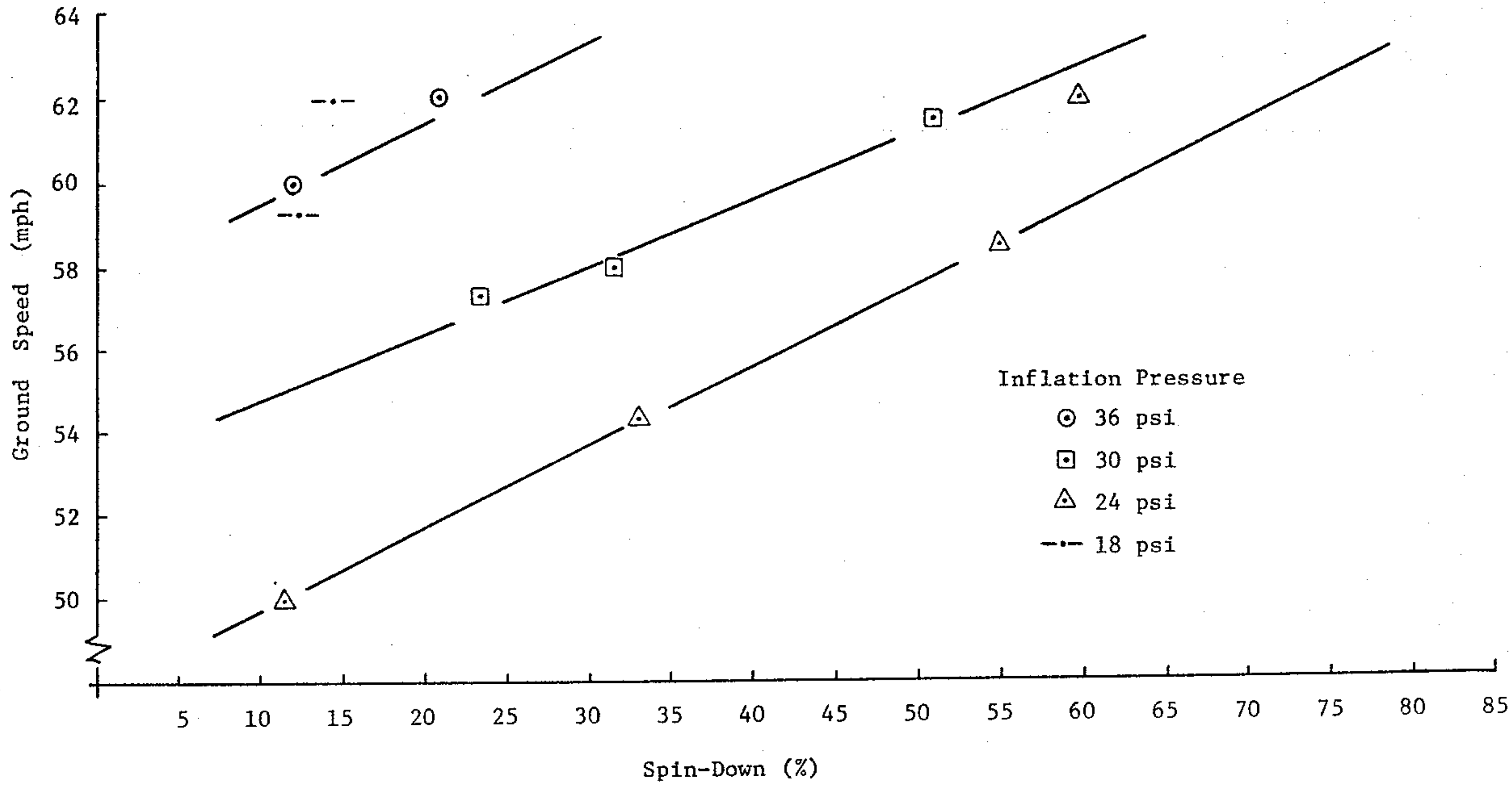


FIGURE 9. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR SEAL COAT SURFACE TREATMENT.

Tire No. 4 F70-14 Wide Tire (Full Tread Depth)
Water Depth - 0.70 in.
Wheel Load - 1085 lbs

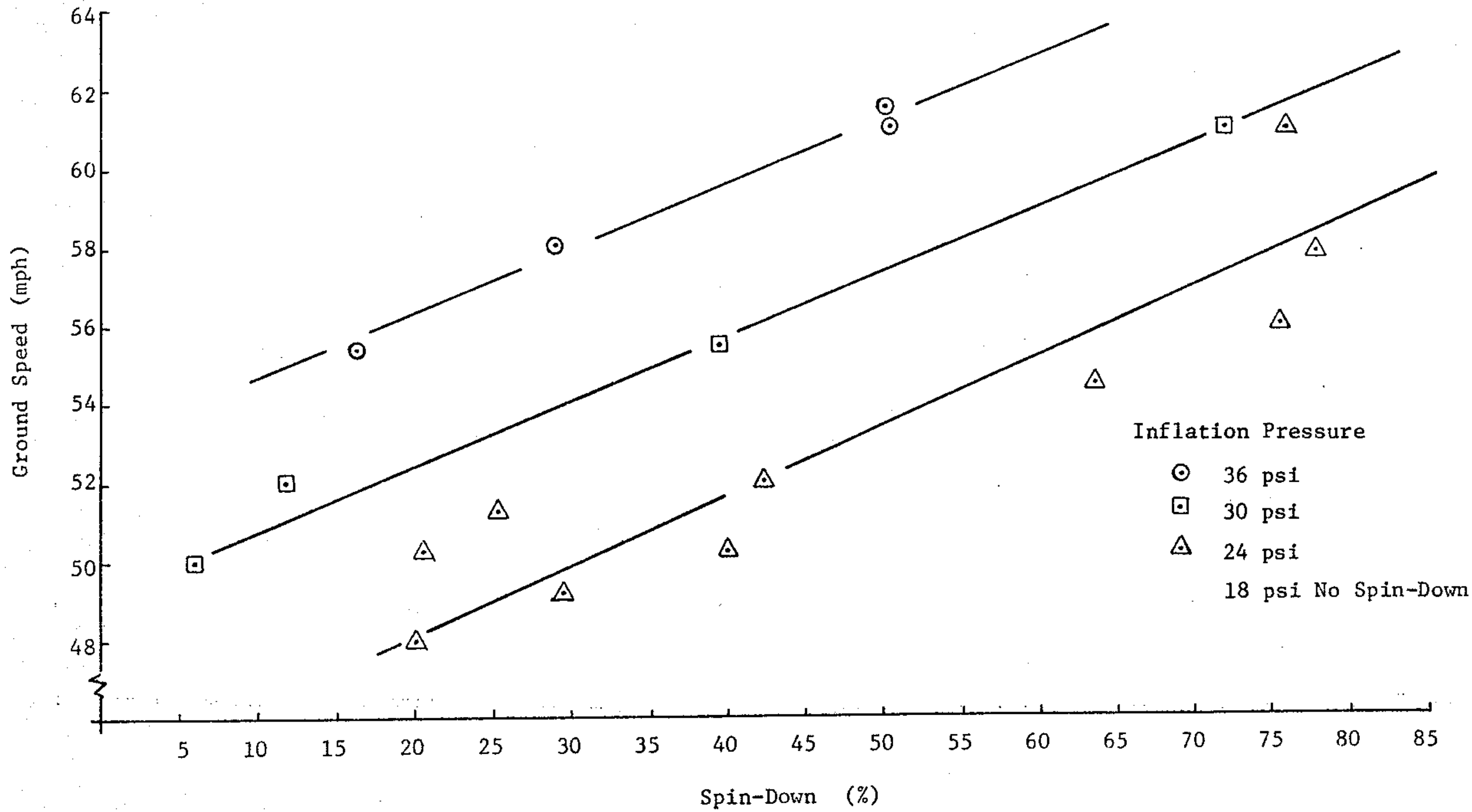


FIGURE 10. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR SEAL COAT SURFACE TREATMENT.

FOR SEAL COAT SURFACE TREATMENT.

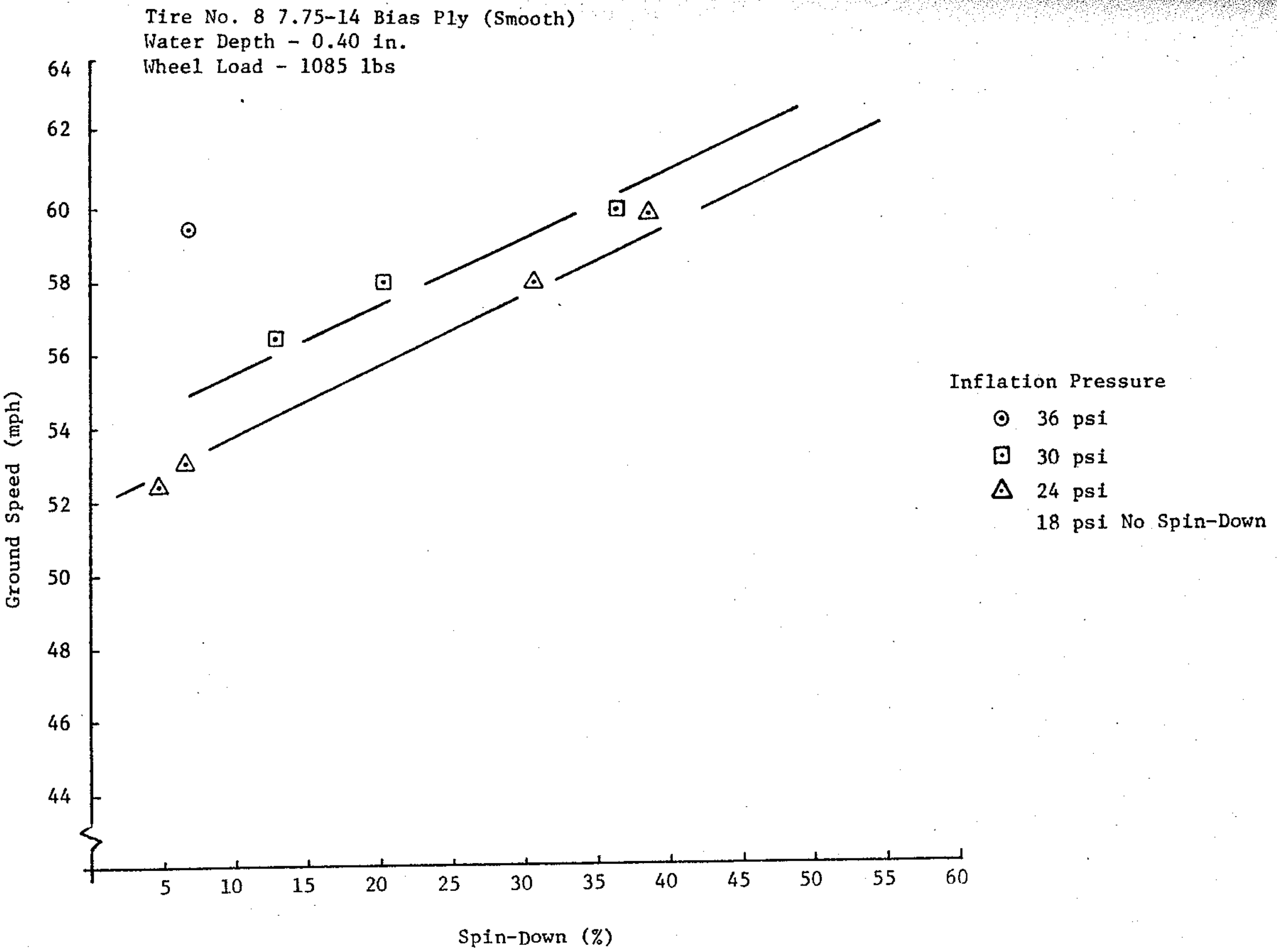


FIGURE 11. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR SEAL COAT SURFACE TREATMENT.

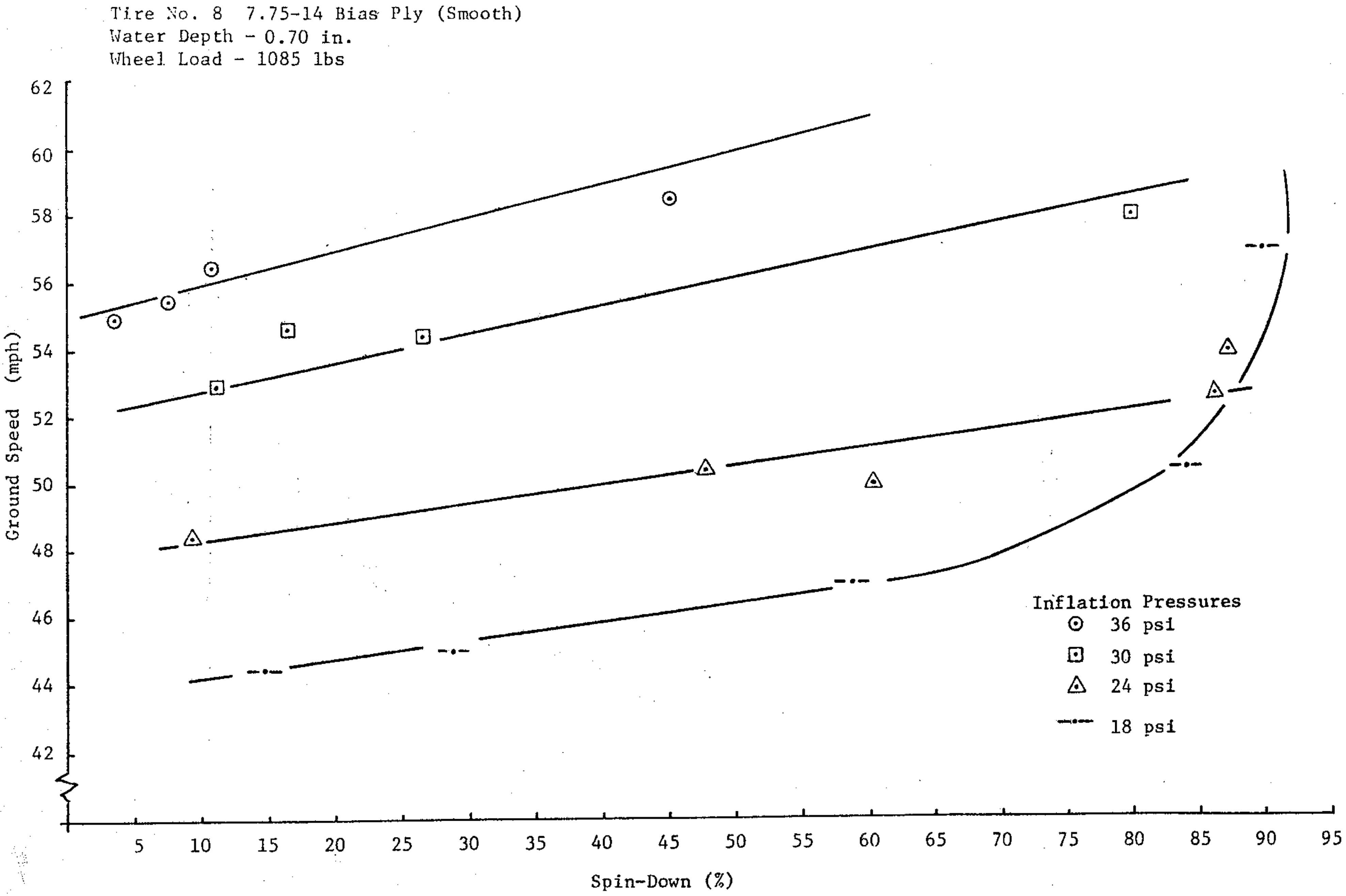


FIGURE 12. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR SEAL COAT SURFACE TREATMENT.

Spin-Down (%)

FIGURE 12. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR SEAL COAT SURFACE TREATMENT.

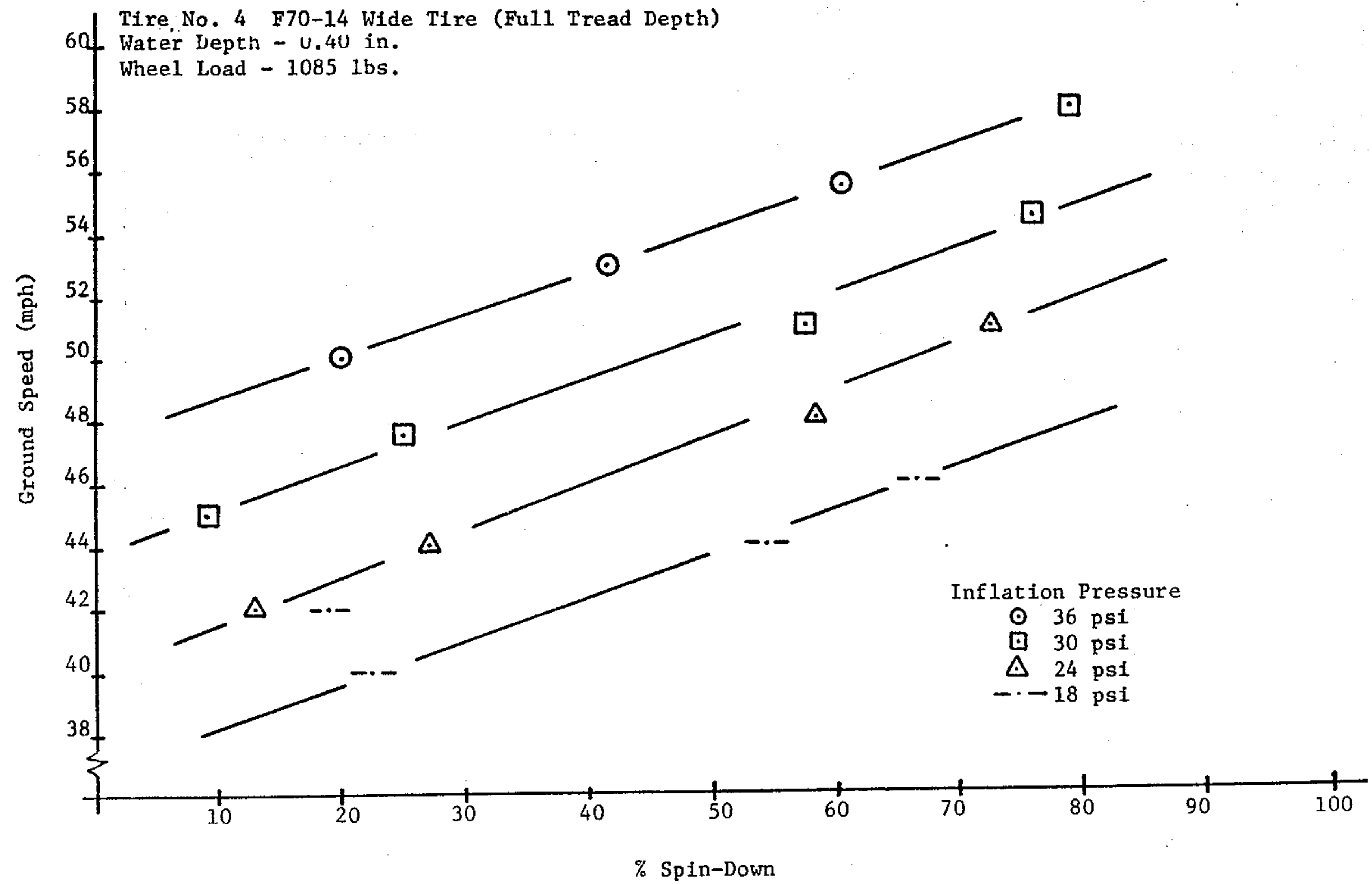


FIGURE 13. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR HOT MIX PAVEMENT.

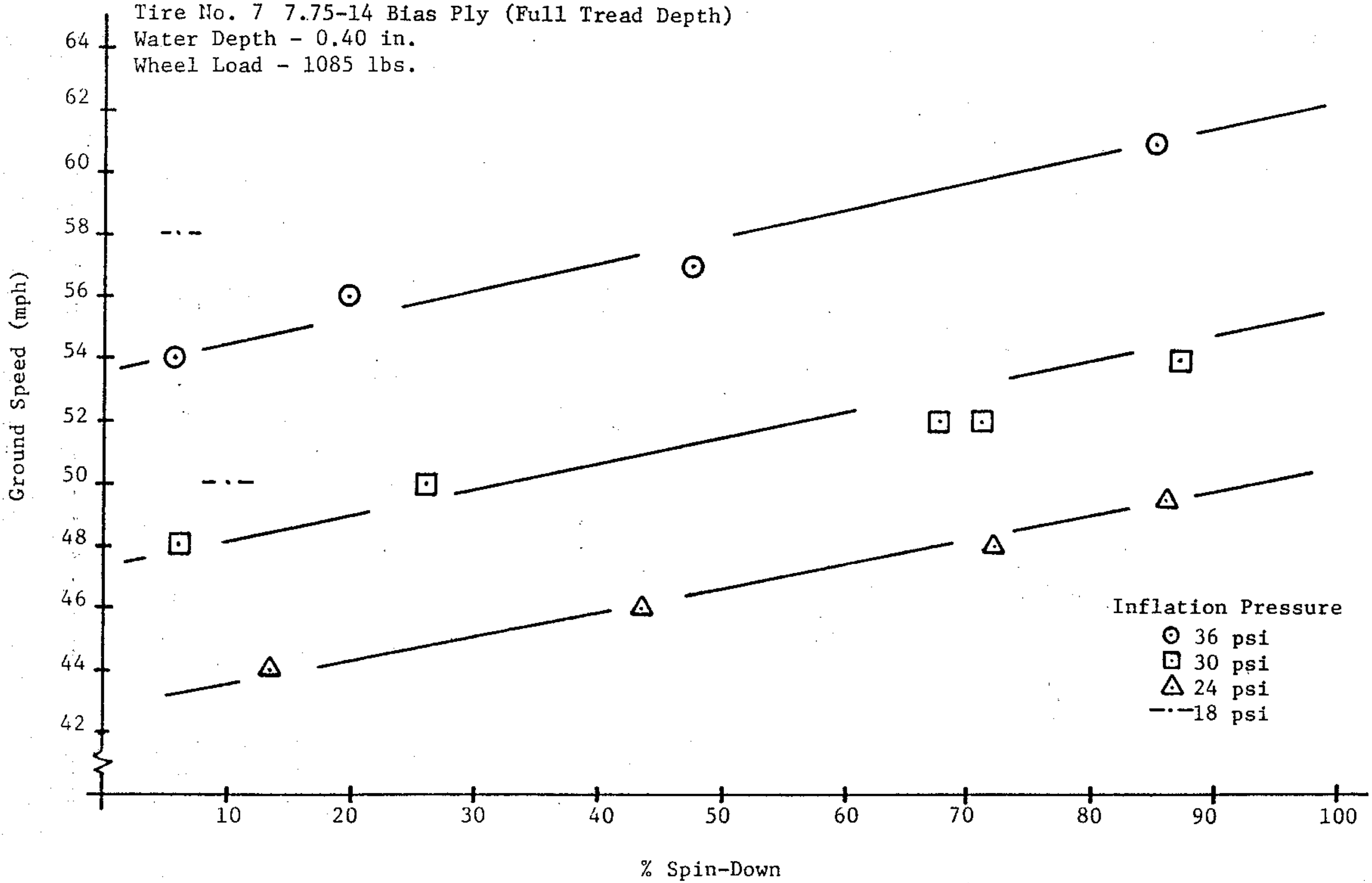


FIGURE 14. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR HOT MIX PAVEMENT.

FOR HOT MIX PAVEMENT.

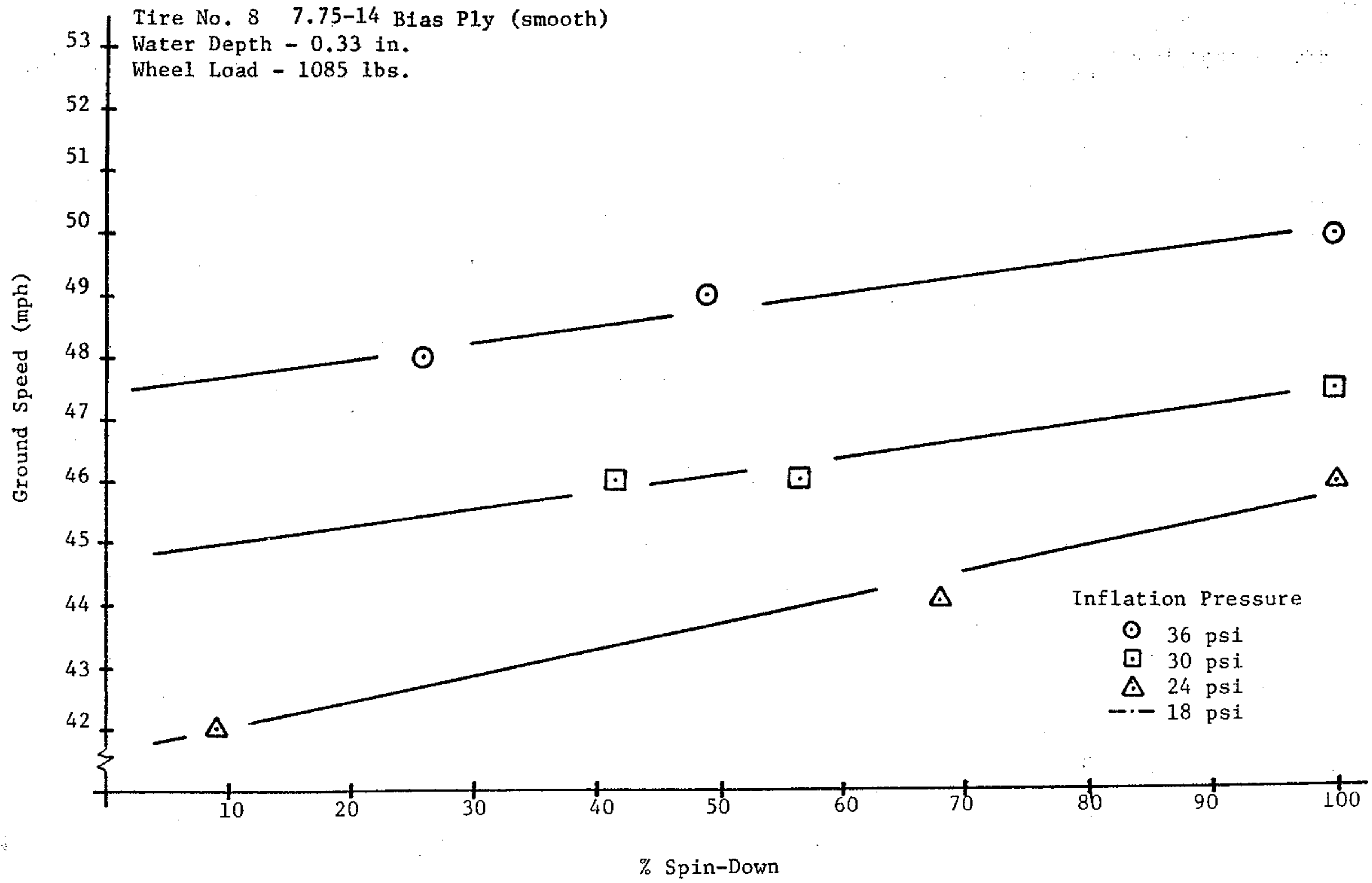


FIGURE 15. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR HOT MIX PAVEMENT.

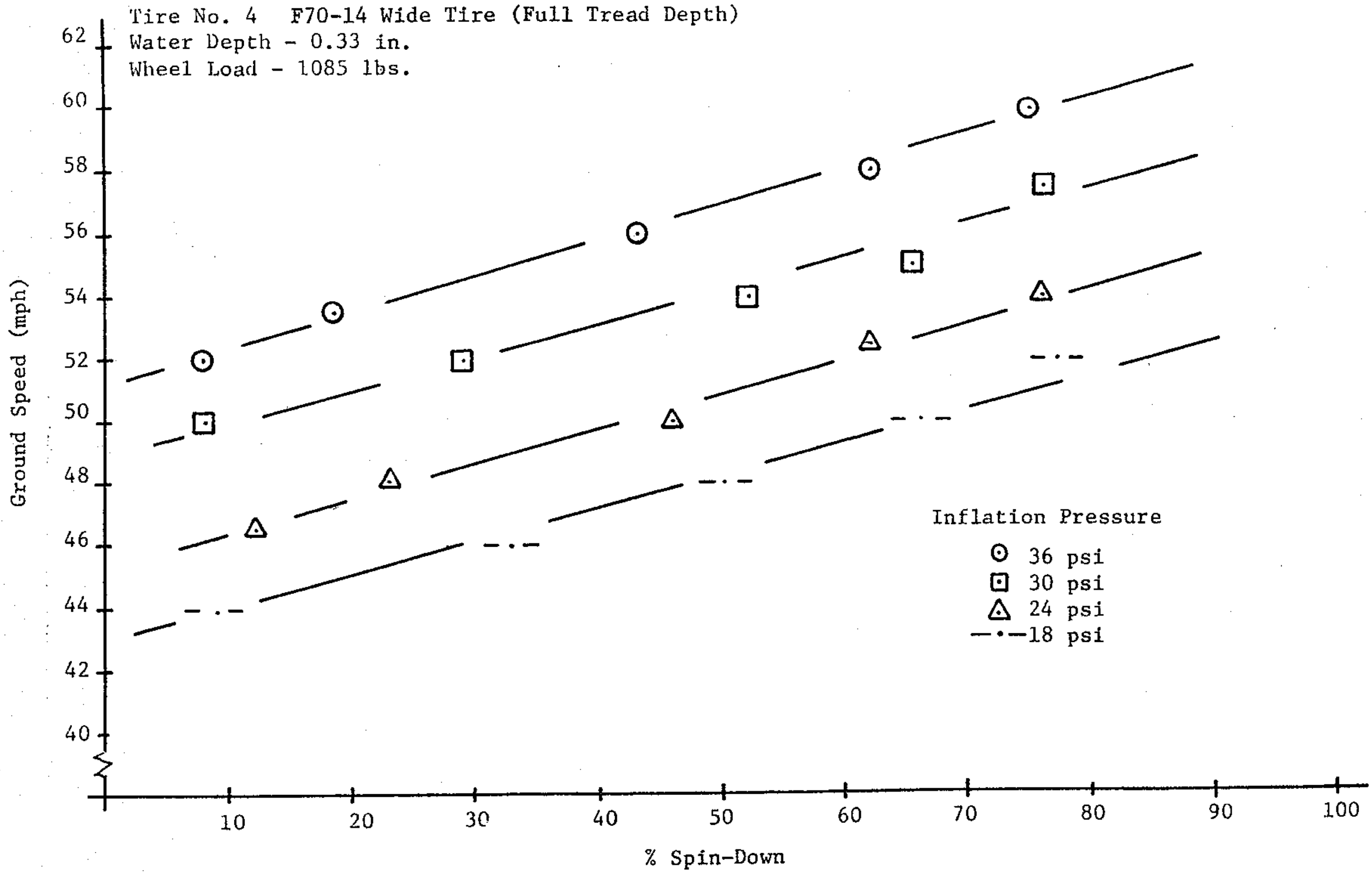


FIGURE 16. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR JENNITE PAVEMENT.

FIGURE 16. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR JENNITE PAVEMENT.

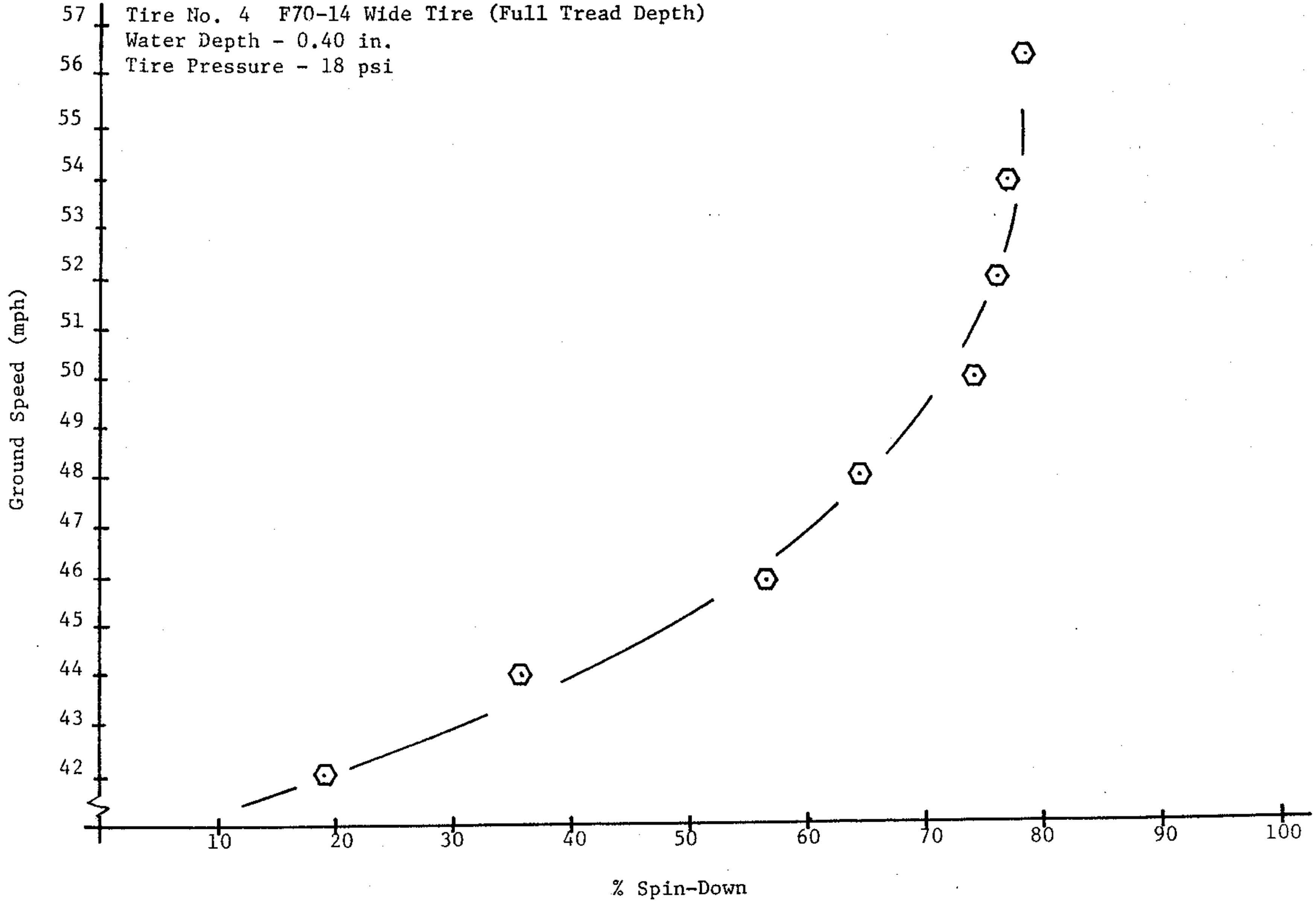


FIGURE 17. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR JENNITE PAVEMENT.

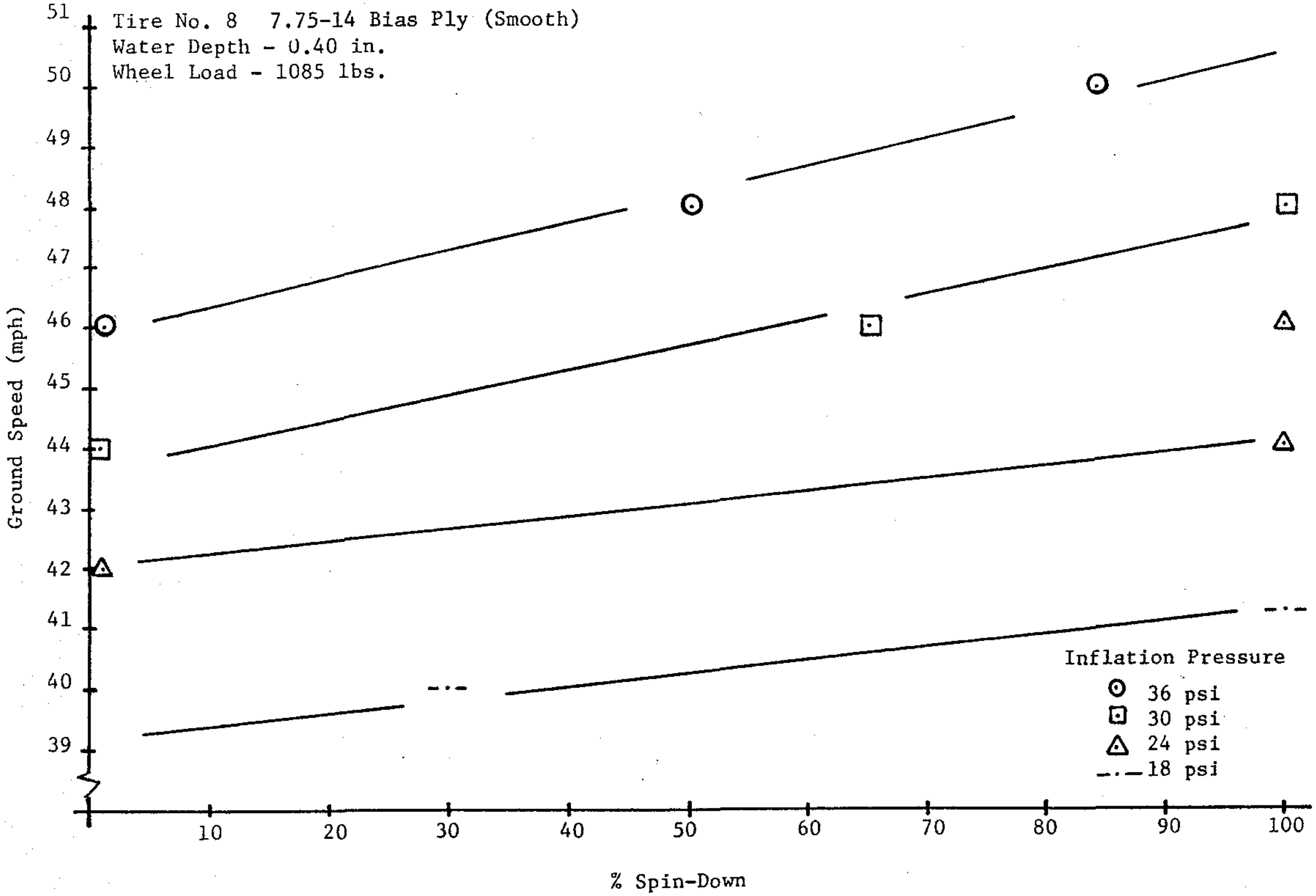


FIGURE 18. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR JENNITE PAVEMENT.

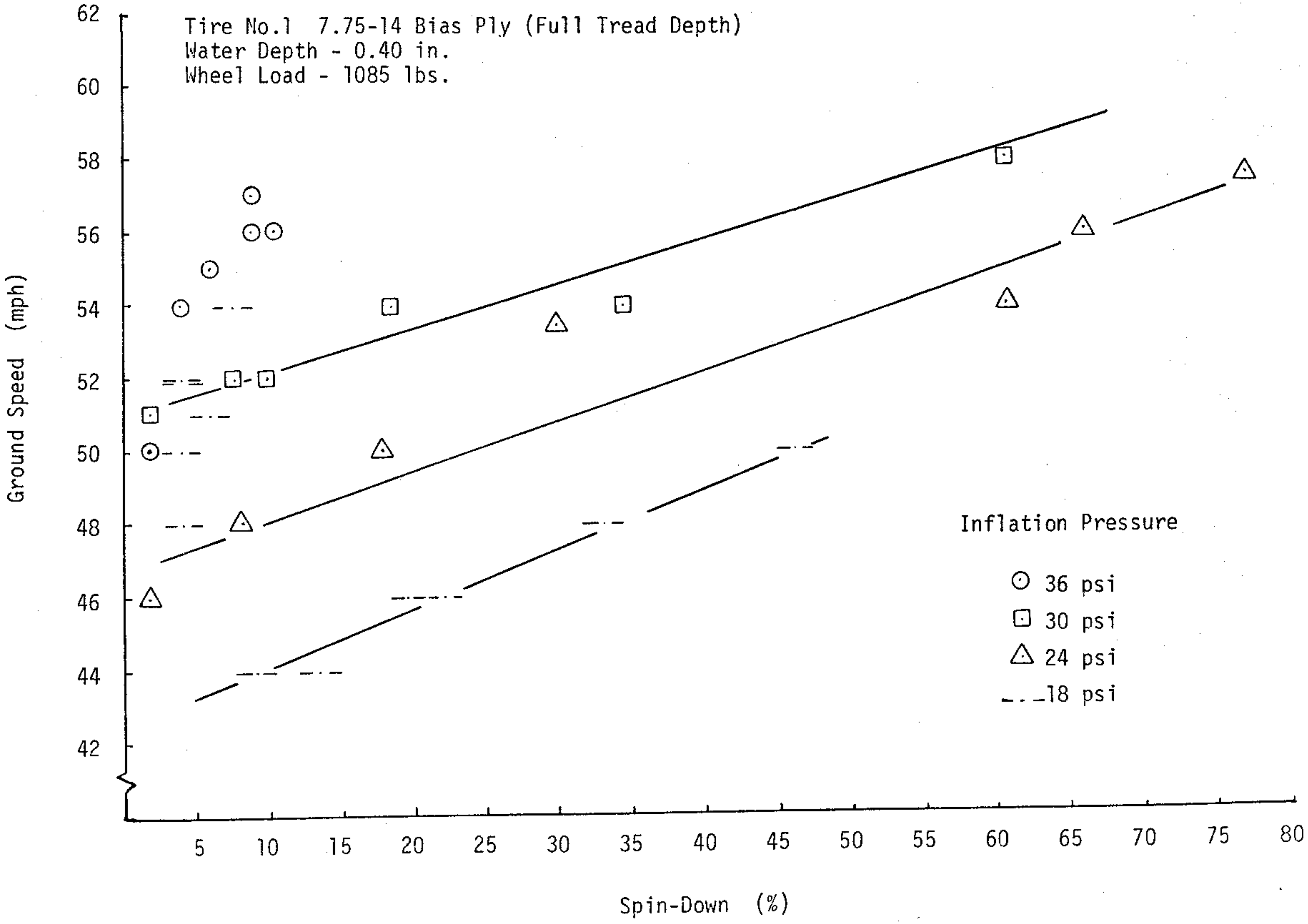


FIGURE 19. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

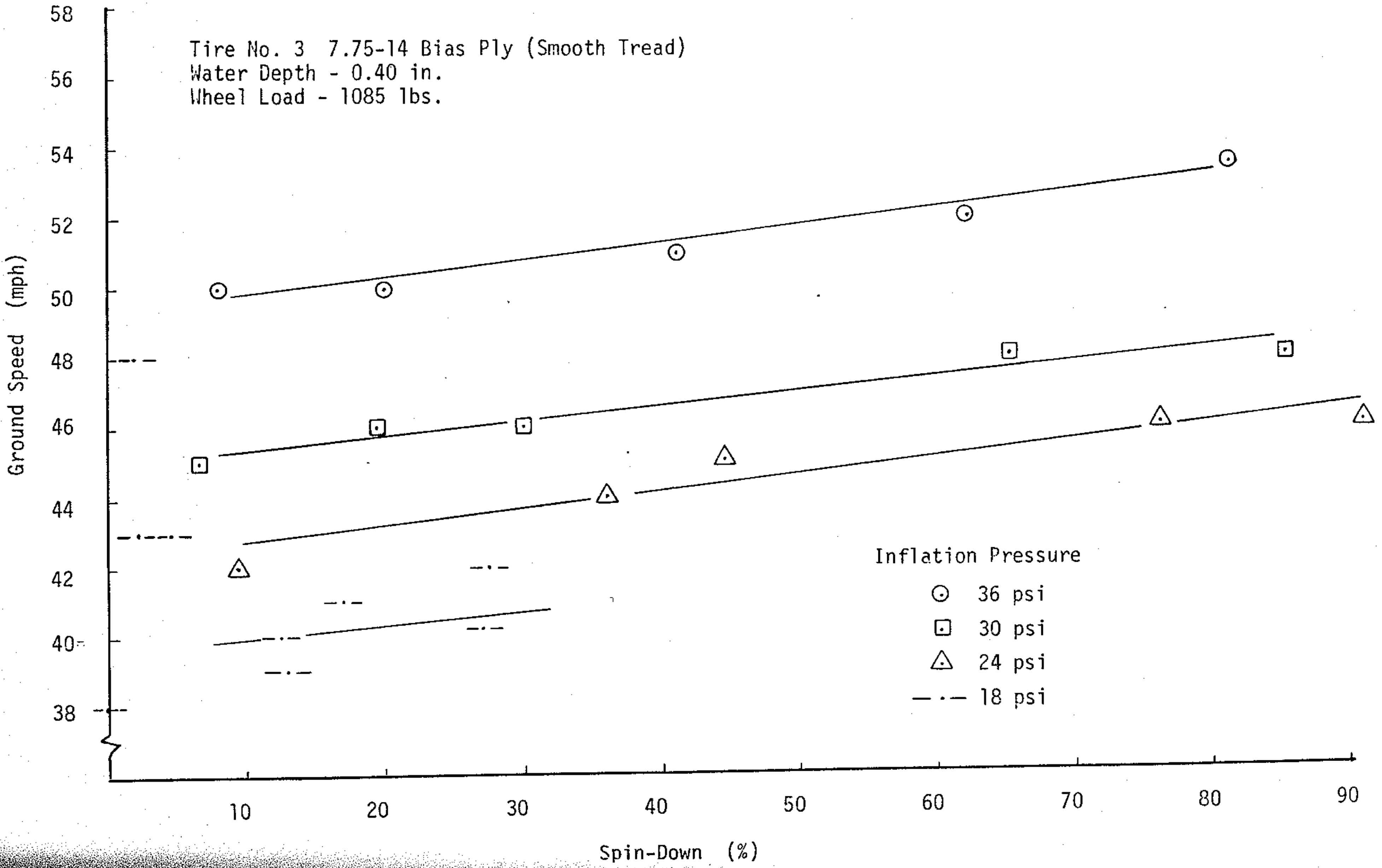


FIGURE 20. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR [illegible] CONCRETE PAVEMENT

Spin-Down (%)

FIGURE 20. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR

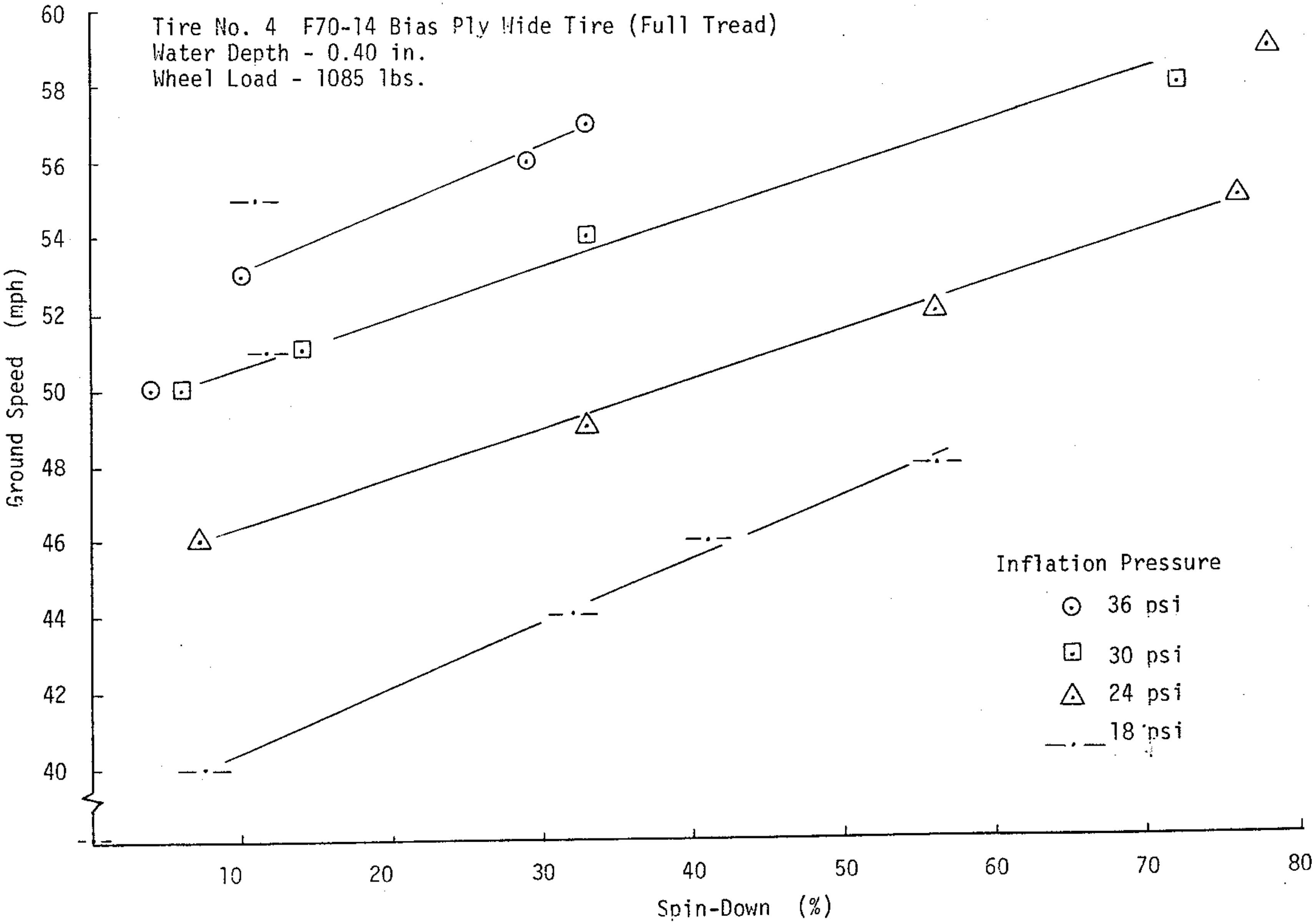


FIGURE 21. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

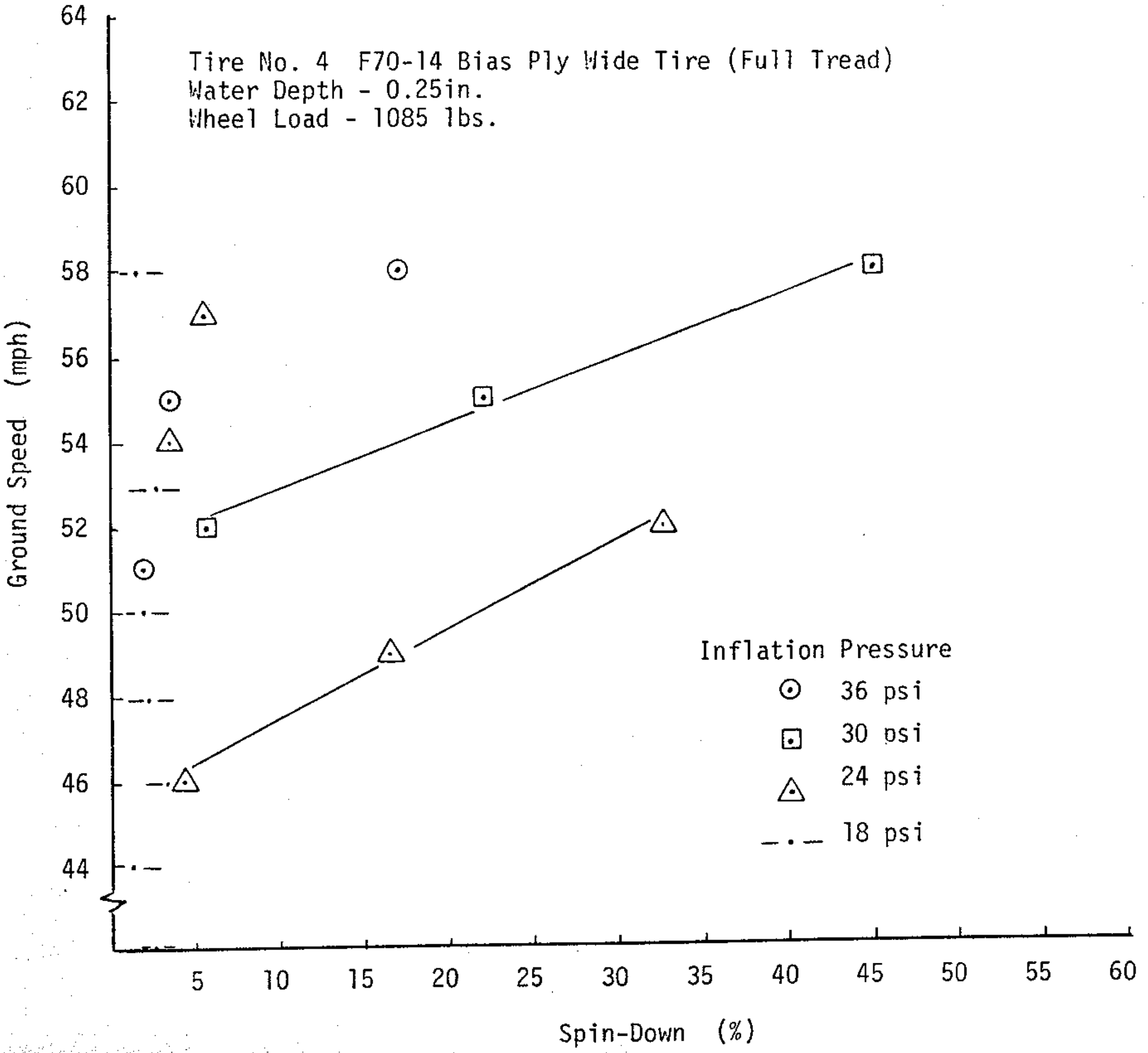


FIGURE 22. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

Spin-Down (%)

FIGURE 22. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

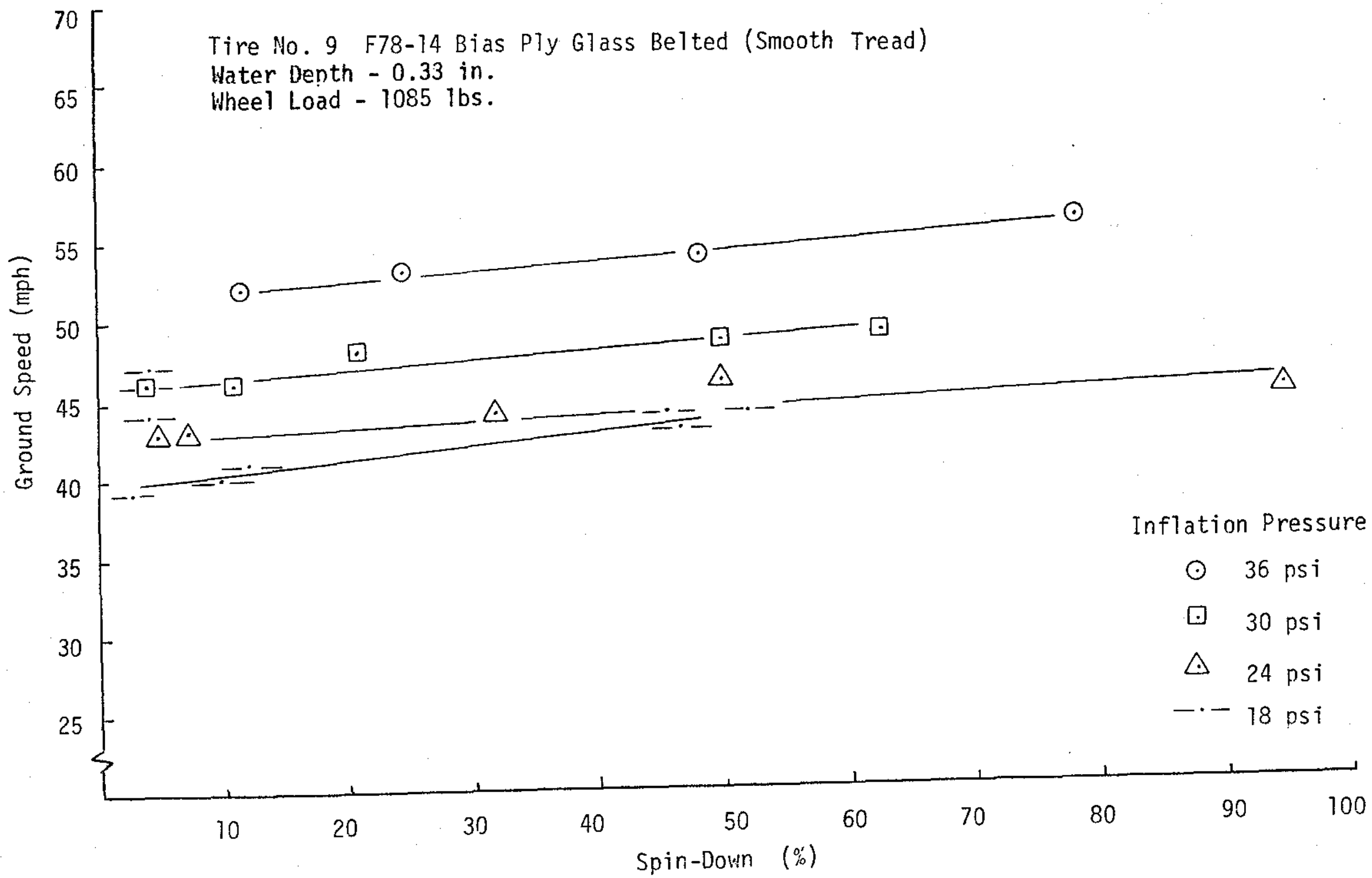

Tire No. 9 F78-14 Bias Ply Glass Belted (Smooth Tread)
Water Depth - 0.33 in.
Wheel Load - 1085 lbs.

FIGURE 23. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

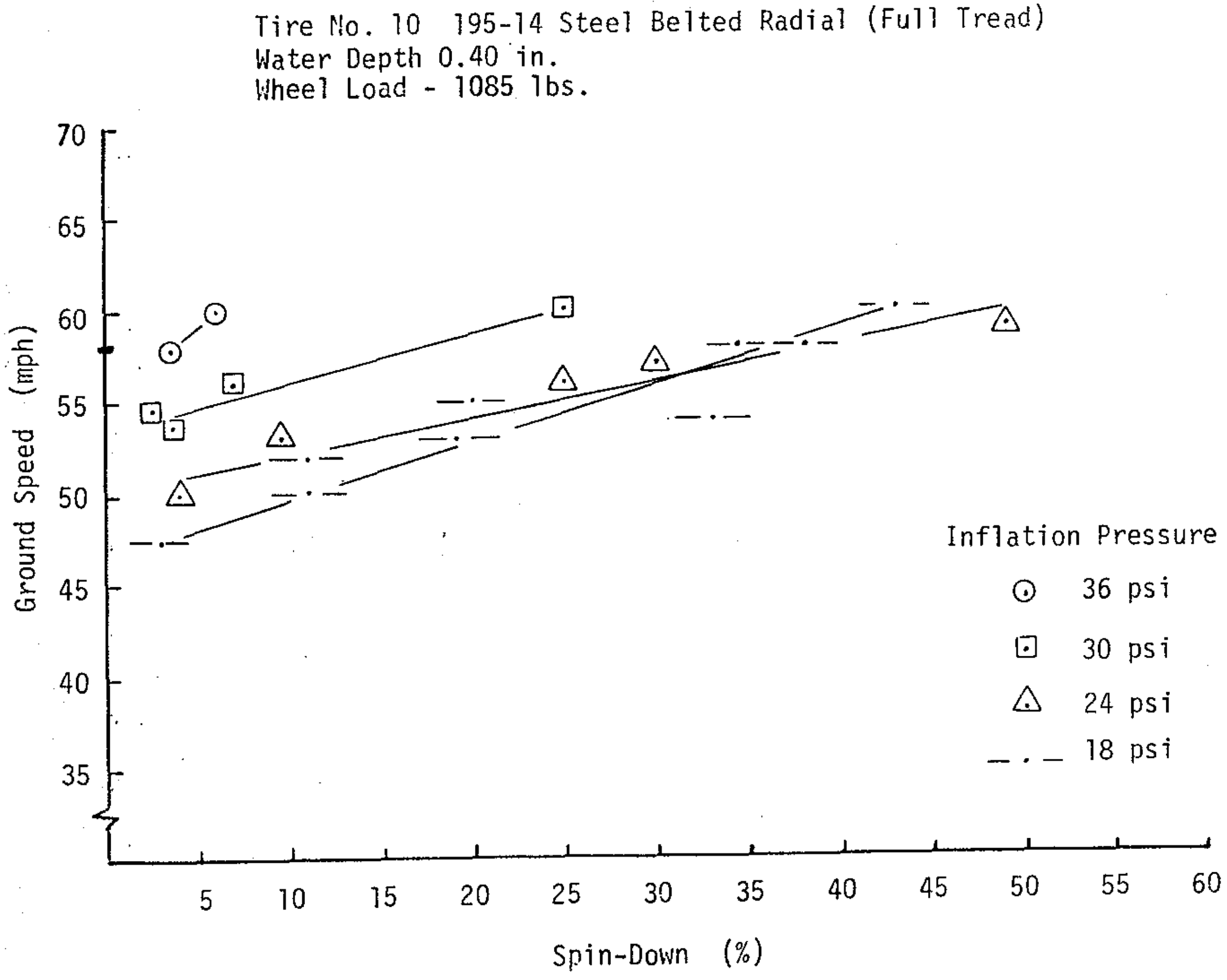


FIGURE 24. EFFECT OF VEHICLE GROUND SPEED ON WHEEL SPIN-DOWN FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

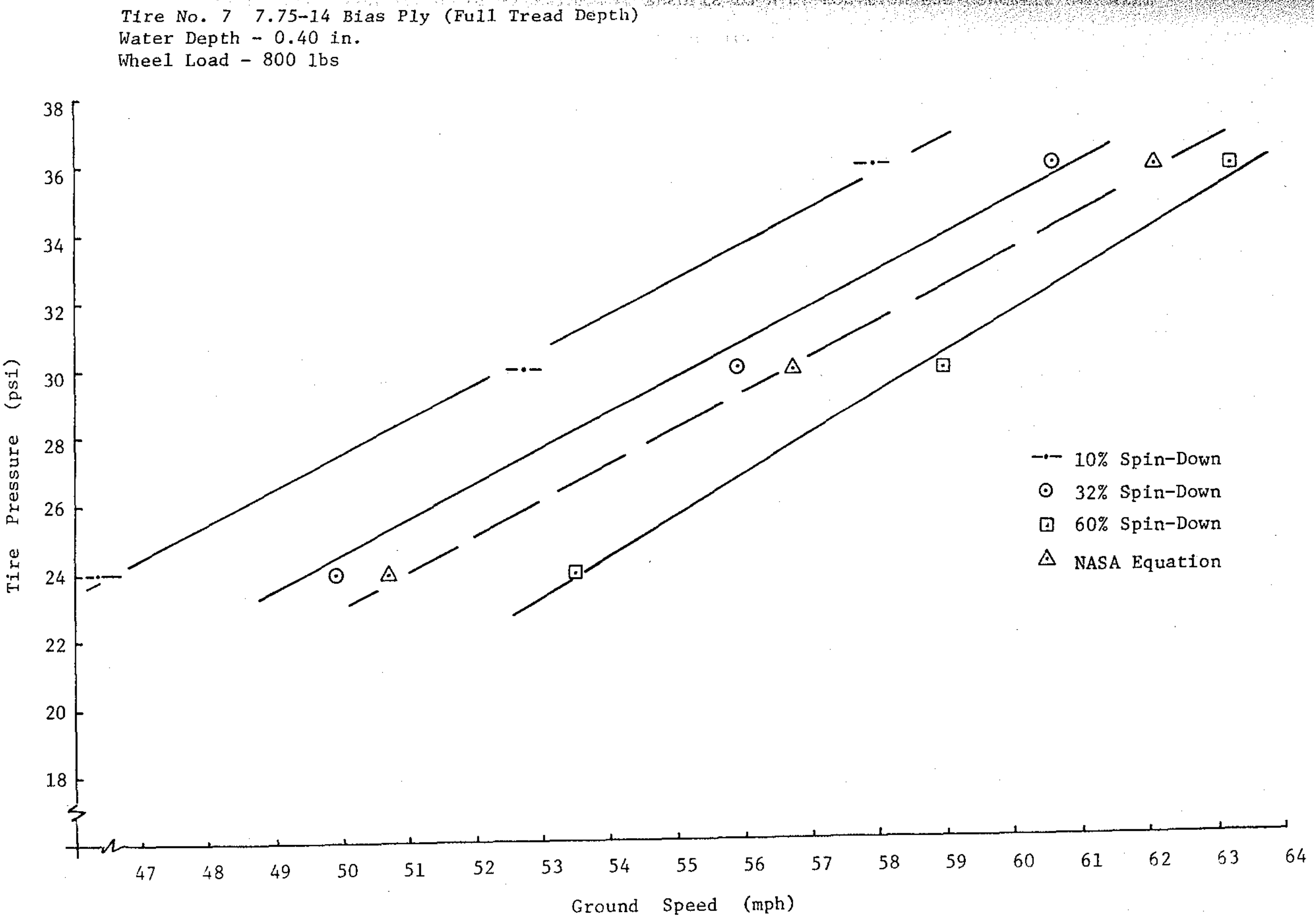


FIGURE 25. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT.

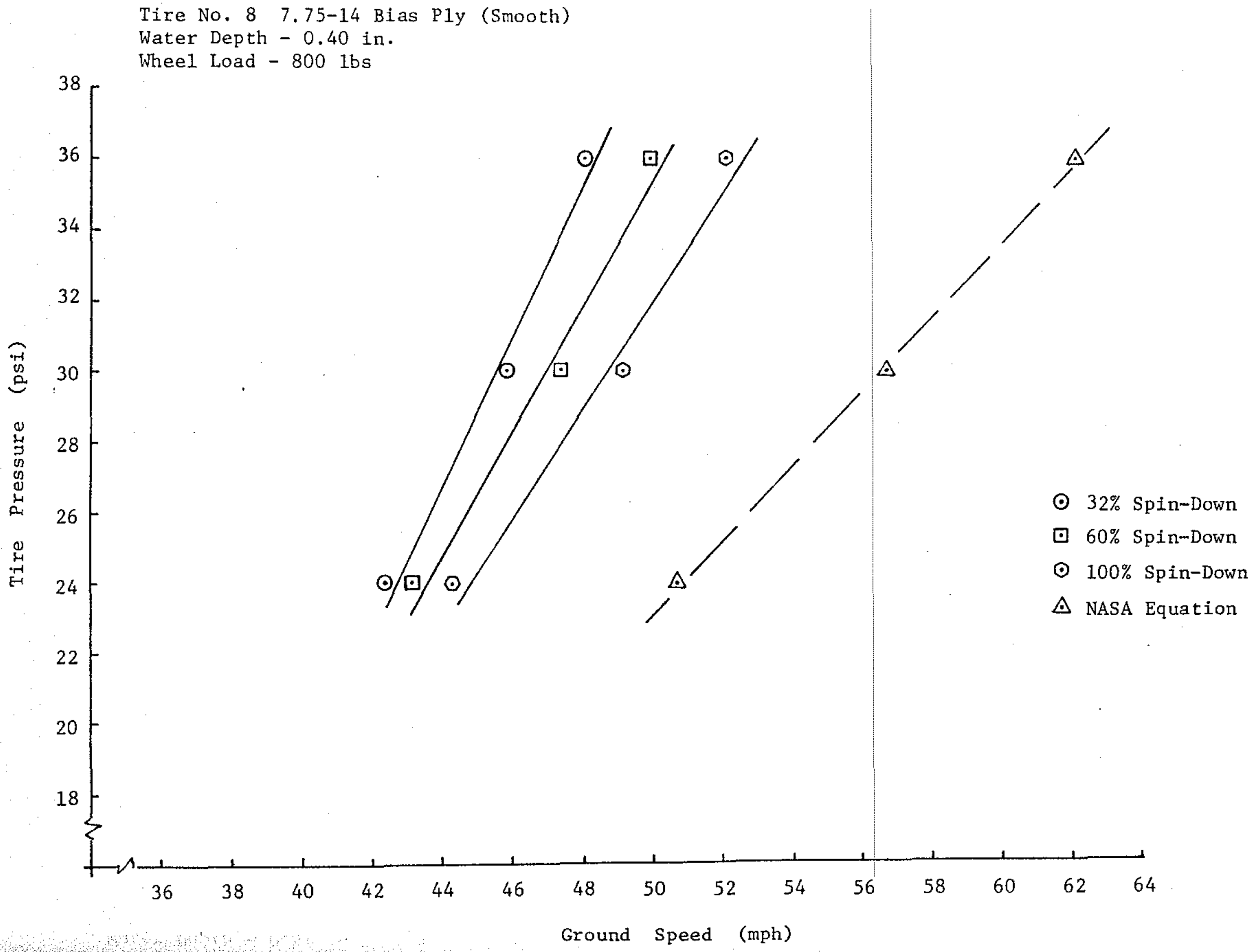


FIGURE 26. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT.

Ground Speed (mph)

FIGURE 26. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT.

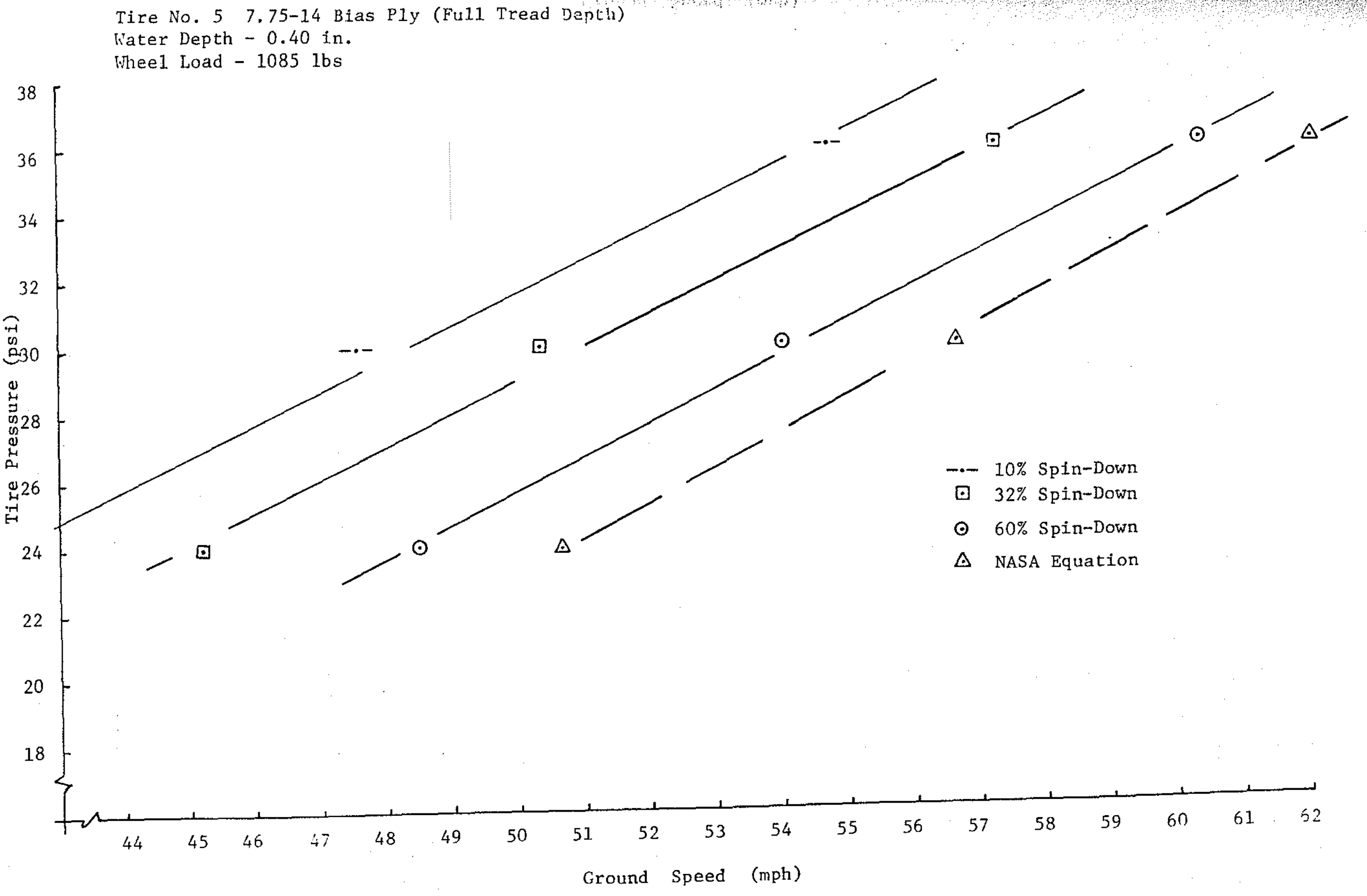


FIGURE 27. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR CONCRETE PAVEMENT.

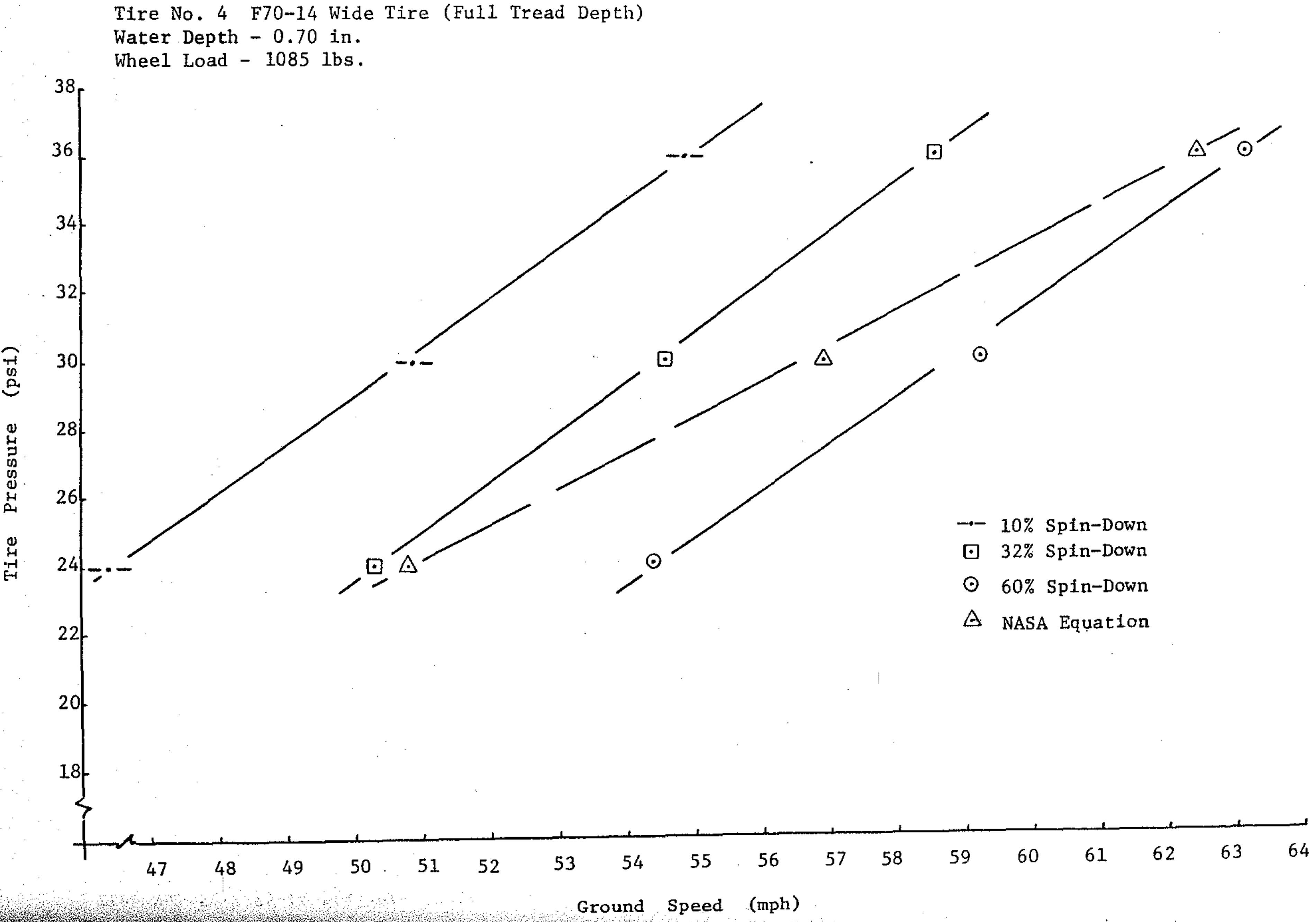


FIGURE 28. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR SEAL COAT SURFACE TREATMENT.

Ground Speed (mph)

FIGURE 28. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR SEAL COAT SURFACE TREATMENT.

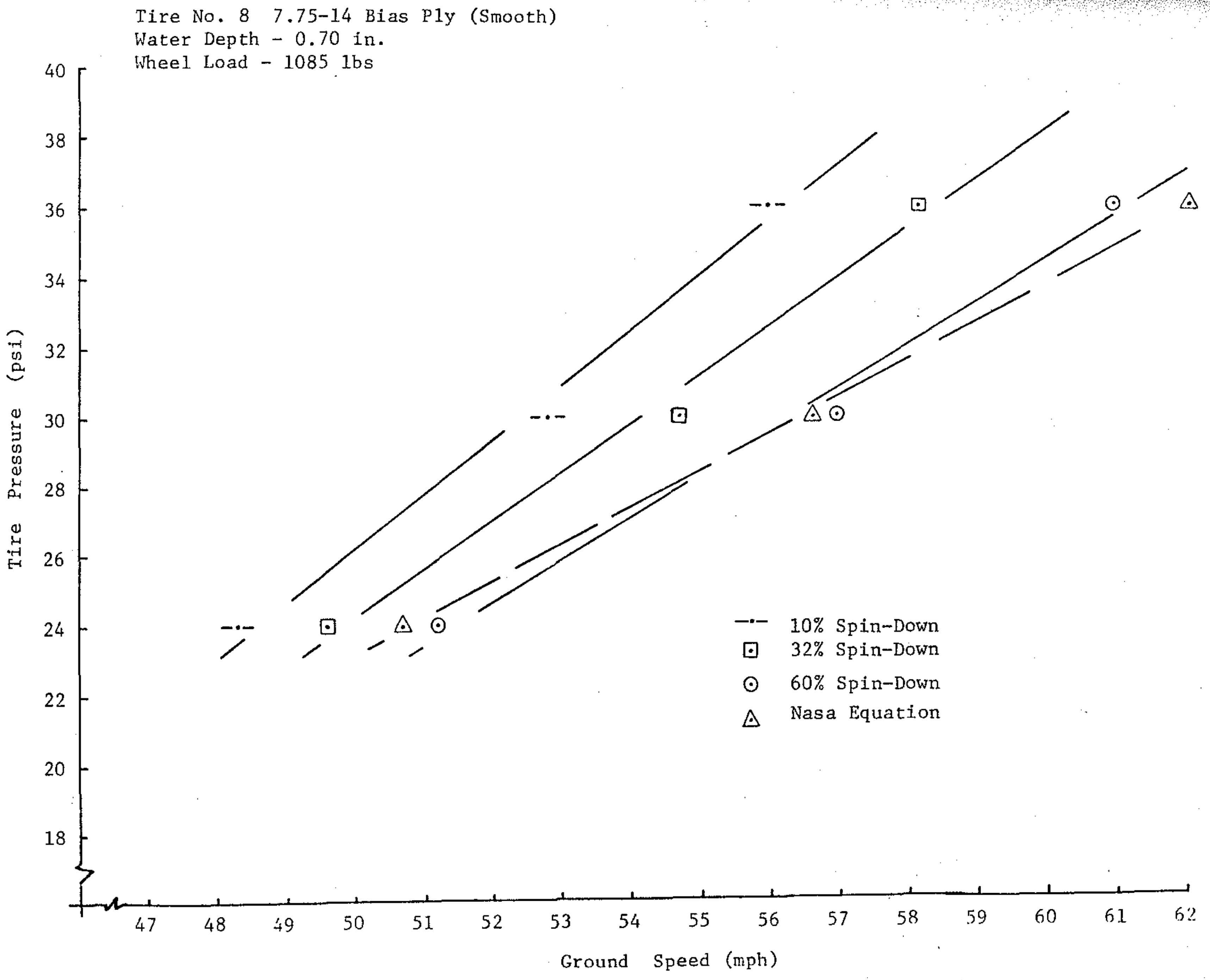


FIGURE 29. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR SEAL COAT SURFACE TREATMENT.

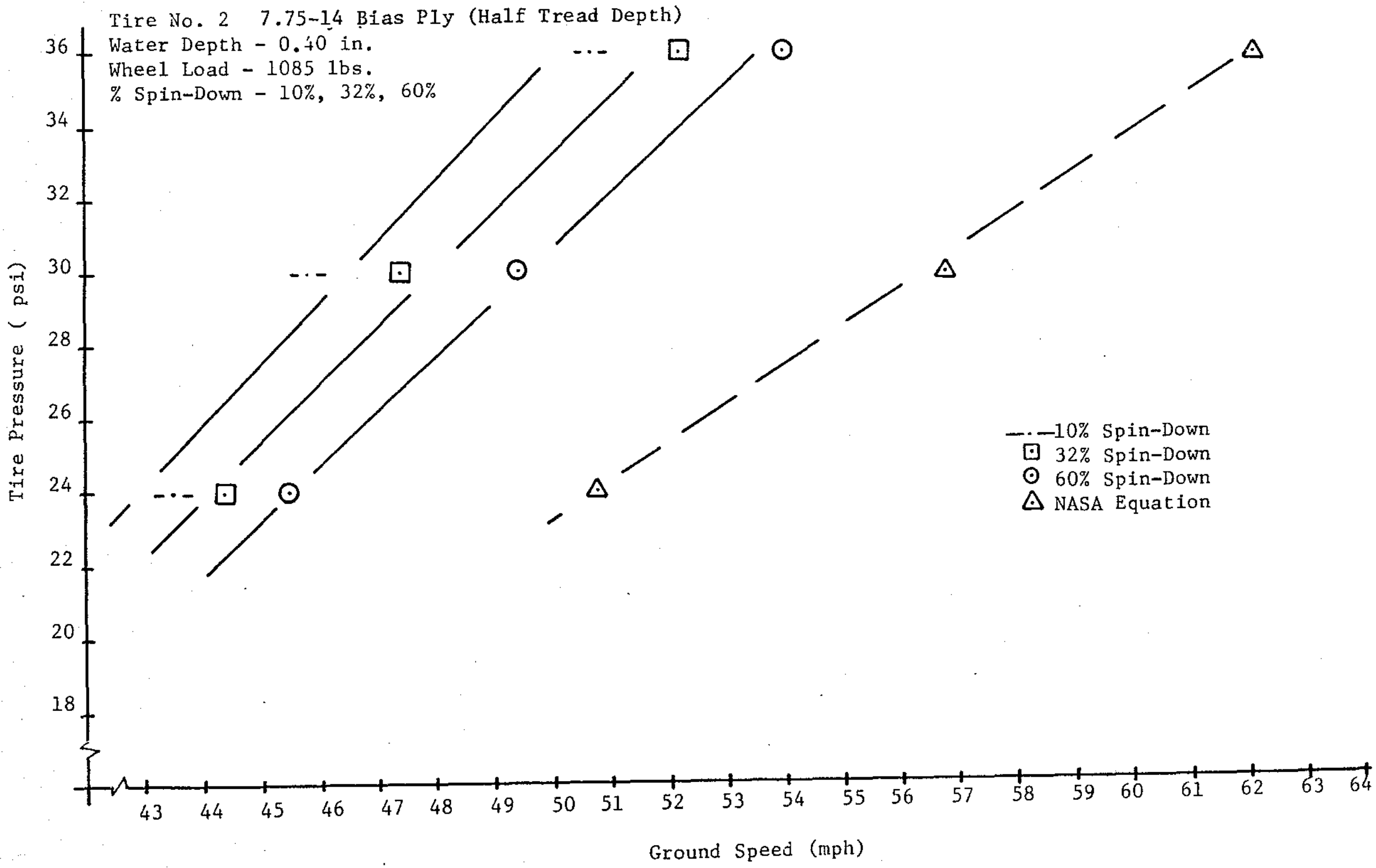


FIGURE 30. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR HOT MIX PAVEMENT.

FIGURE 30. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR HOT MIX PAVEMENT.

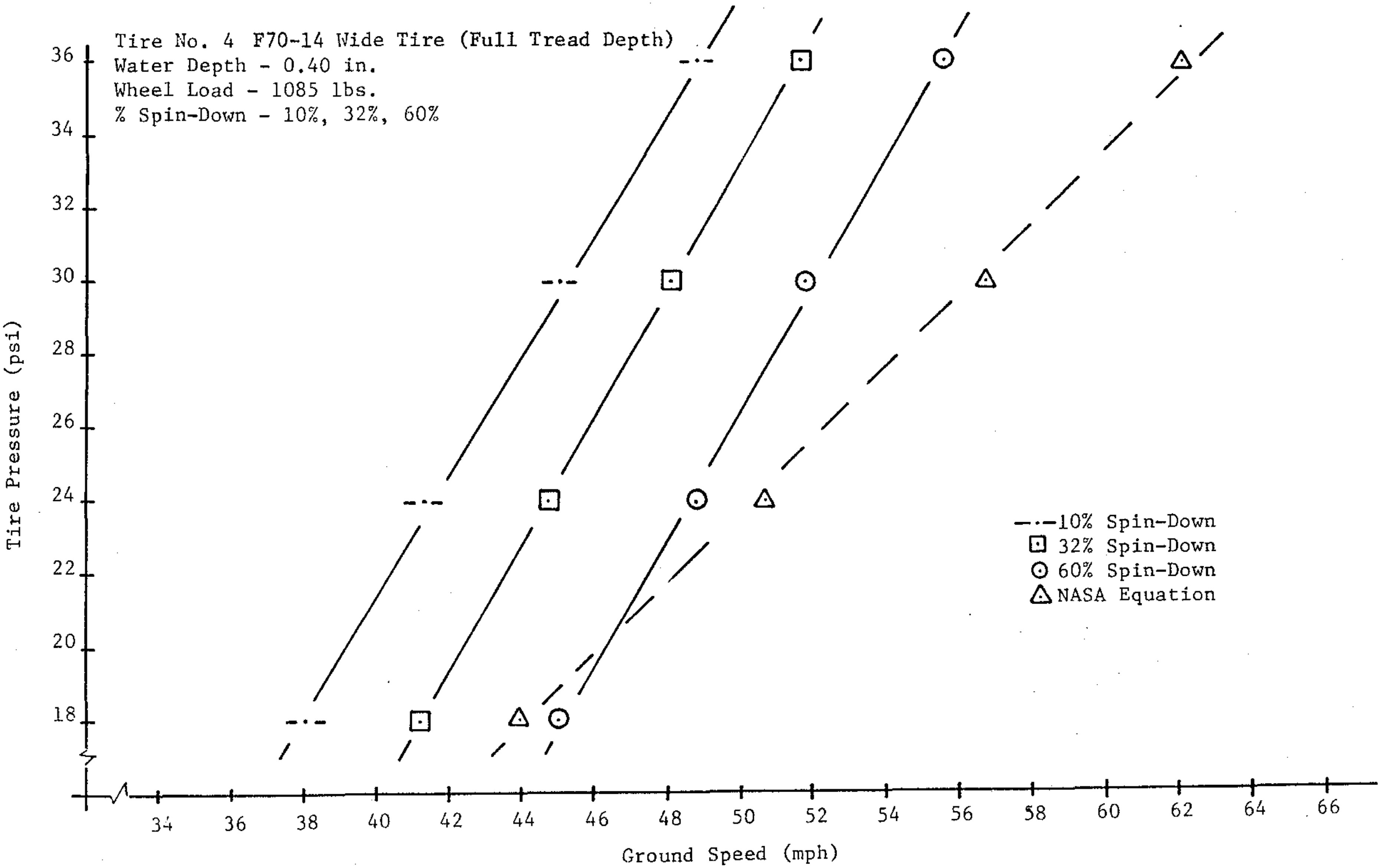


FIGURE 31. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR HOT MIX PAVEMENT.

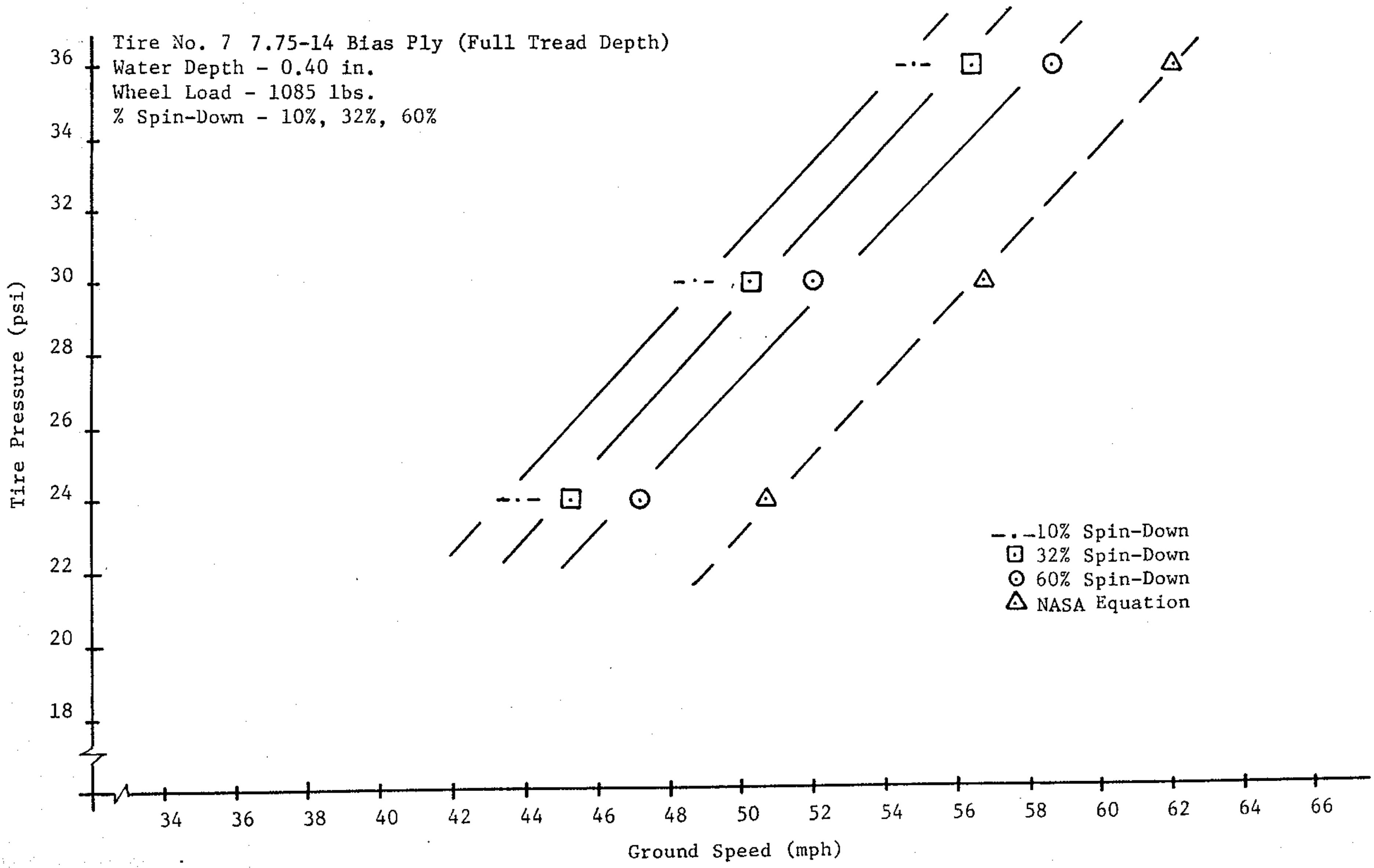


FIGURE 32. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR HOT MIX PAVEMENT.

FIGURE 32. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR HOT MIX PAVEMENT.

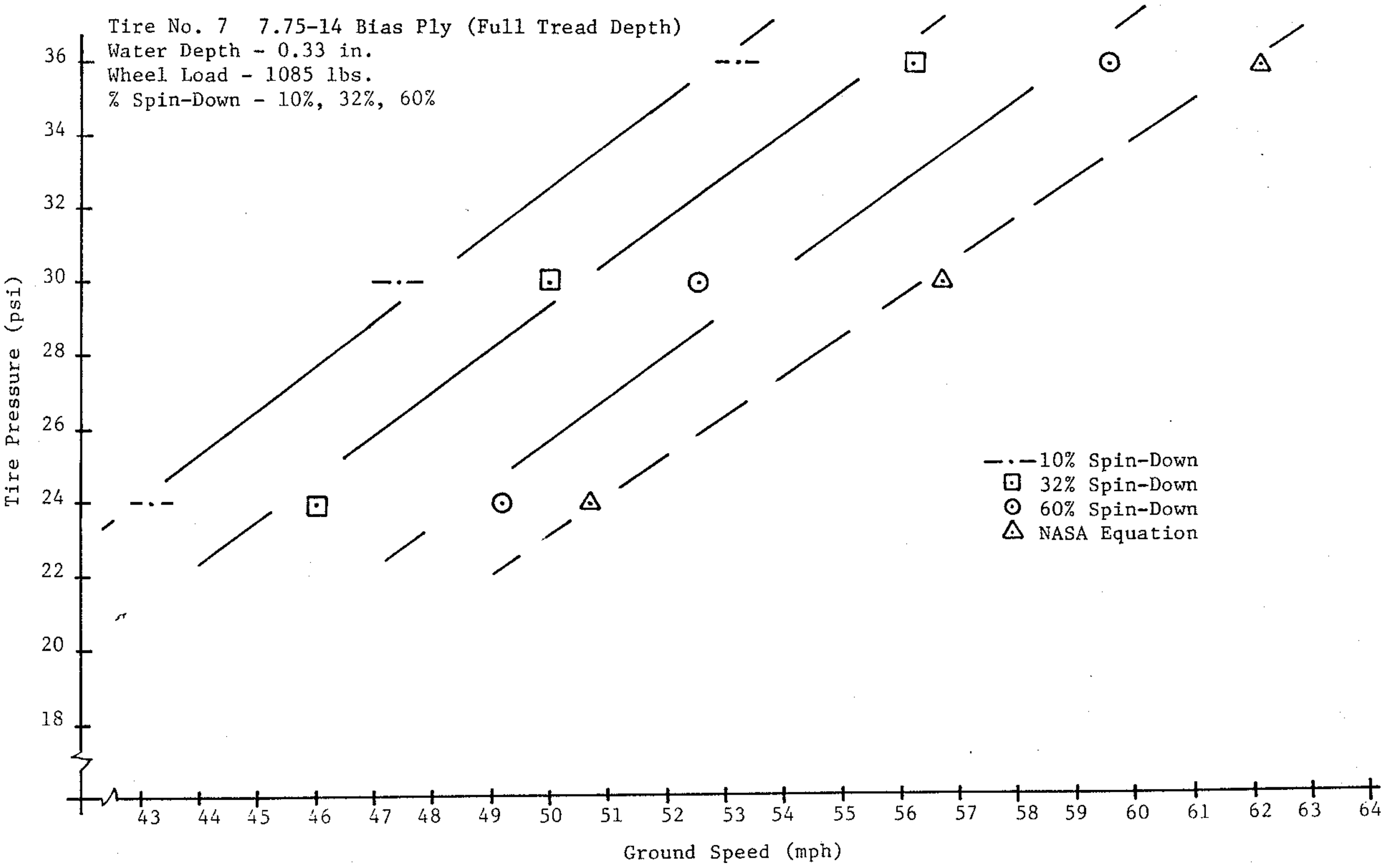


FIGURE 33. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR HOT MIX PAVEMENT.

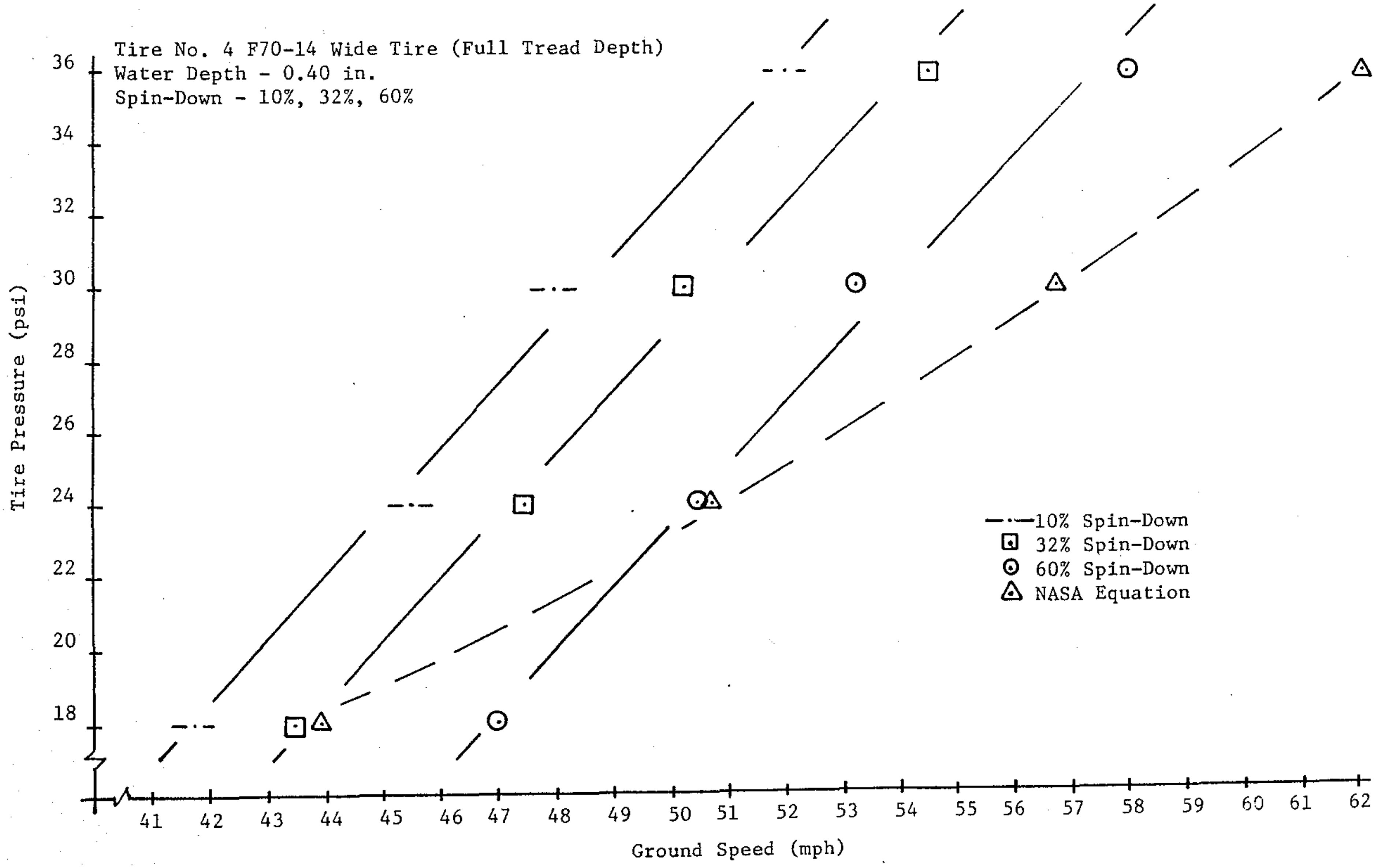


FIGURE 34. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR JENNITE PAVEMENT.

FIGURE 34. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR JENNITE PAVEMENT.

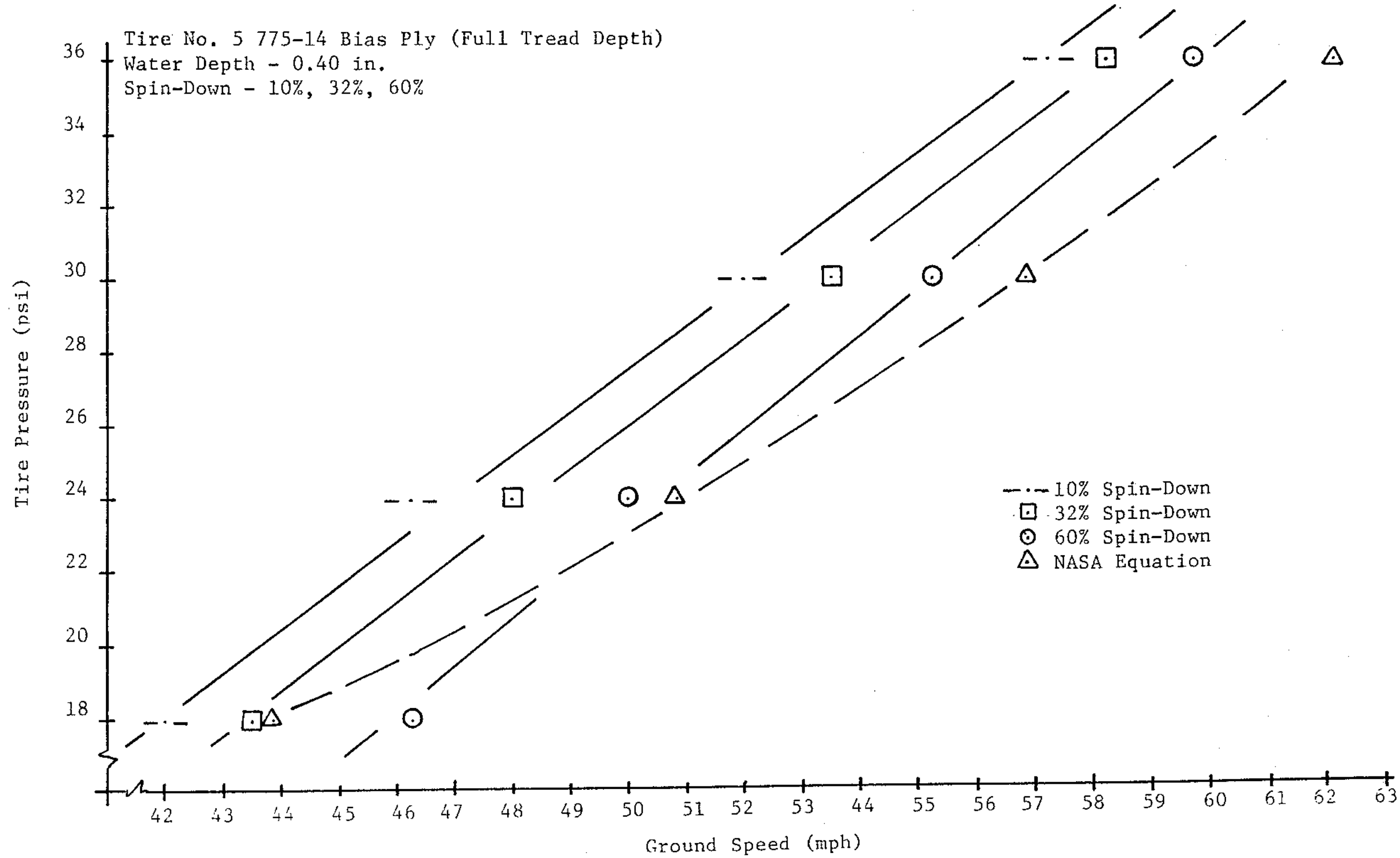


FIGURE 35. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR JENNITE PAVEMENT.

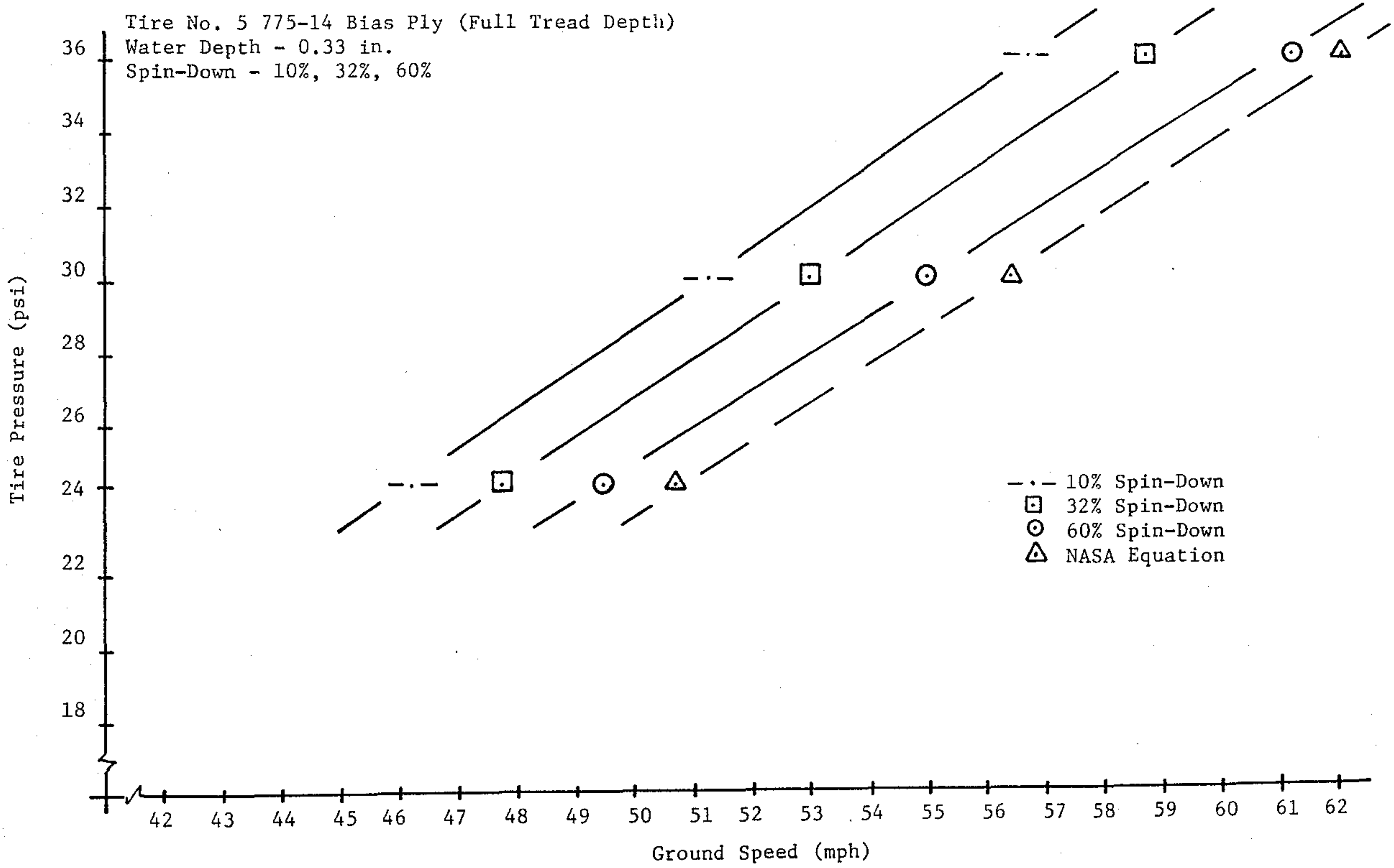


FIGURE 36. COMPARISON OF EXPERIMENTAL RESULTS WITH NASA EQUATION FOR JENNITE PAVEMENT.

FIGURE 36. COMPARISON OF EXPERIMENTAL RESULTS WITH NASA EQUATION FOR JENNITE PAVEMENT.

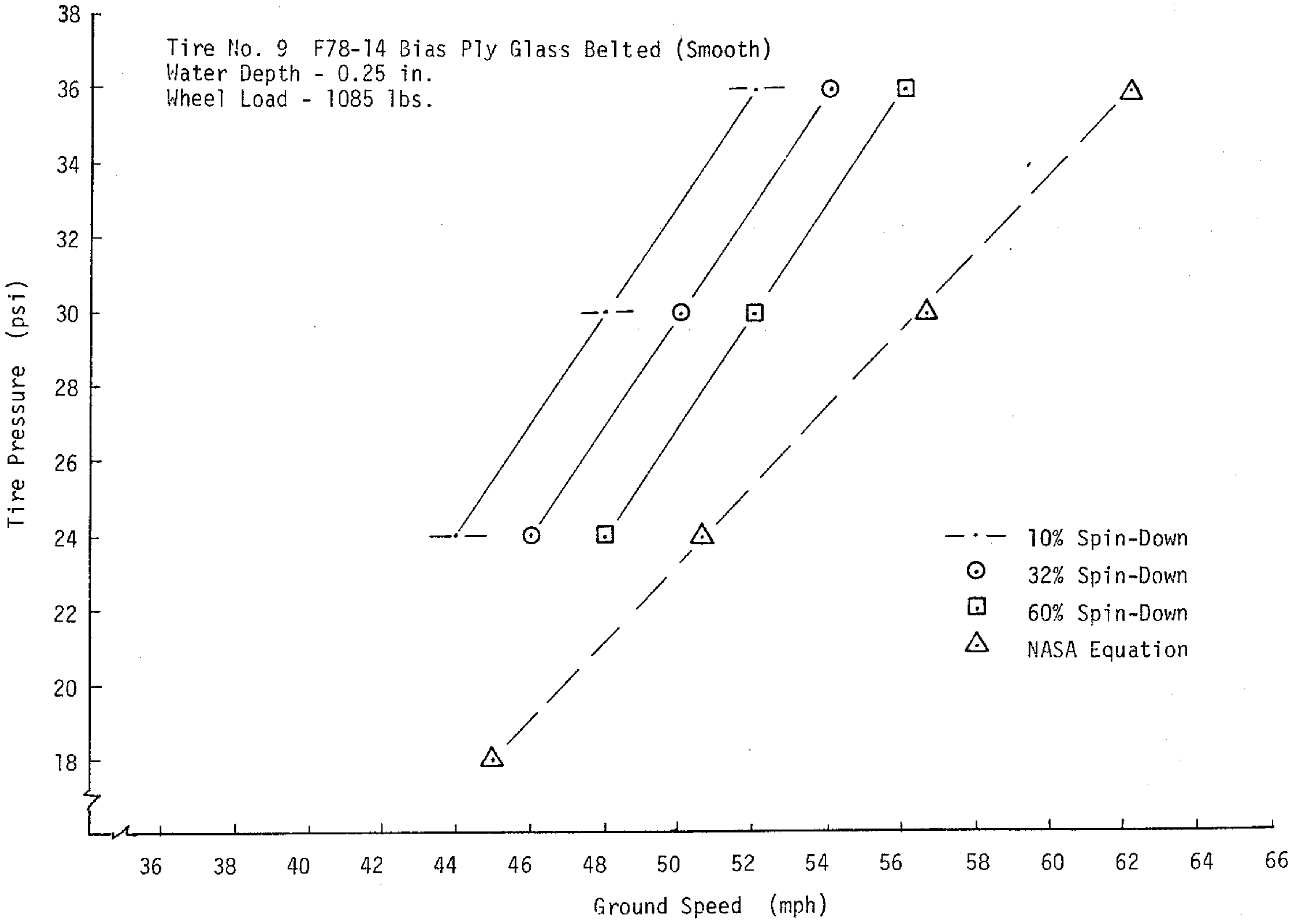


FIGURE 37. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

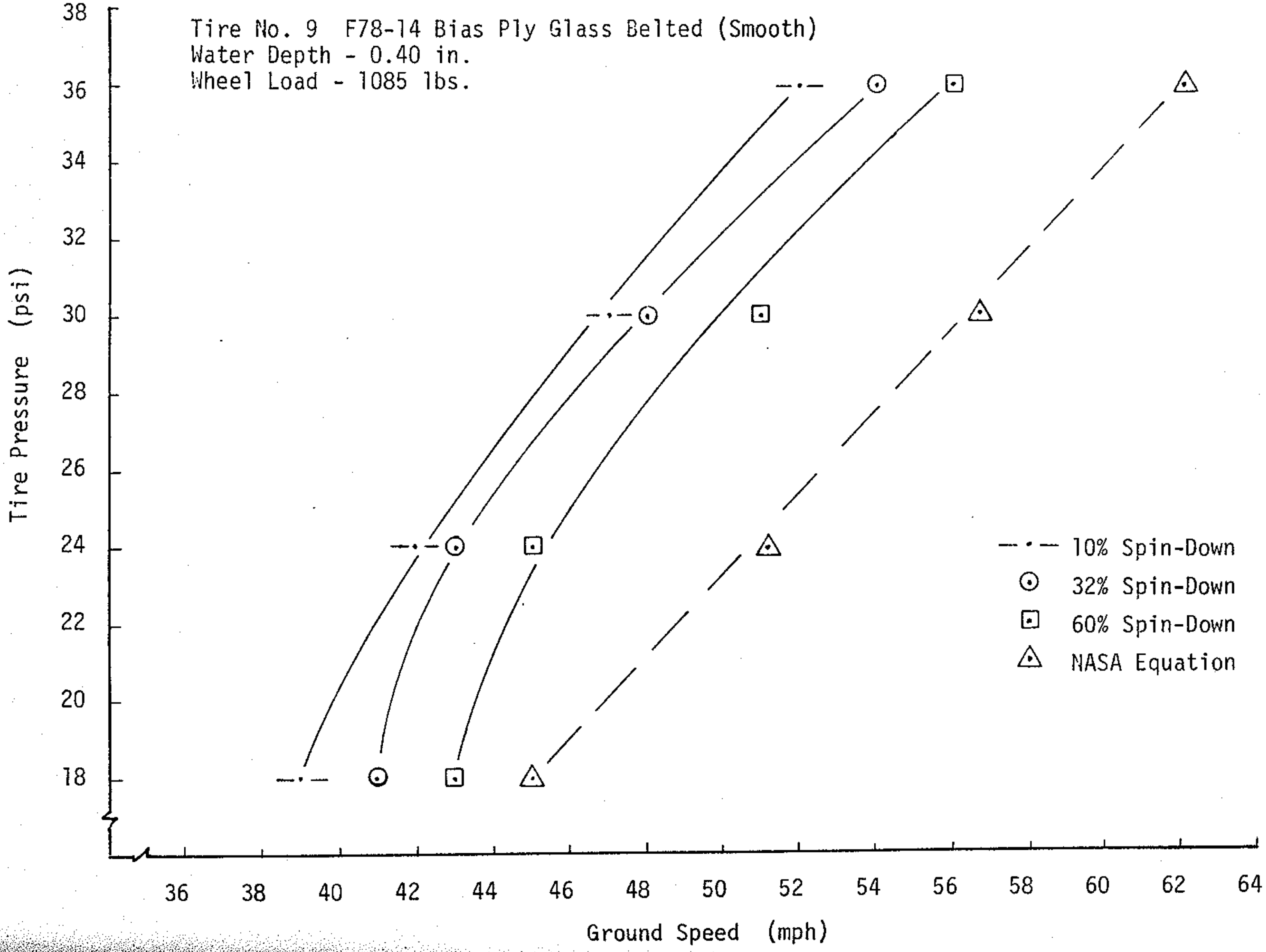


FIGURE 38. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT

FIGURE 38. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

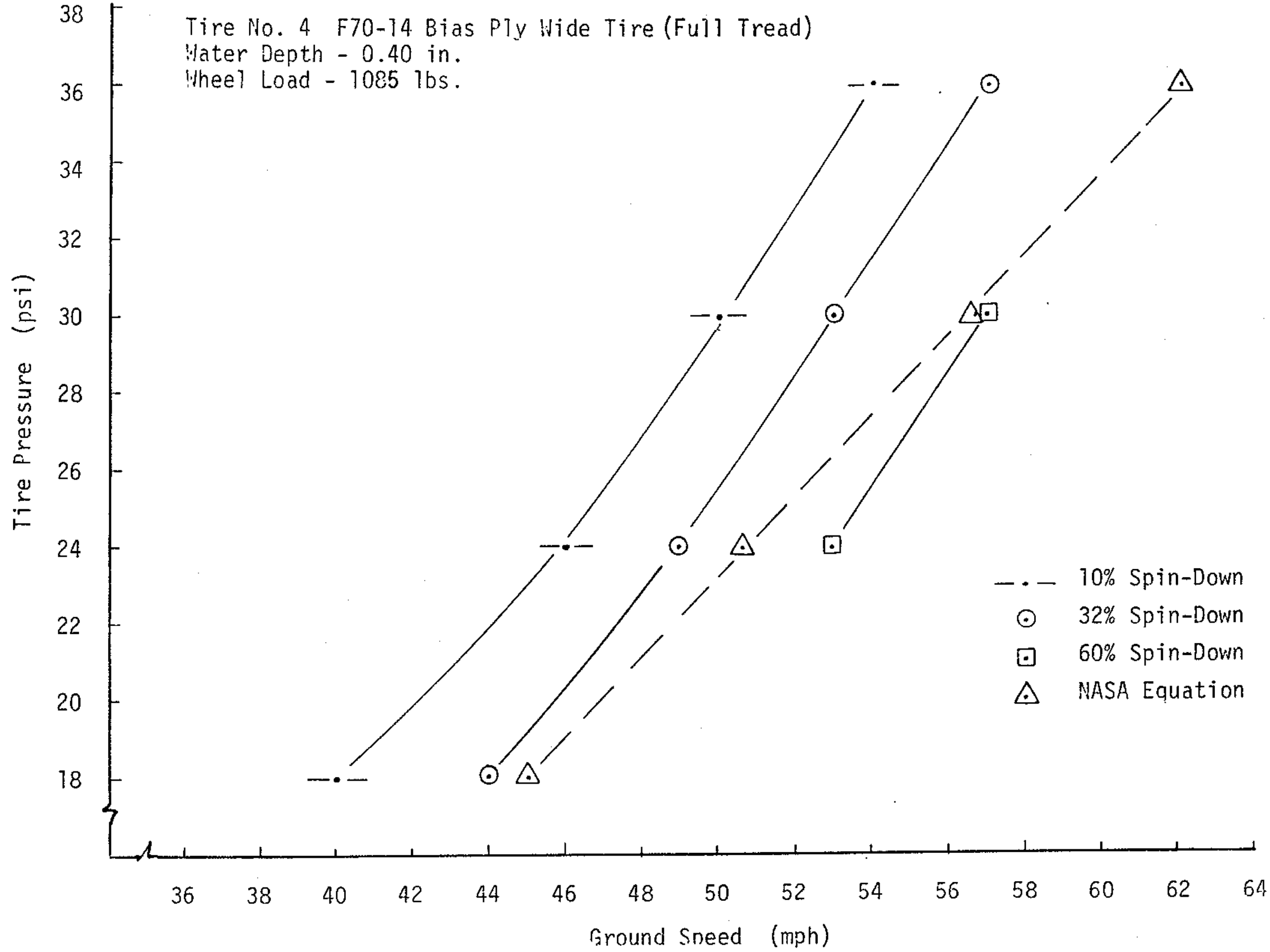


FIGURE 39. COMPARISON OF EXPERIMENTAL RESULTS TO NASA EQUATION FOR LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

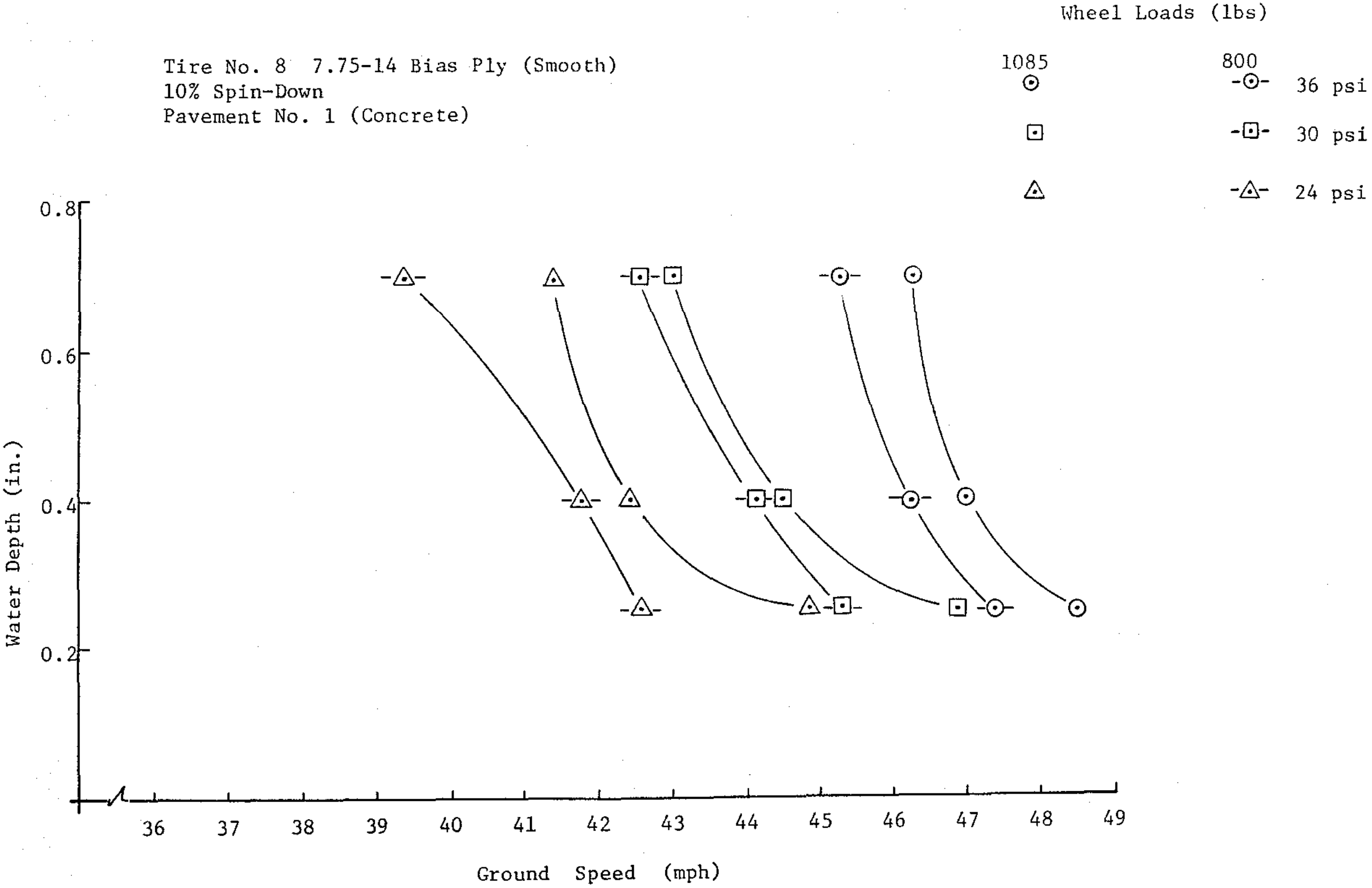


FIGURE 40. EFFECT OF WATER DEPTH AND WHEEL LOAD ON GROUND SPEED TO CAUSE 10% SPIN-DOWN.

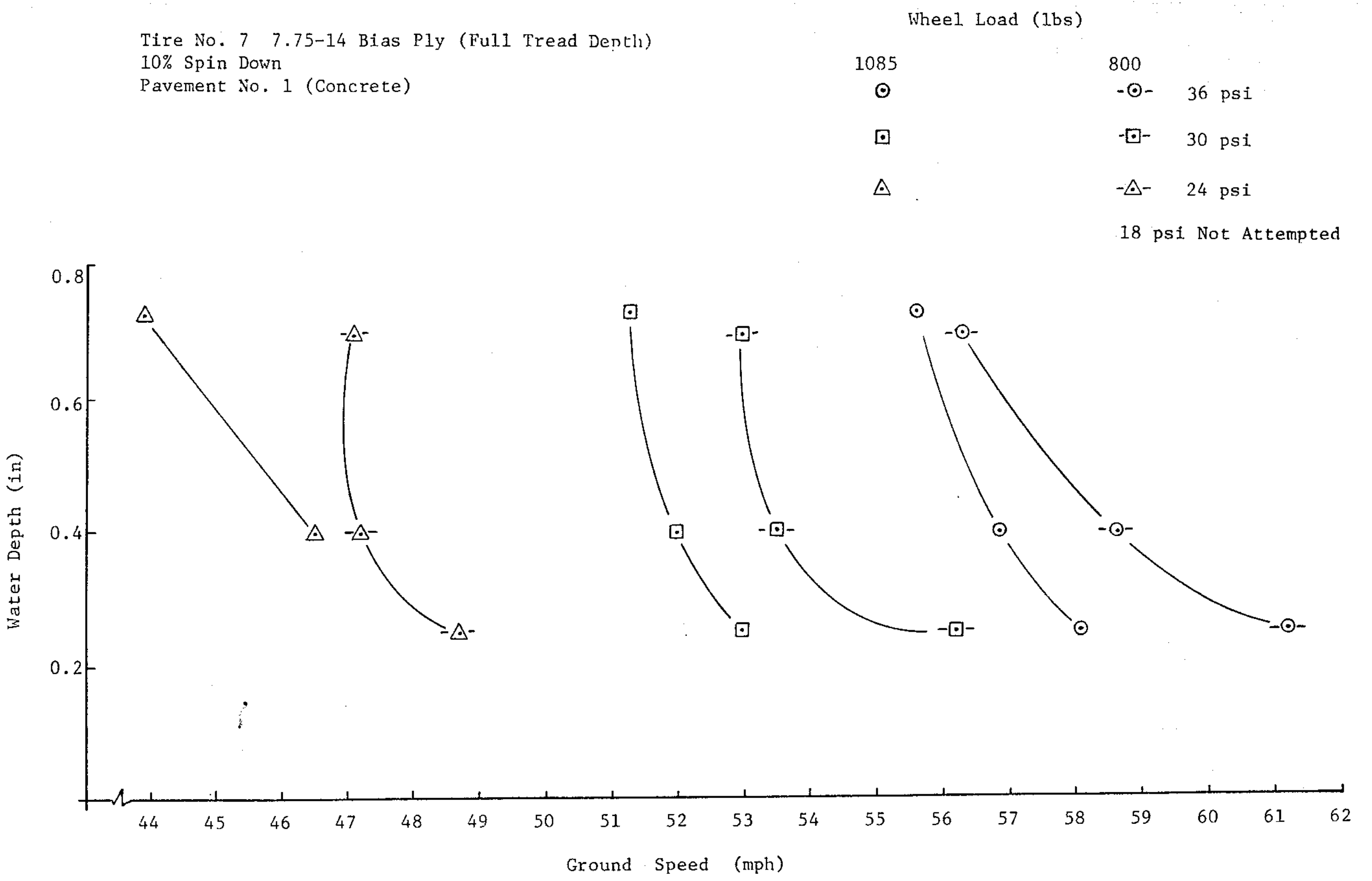


FIGURE 41. EFFECT OF WATER DEPTH AND WHEEL LOAD ON GROUND SPEED TO CAUSE 10% SPIN-DOWN.

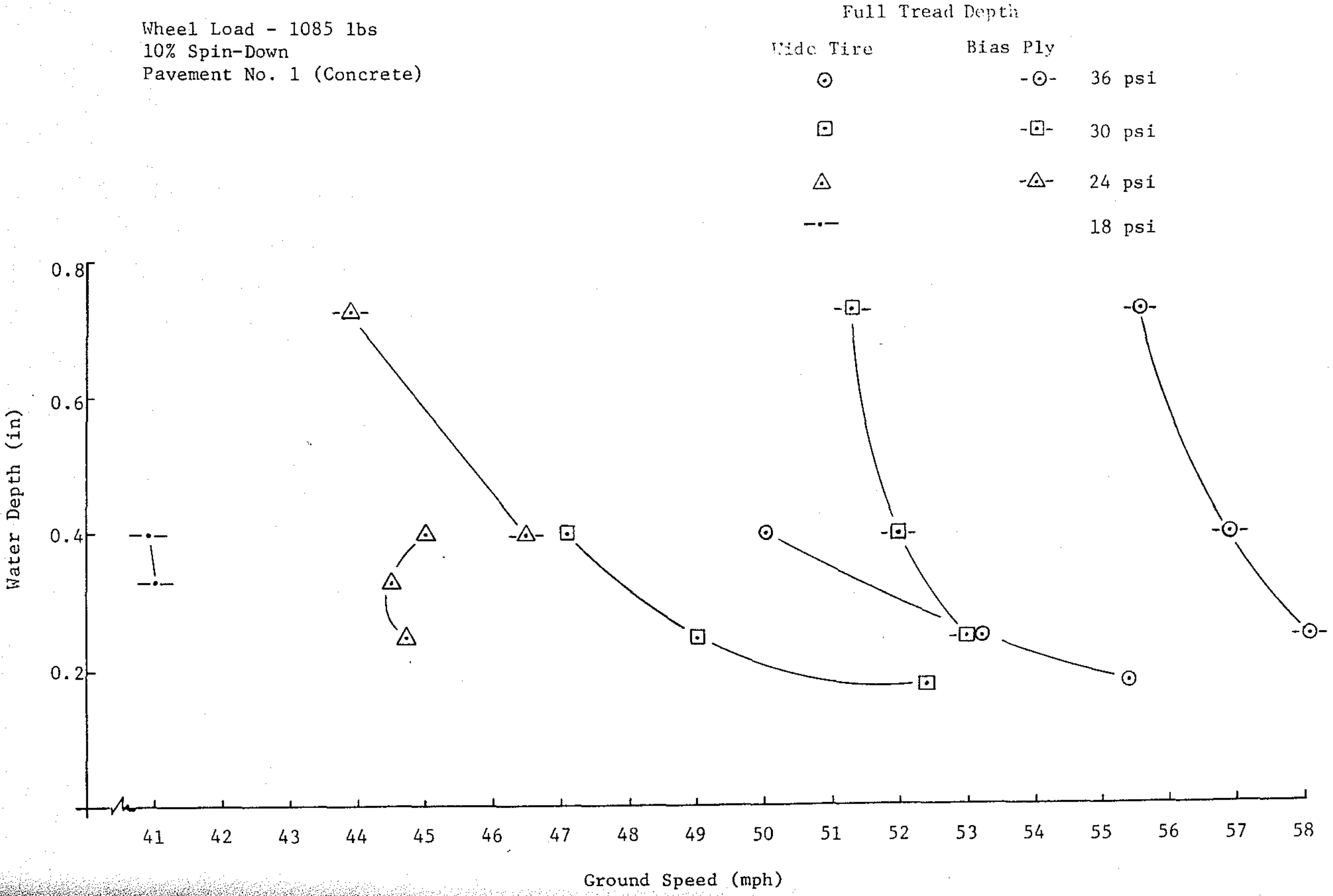


FIGURE 42. EFFECT OF WATER DEPTH AND TIRE ASPECT RATIO ON SPEED TO CAUSE 10% SPIN-DOWN.

Ground Speed (mph)

FIGURE 42. EFFECT OF WATER DEPTH AND TIRE ASPECT RATIO ON SPEED TO CAUSE 10% SPIN-DOWN.

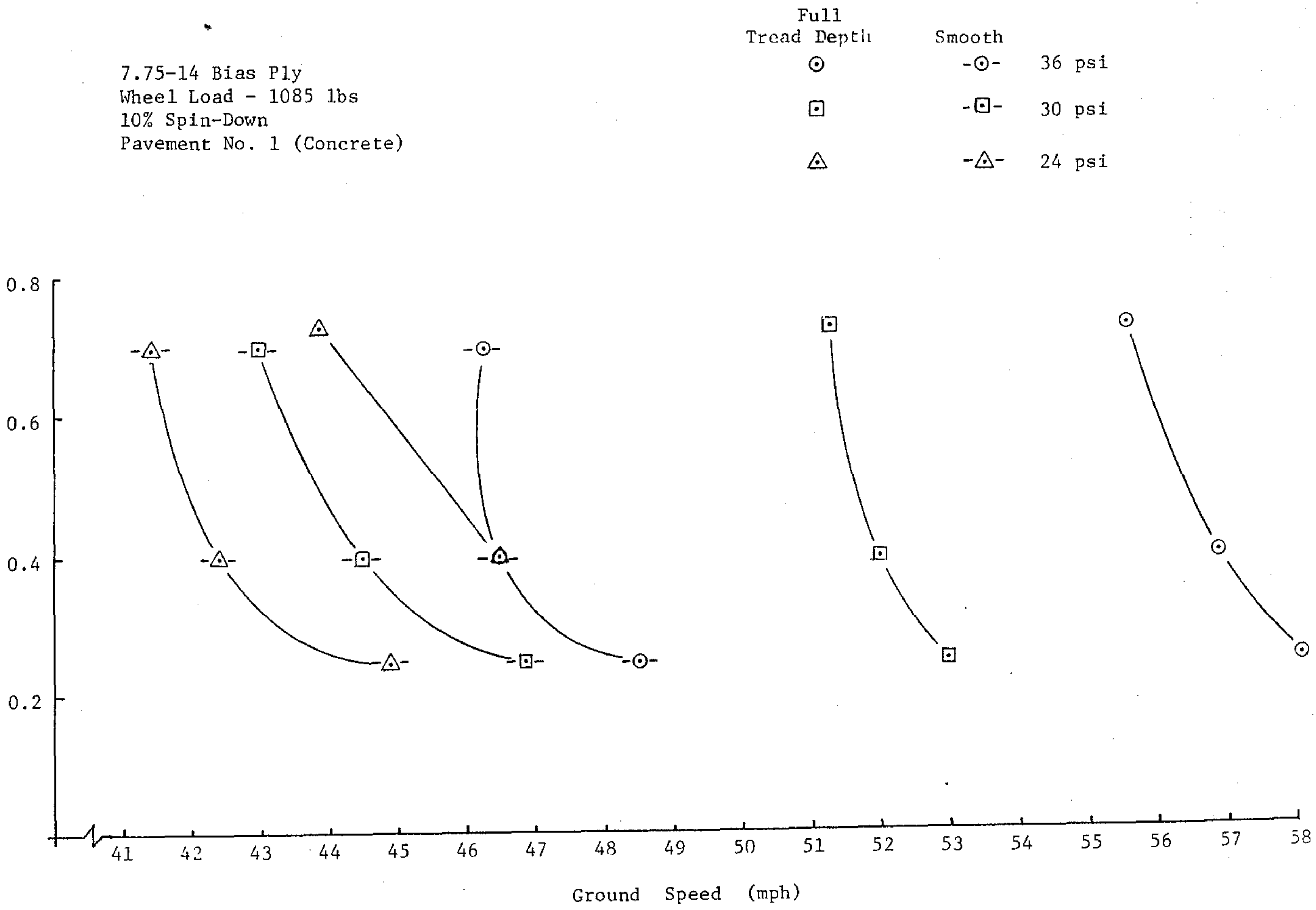


FIGURE 43. EFFECT OF WATER DEPTH AND TREAD DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN.

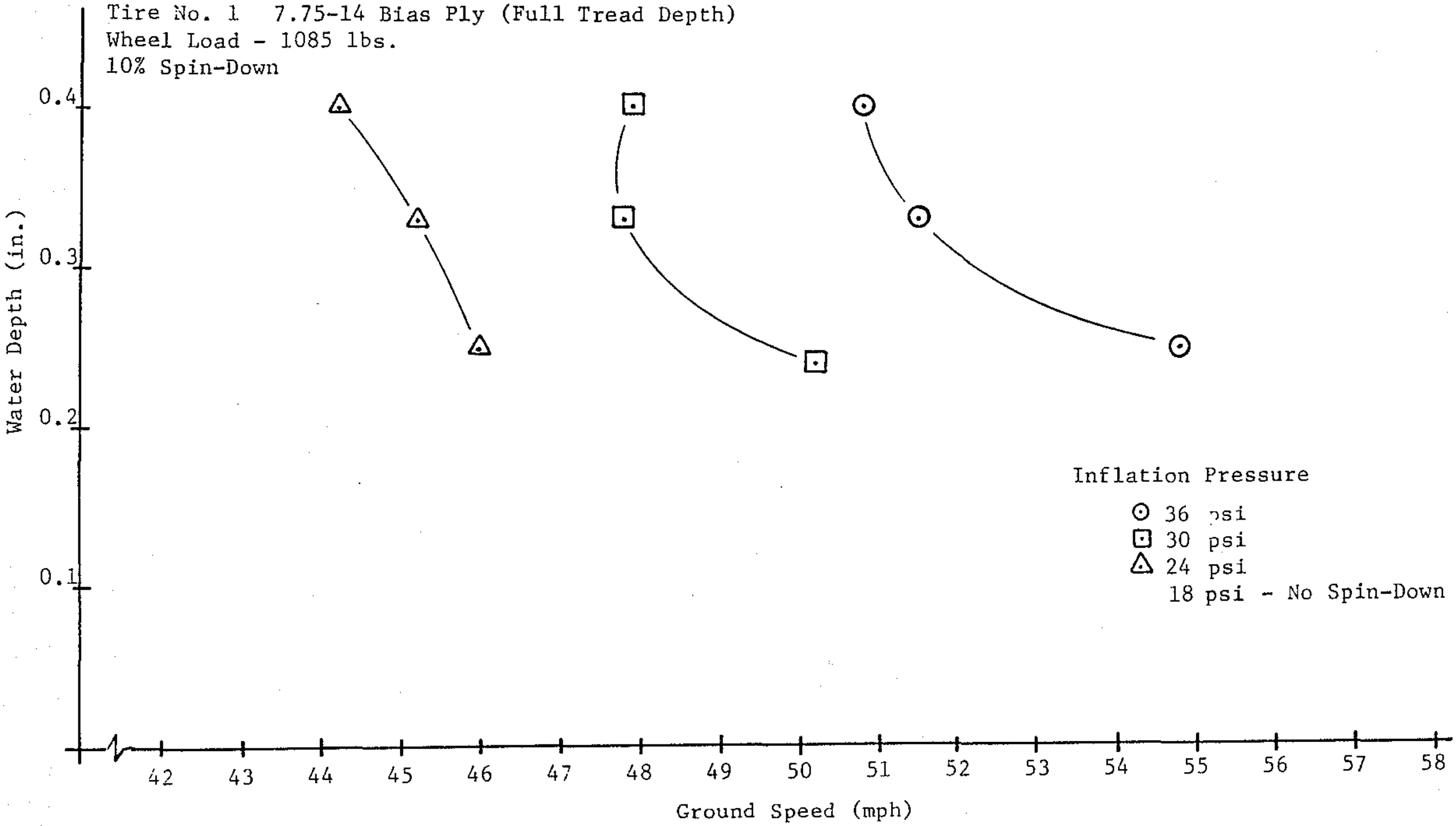


FIGURE 44. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN - HOT MIX PAVEMENT.

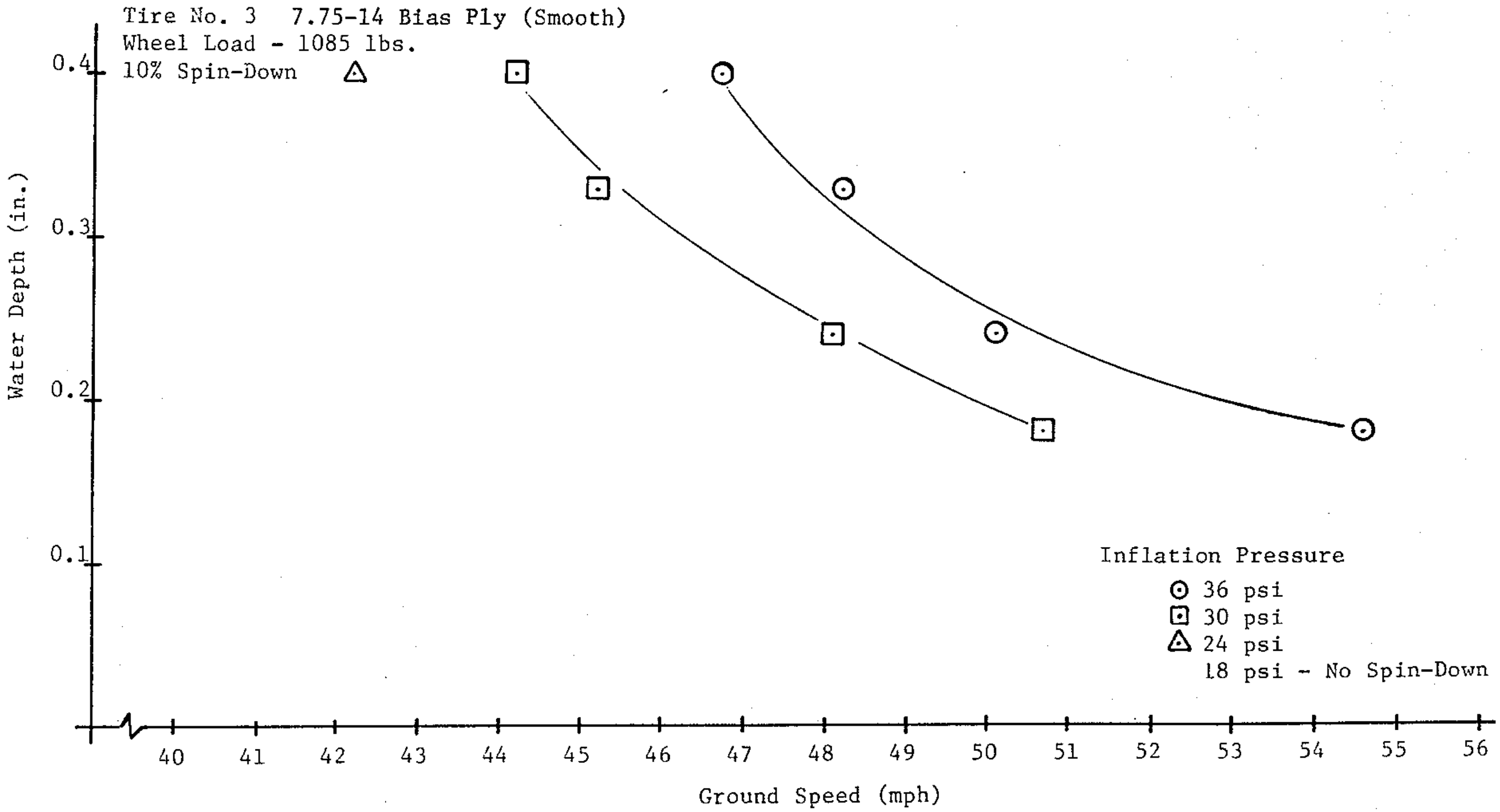


FIGURE 45. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN - HOT MIX PAVEMENT.

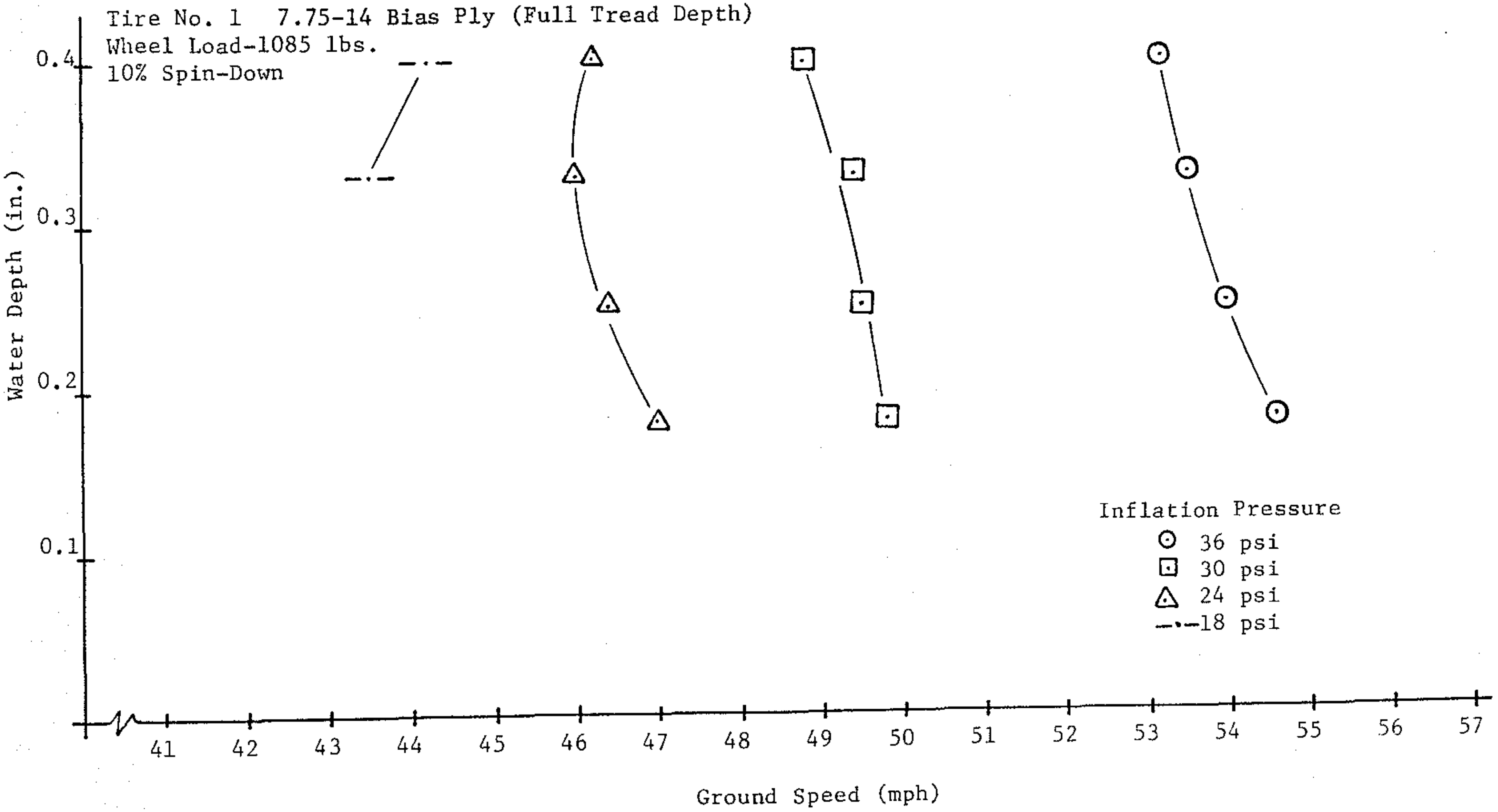


FIGURE 46. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN - JENNITE PAVEMENT.

FIGURE 46. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN - JENNITE PAVEMENT.

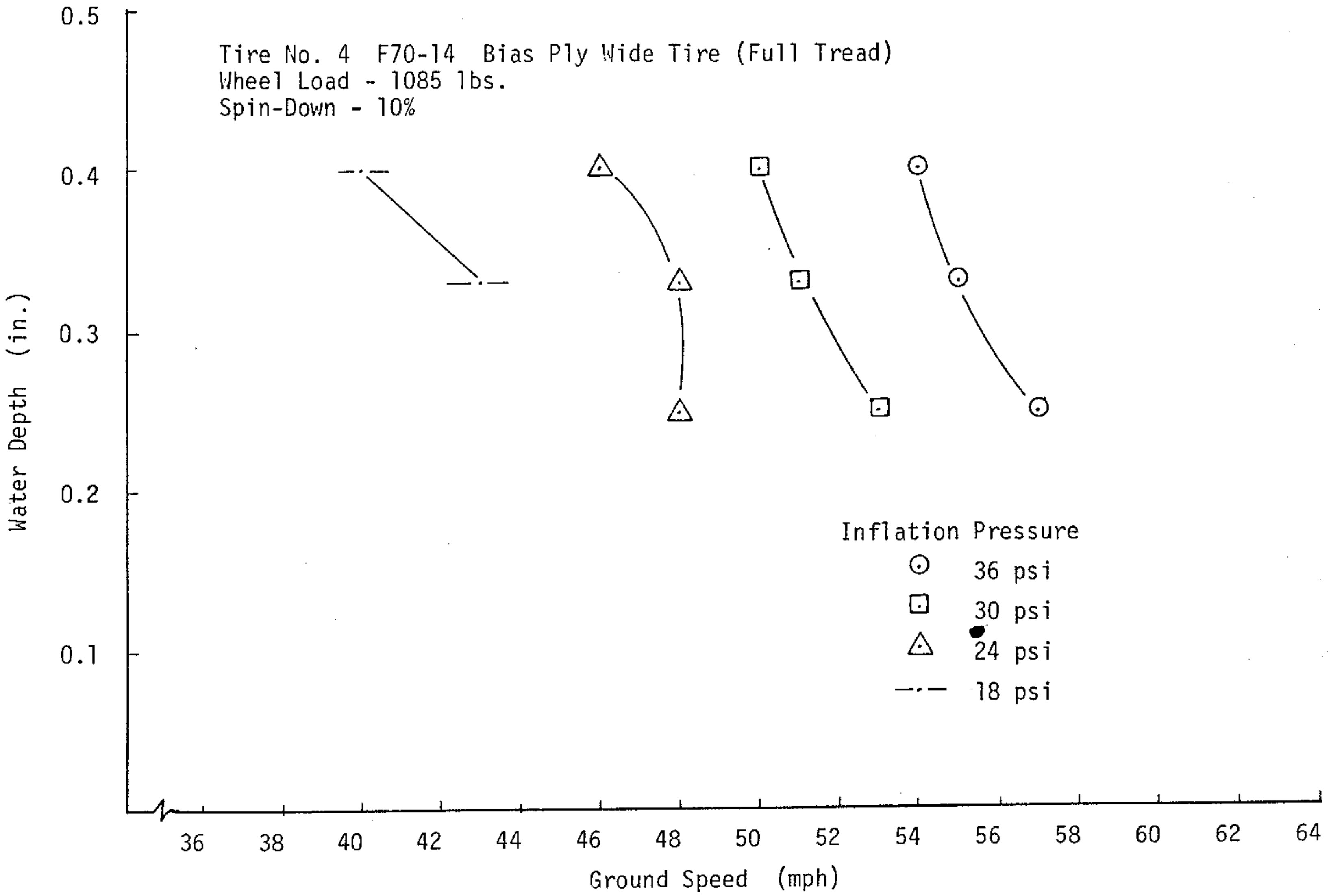


FIGURE 47. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN -LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

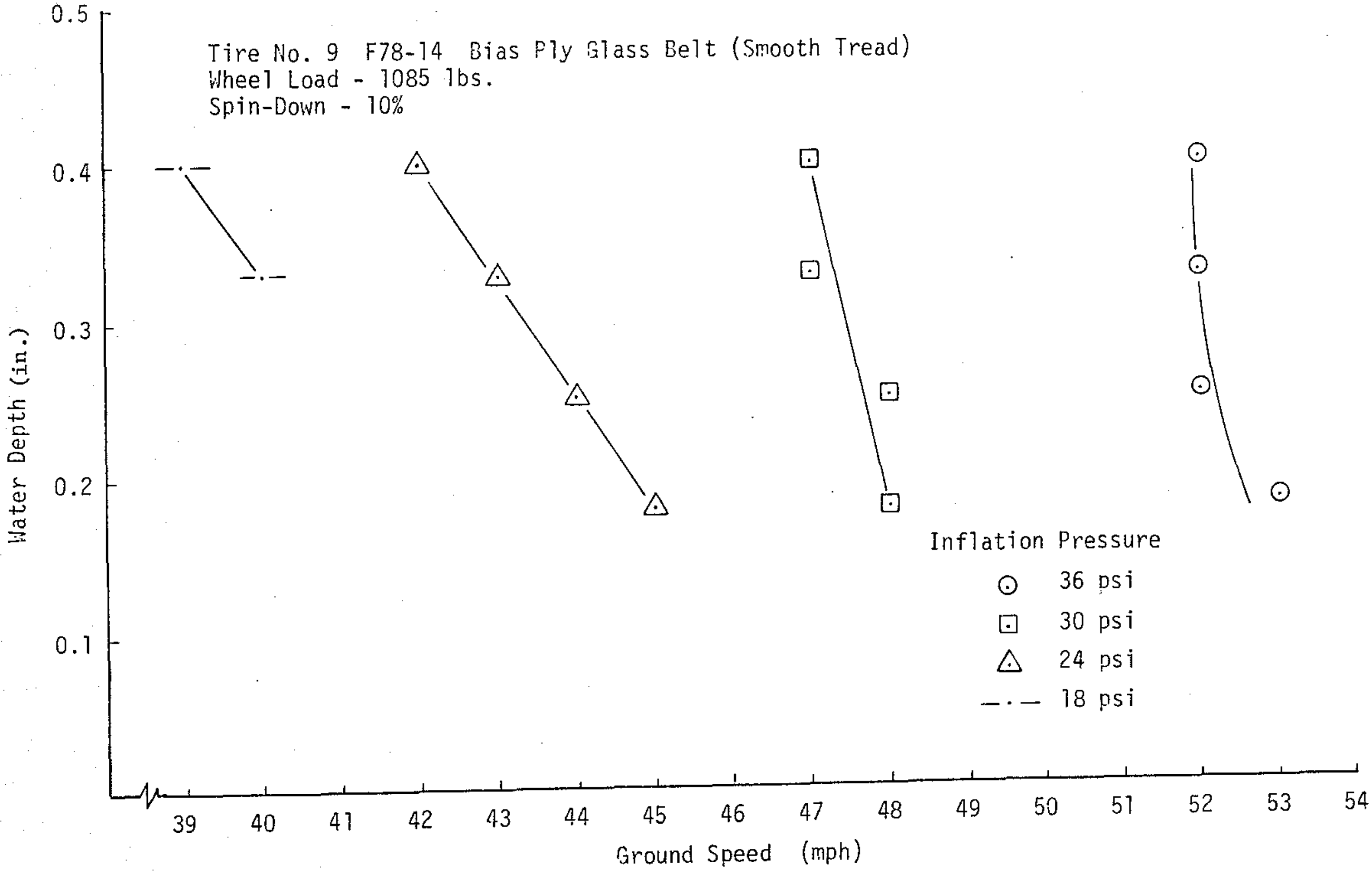


FIGURE 48. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN -LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

FIGURE 48. EFFECT OF WATER DEPTH ON SPEED TO CAUSE 10% SPIN-DOWN -LONGITUDINALLY GROOVED CONCRETE PAVEMENT.

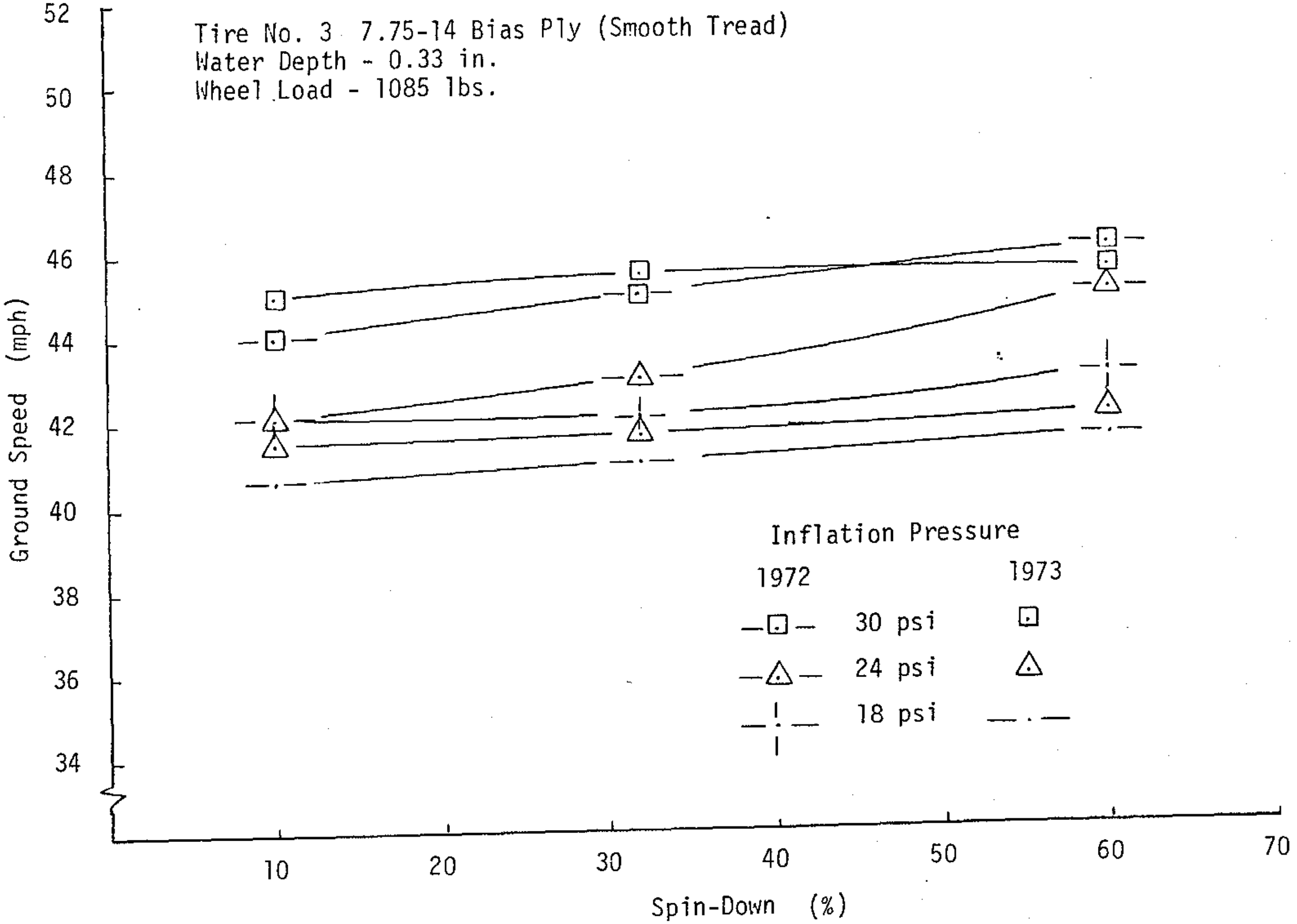


FIGURE 49. REPEATABILITY CHECK OF DATA FOR JENNITE PAVEMENT.

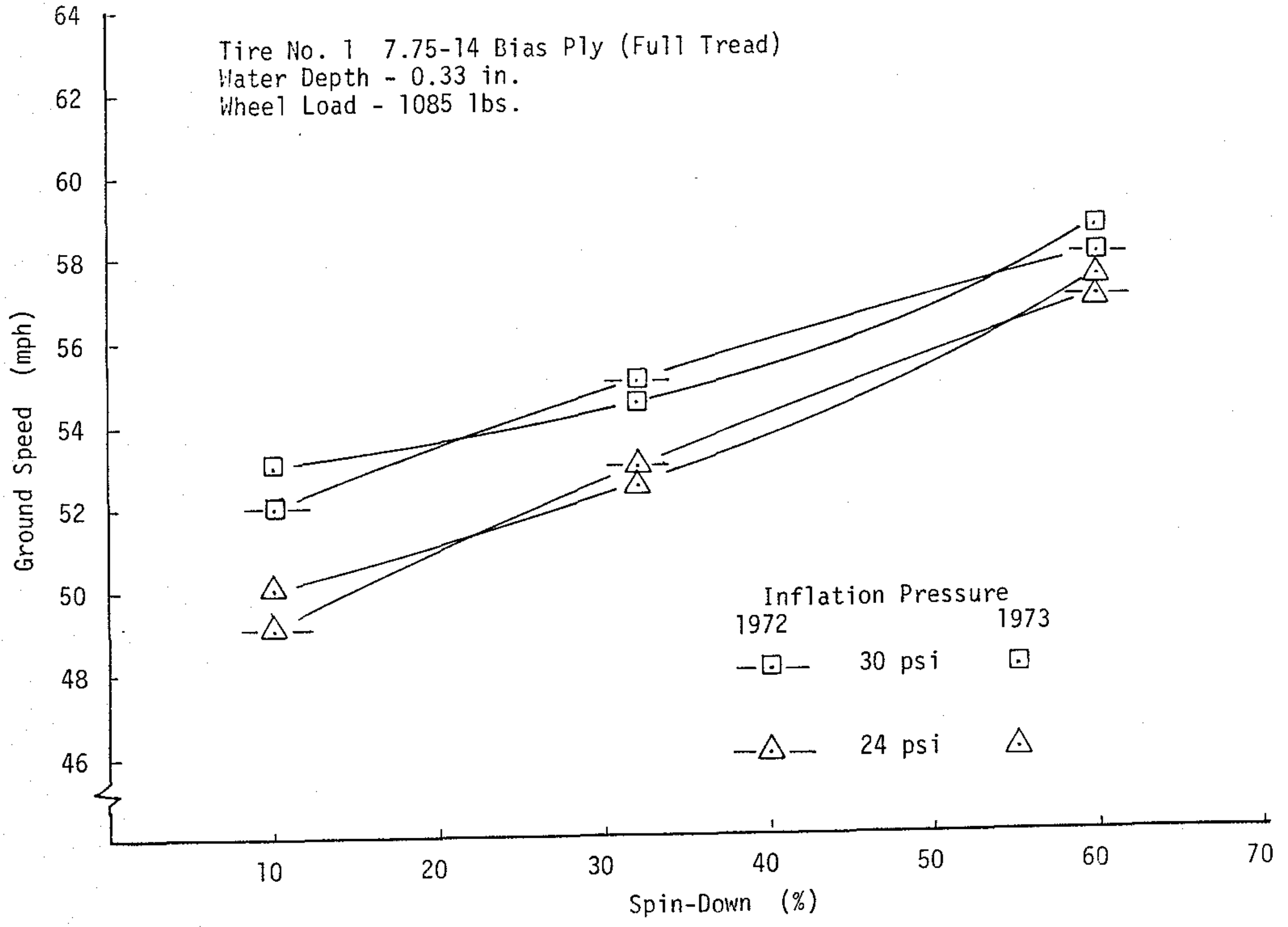


FIGURE 50. REPEATABILITY CHECK OF DATA FOR CONCRETE PAVEMENT.

FIGURE 50. REPEATABILITY CHECK OF DATA FOR CONCRETE PAVEMENT.

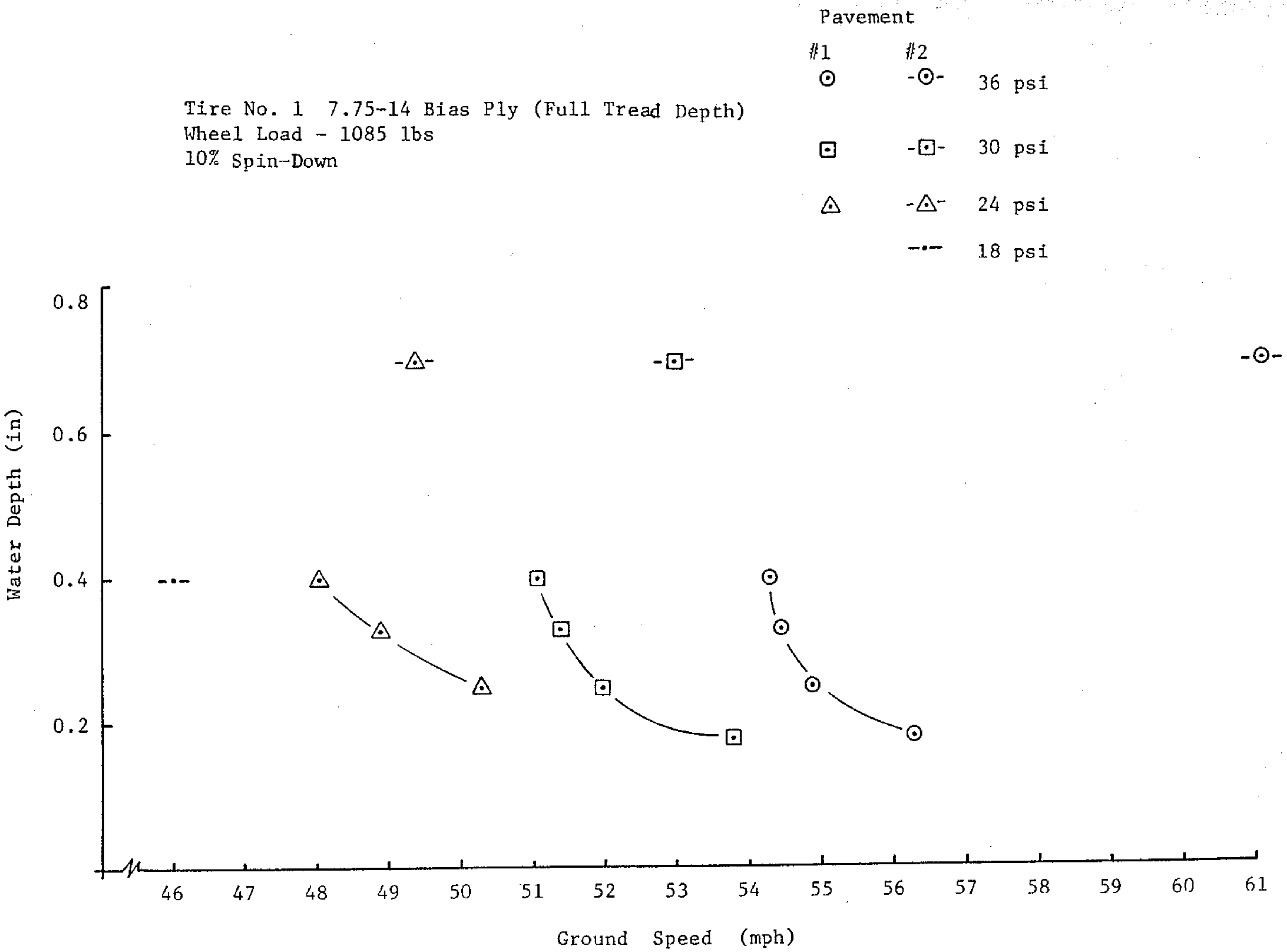


FIGURE 51. COMPARISON OF CONCRETE AND SEAL COAT SURFACE TREATMENT.

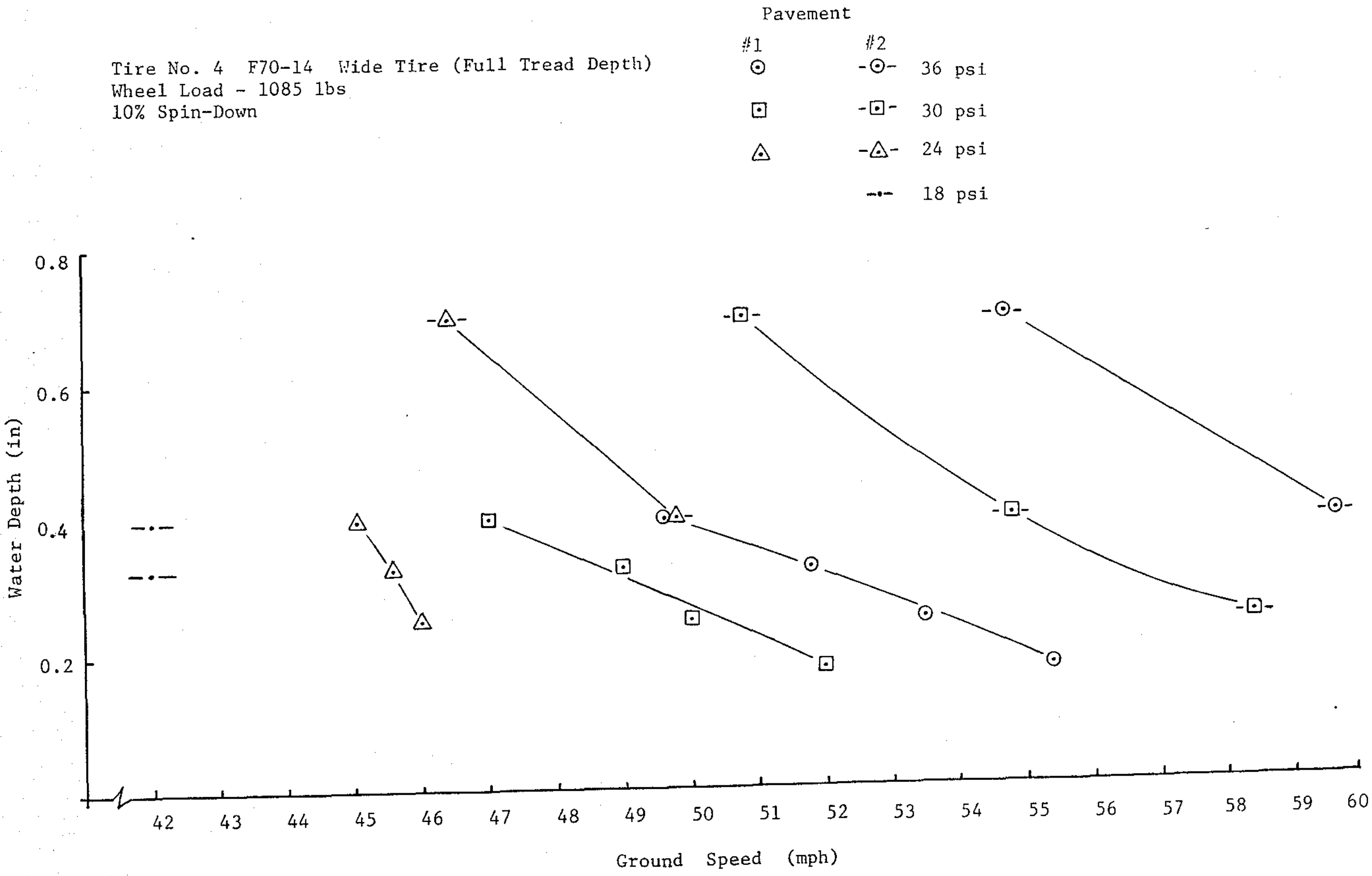


FIGURE 52. COMPARISON OF CONCRETE AND SEAL COAT SURFACE TREATMENT.

FIGURE 52. COMPARISON OF CONCRETE AND SEAL COAT SURFACE TREATMENT.

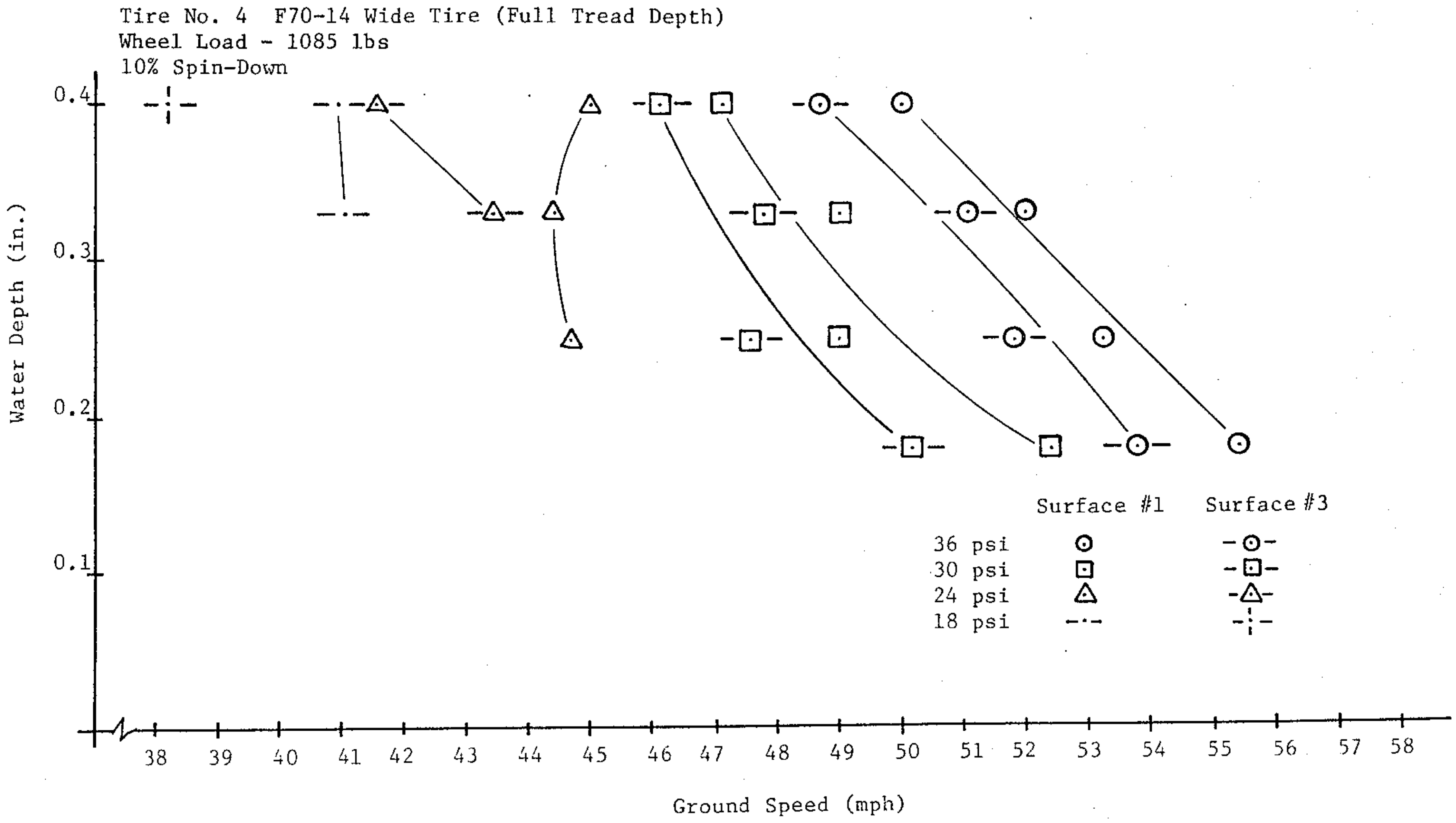


FIGURE 53. COMPARISON OF CONCRETE AND HOT MIX PAVEMENTS.

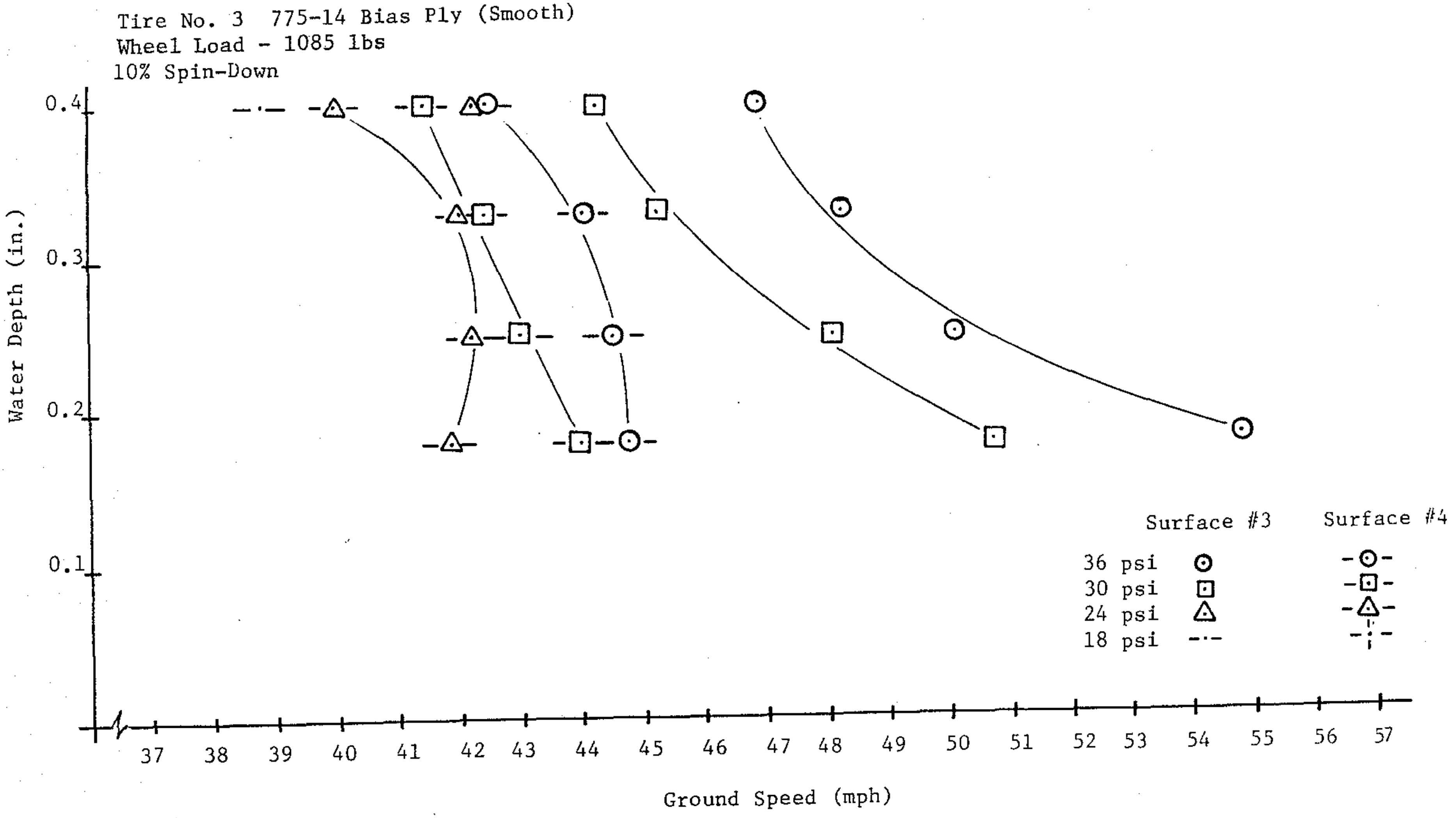


FIGURE 54. COMPARISON OF HOT MIX AND JENNITE PAVEMENTS.

FIGURE 54. COMPARISON OF HOT MIX AND JENNITE PAVEMENTS.

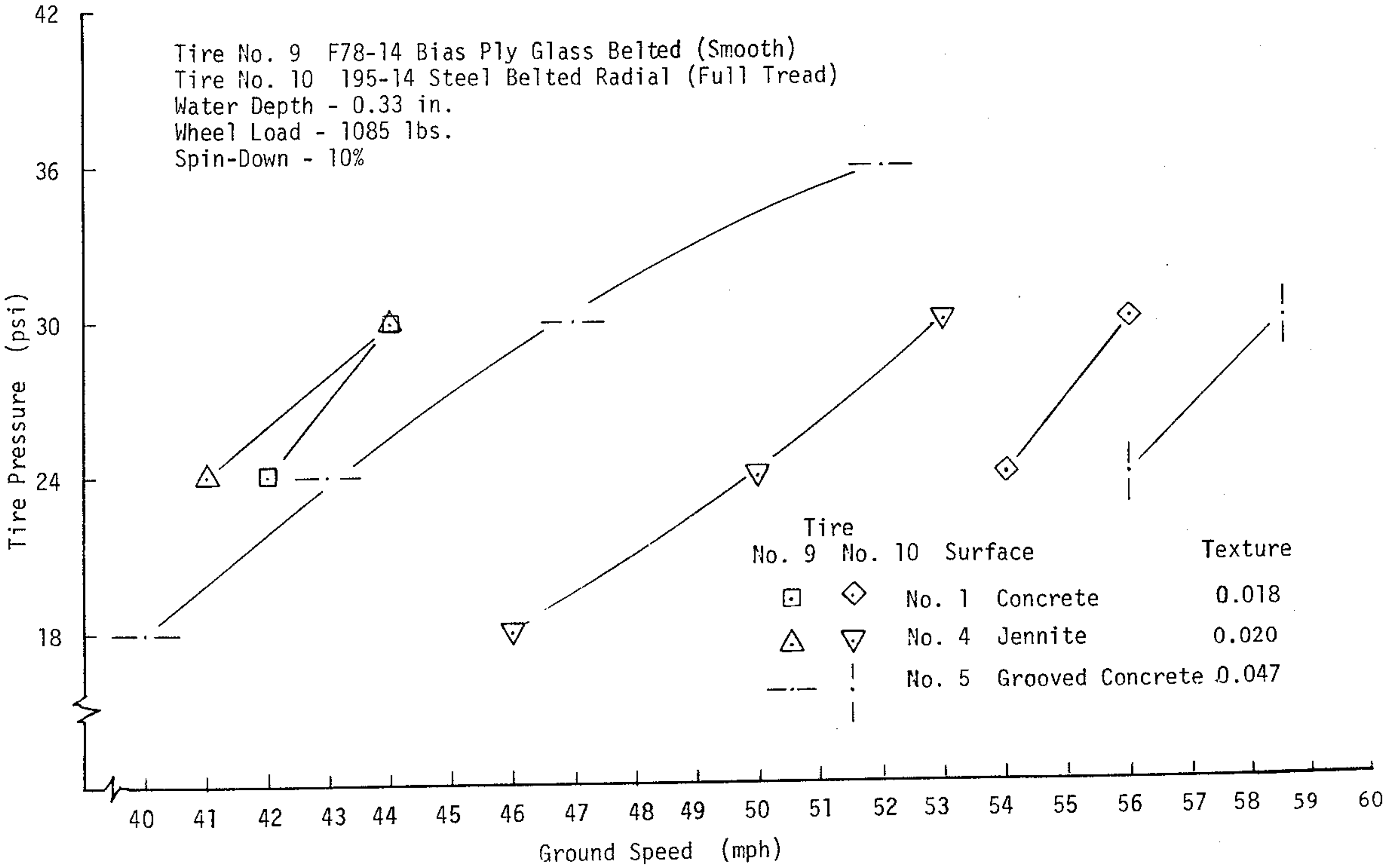


FIGURE 55. 10% SPIN-DOWN FOR TWO TIRES AND THREE SURFACES AT SELECTED TIRE PRESSURES.

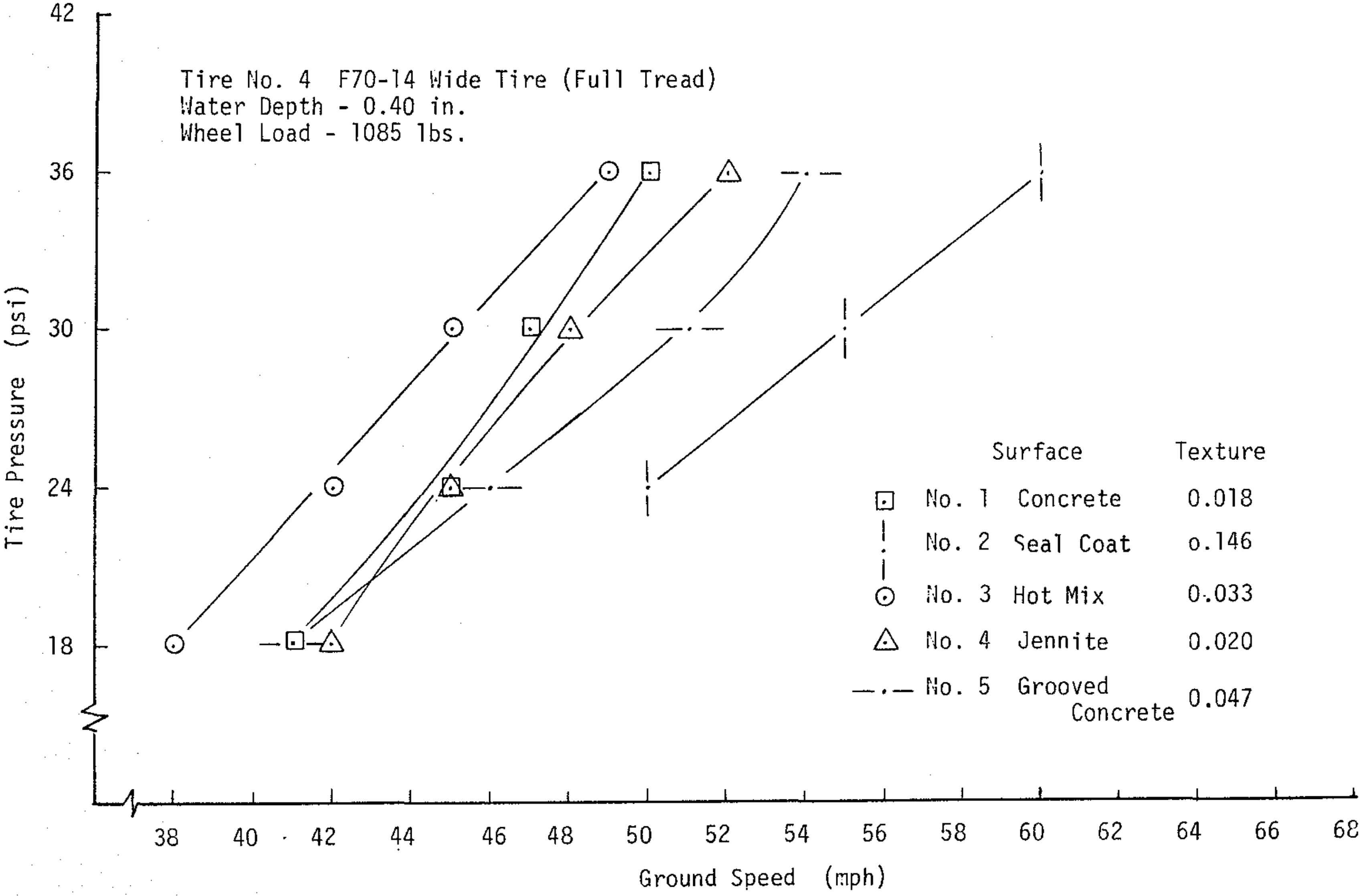


FIGURE 56. EFFECT OF SURFACE AND TIRE PRESSURE AND GROUND SPEED FOR 10% SPIN-DOWN.

FIGURE 56. EFFECT OF SURFACE AND TIRE PRESSURE AND GROUND SPEED FOR 10% SPIN-DOWN.

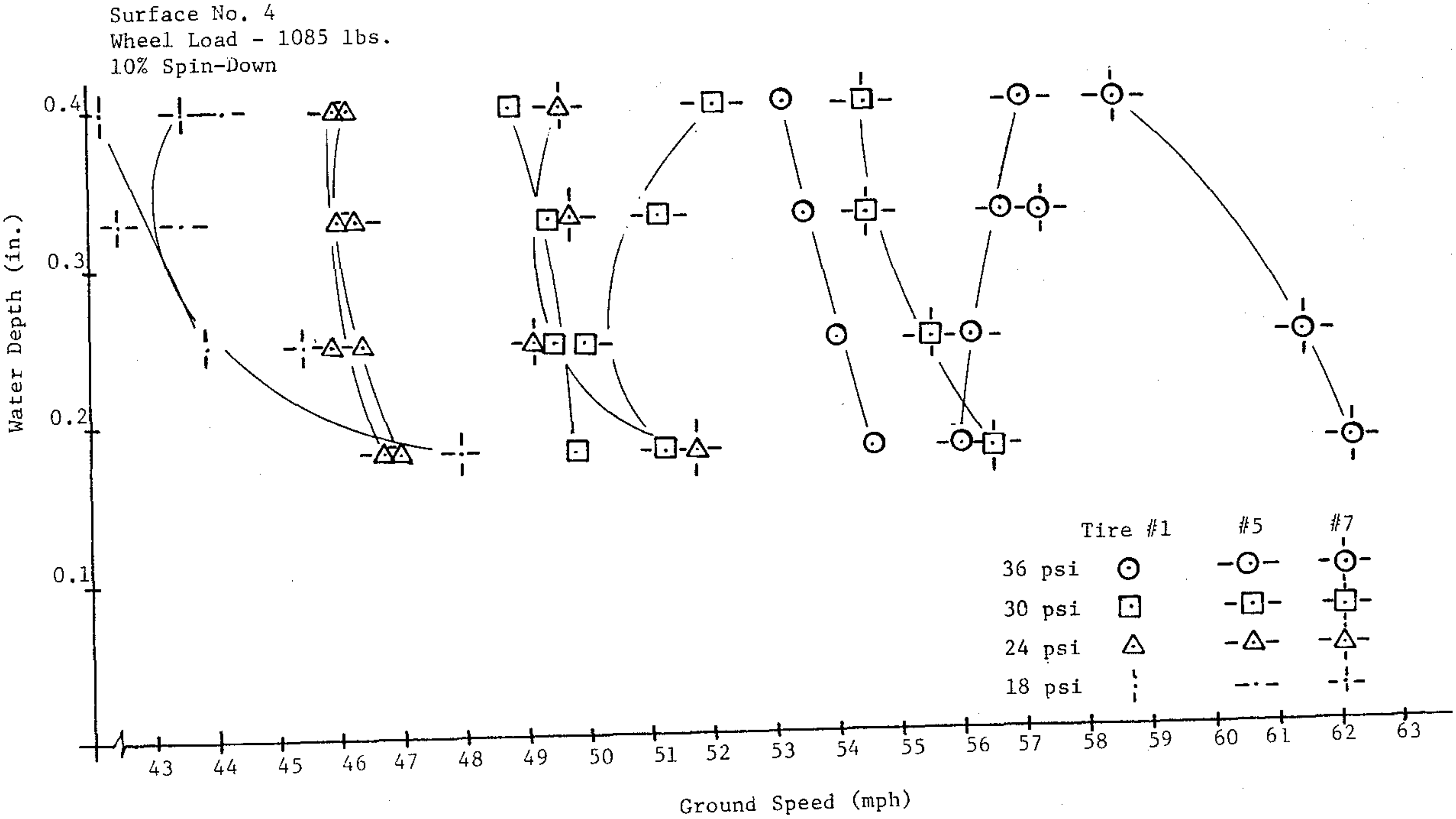


FIGURE 57. COMPARISON OF BIAS PLY TIRES (1, 5, & 7)

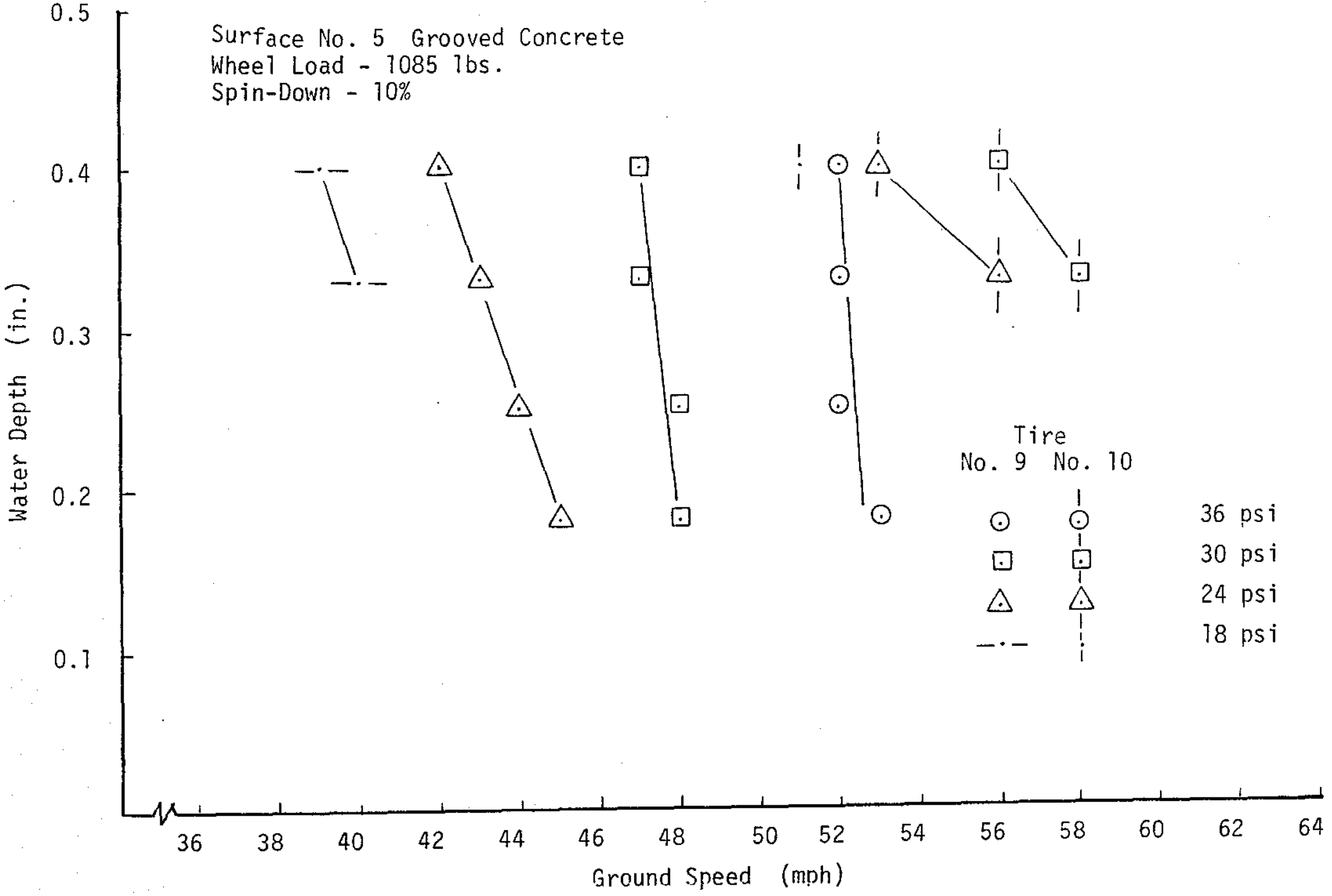


FIGURE 58. COMPARISON OF BELTED TIRES TESTED (9,10)

FIGURE 58. COMPARISON OF BELTED TIRES TESTED (9,10)

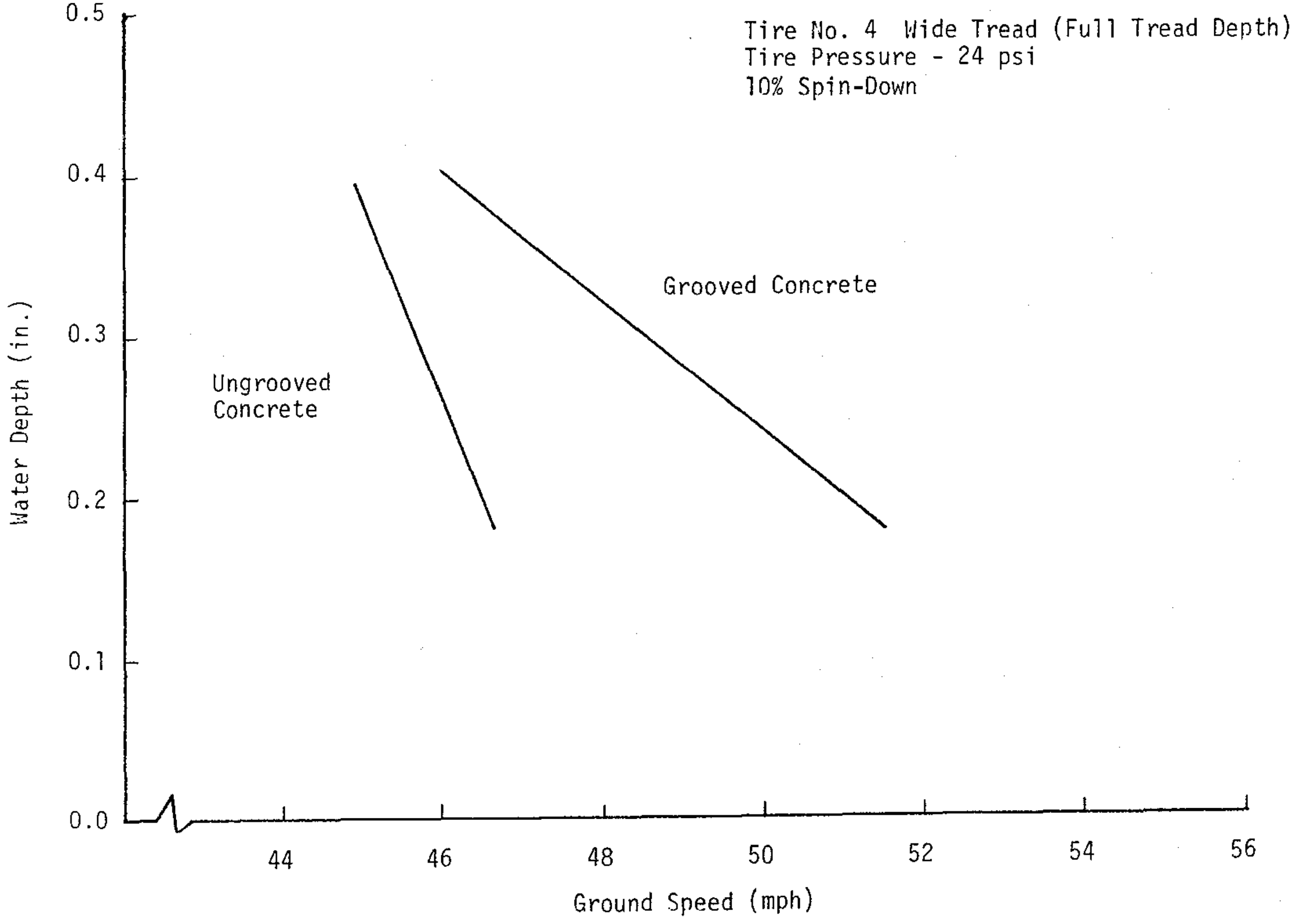


FIGURE 59. COMPARISON OF UNGROOVED AND GROOVED CONCRETE SURFACES WITH VARIOUS WATER DEPTHS.

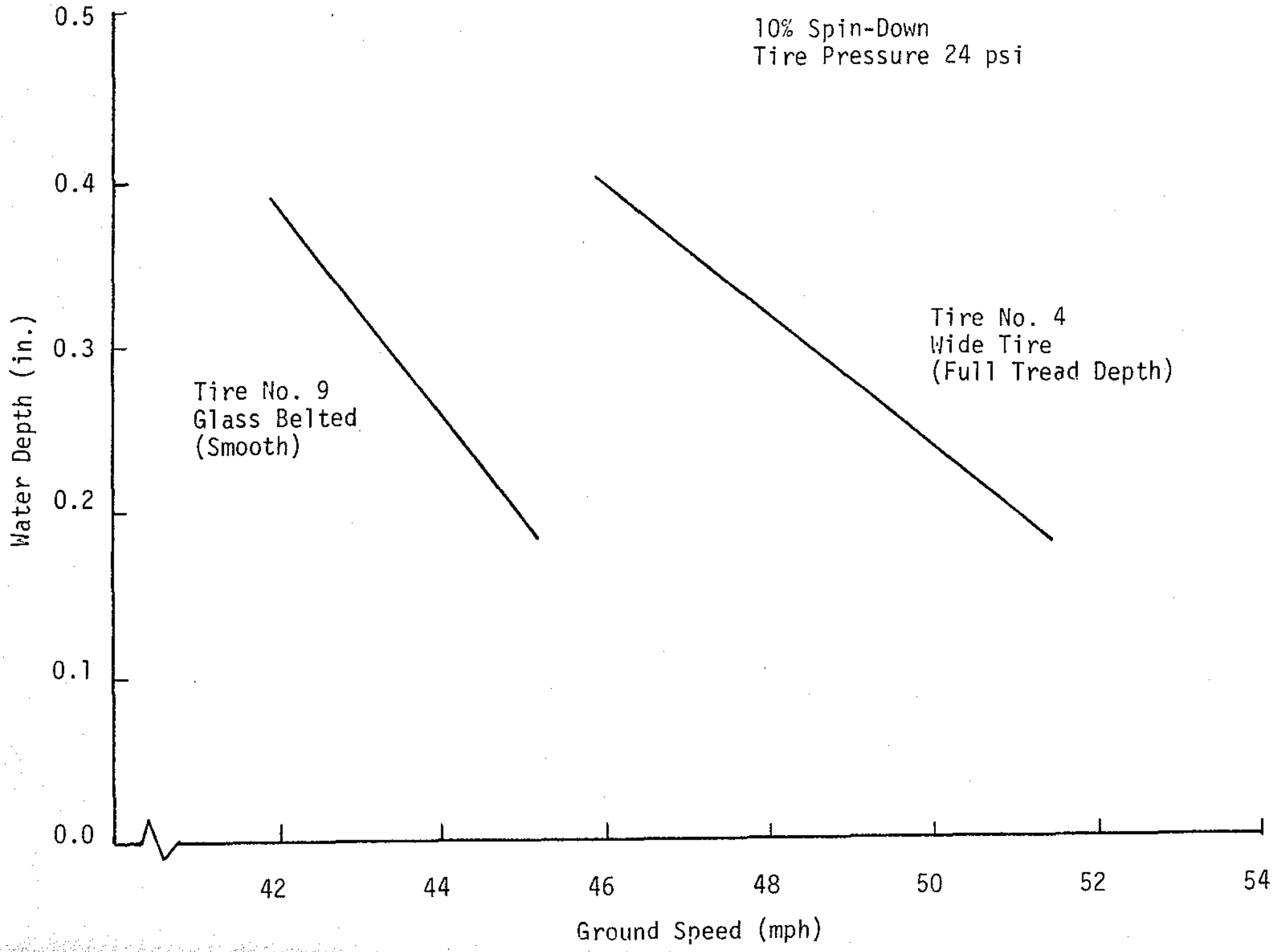


FIGURE 60. EFFECT OF WATER DEPTH ON GROOVED CONCRETE SURFACE.

Ground Speed (mph)

FIGURE 60. EFFECT OF WATER DEPTH ON GROOVED CONCRETE SURFACE.

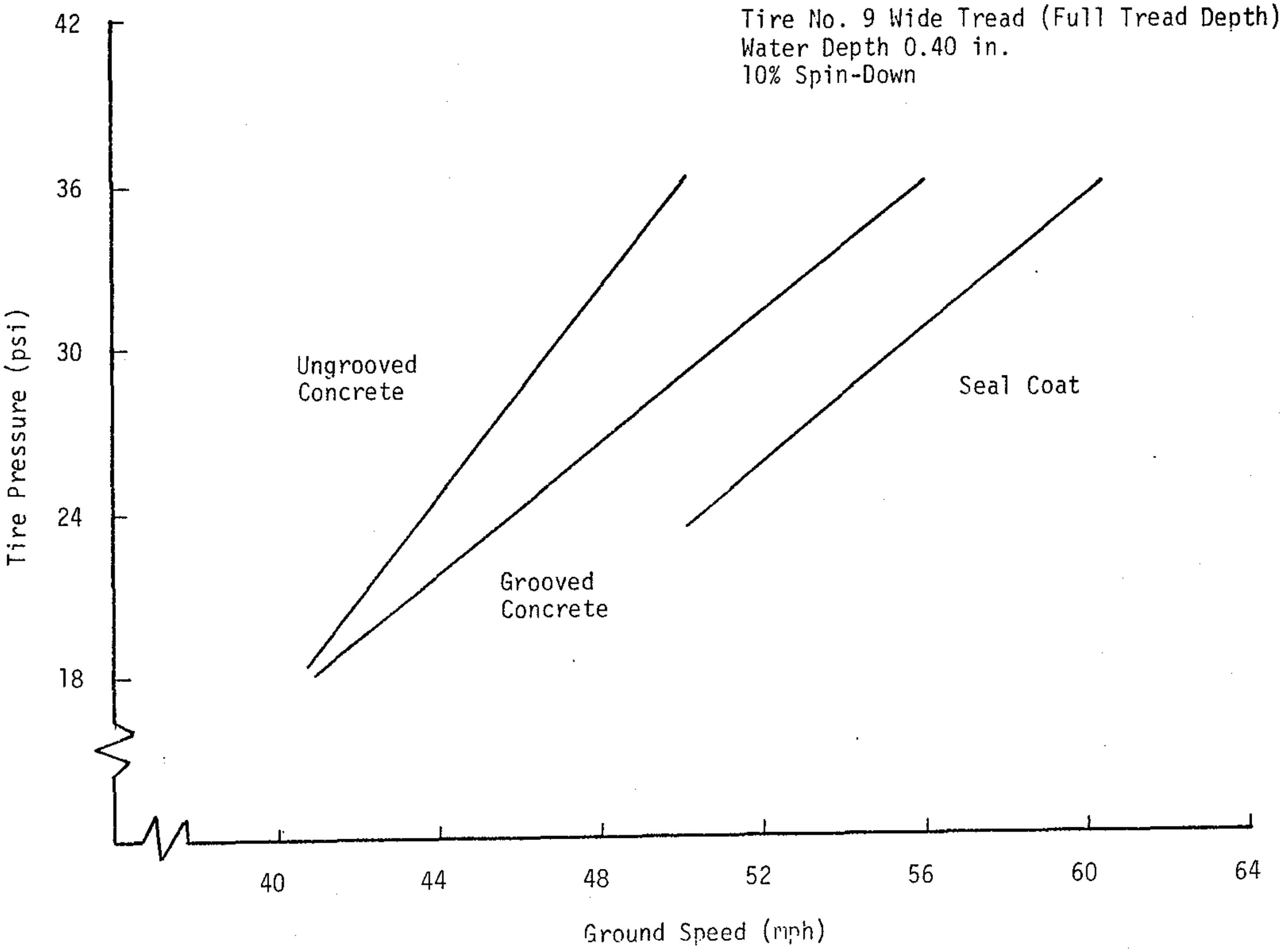


FIGURE 61. COMPARISON OF UNGROOVED CONCRETE, GROOVED CONCRETE AND SEAL COAT SURFACES.

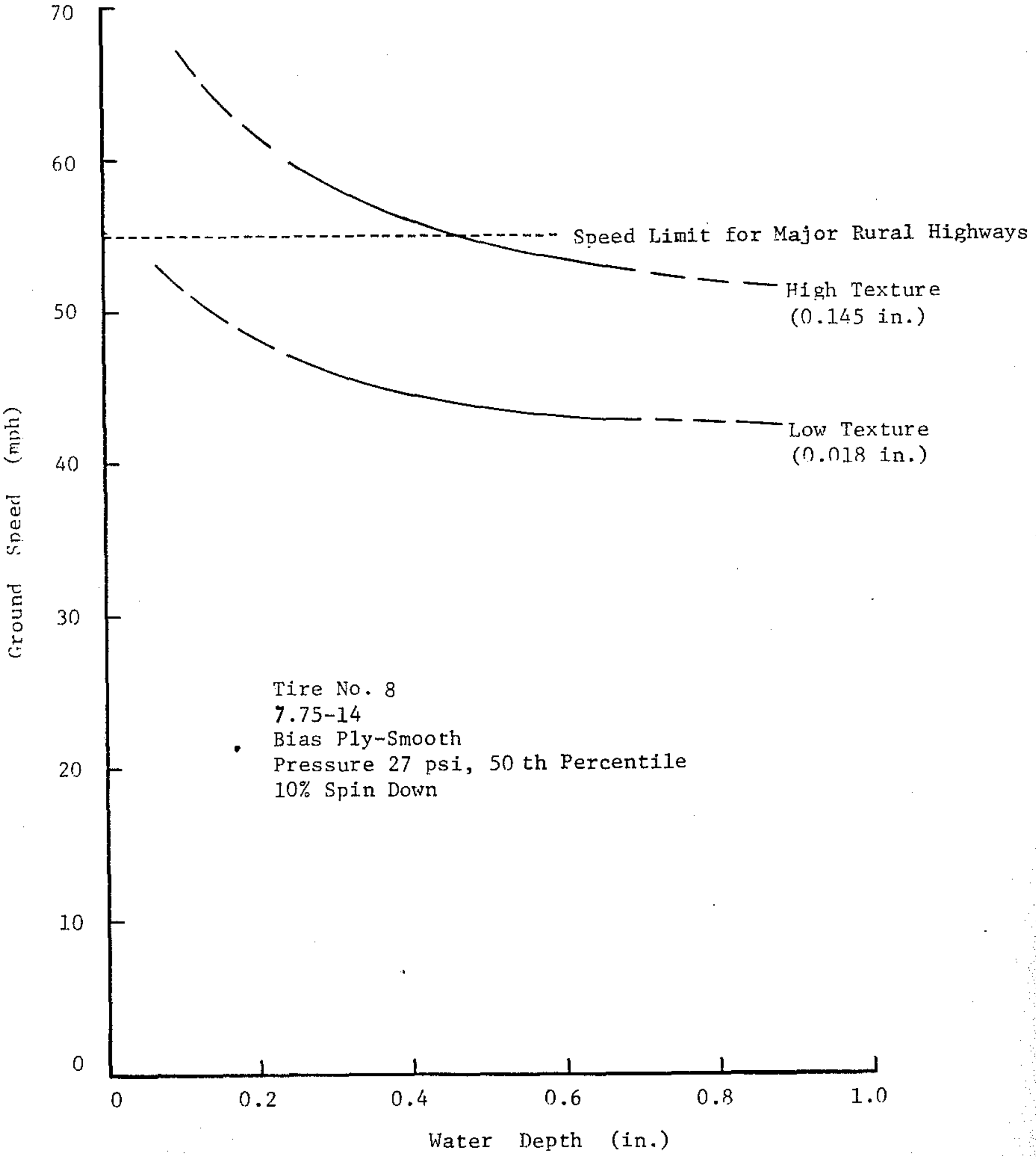


FIGURE 62. EFFECT OF TEXTURE ON HYDROPLANING.

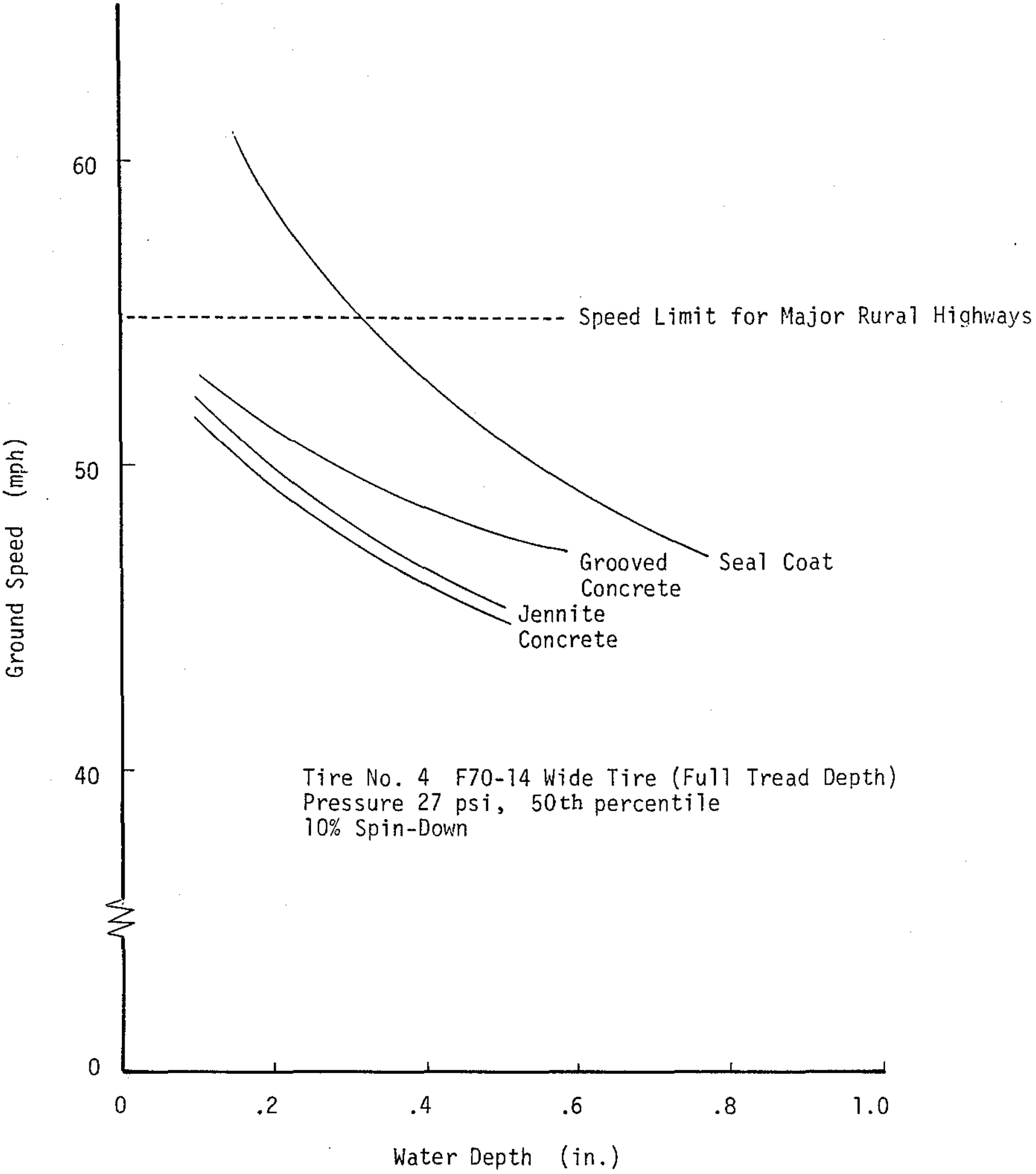


FIGURE 63. EFFECT OF TEXTURE ON HYDROPLANING.

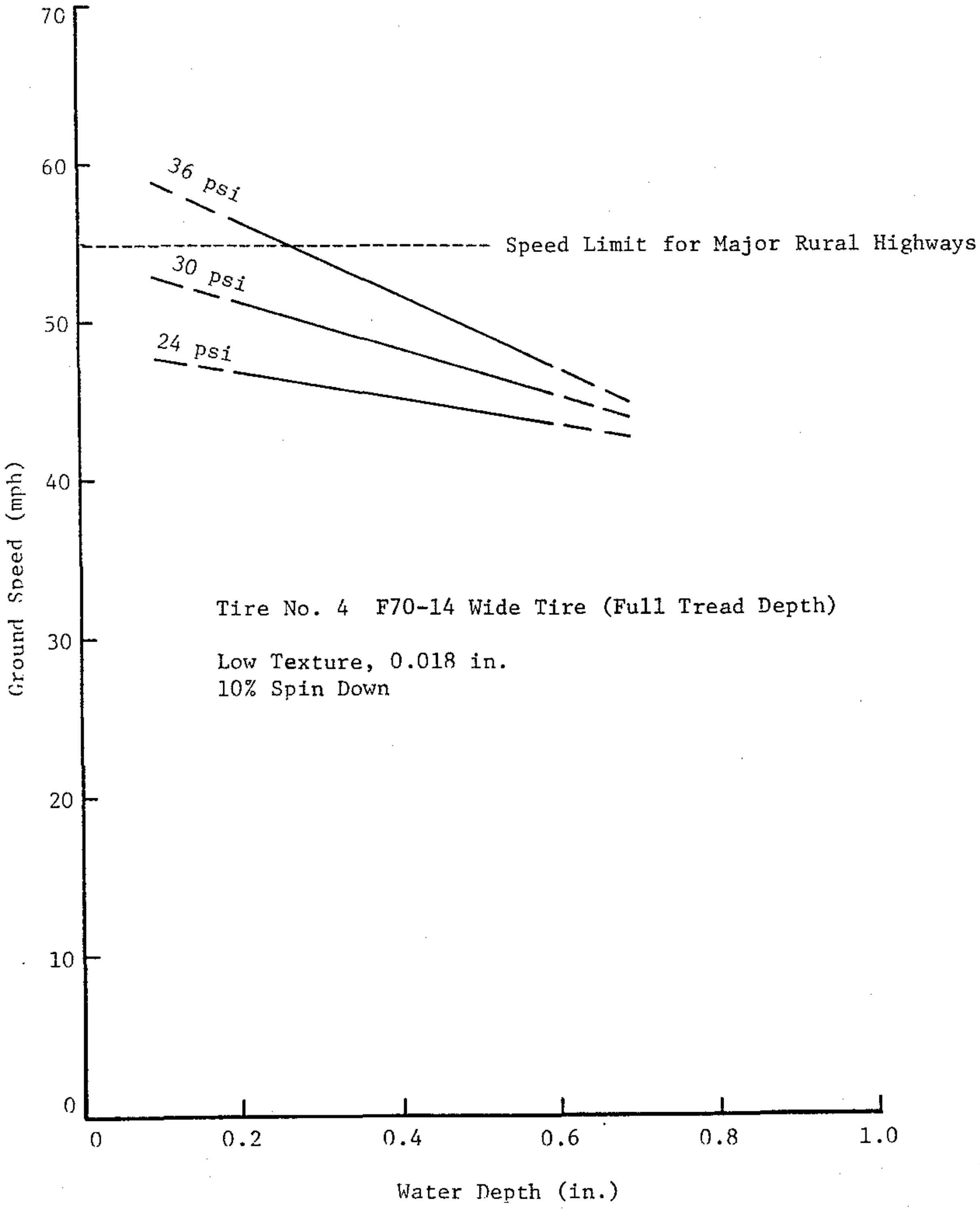


FIGURE 64. EFFECT OF PRESSURE ON HYDROPLANING.

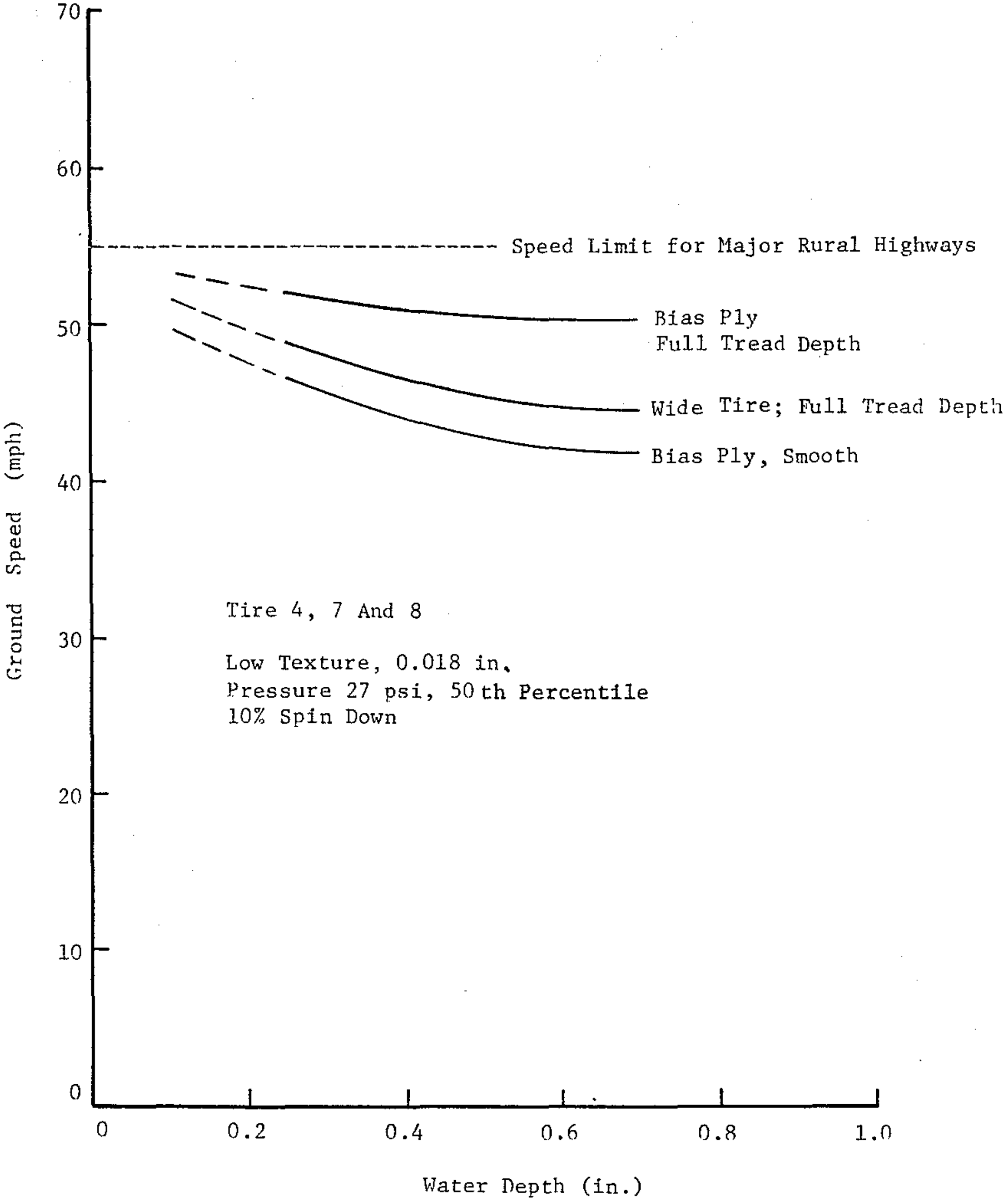


FIGURE 65. EFFECT OF TIRE ON HYDROPLANING.

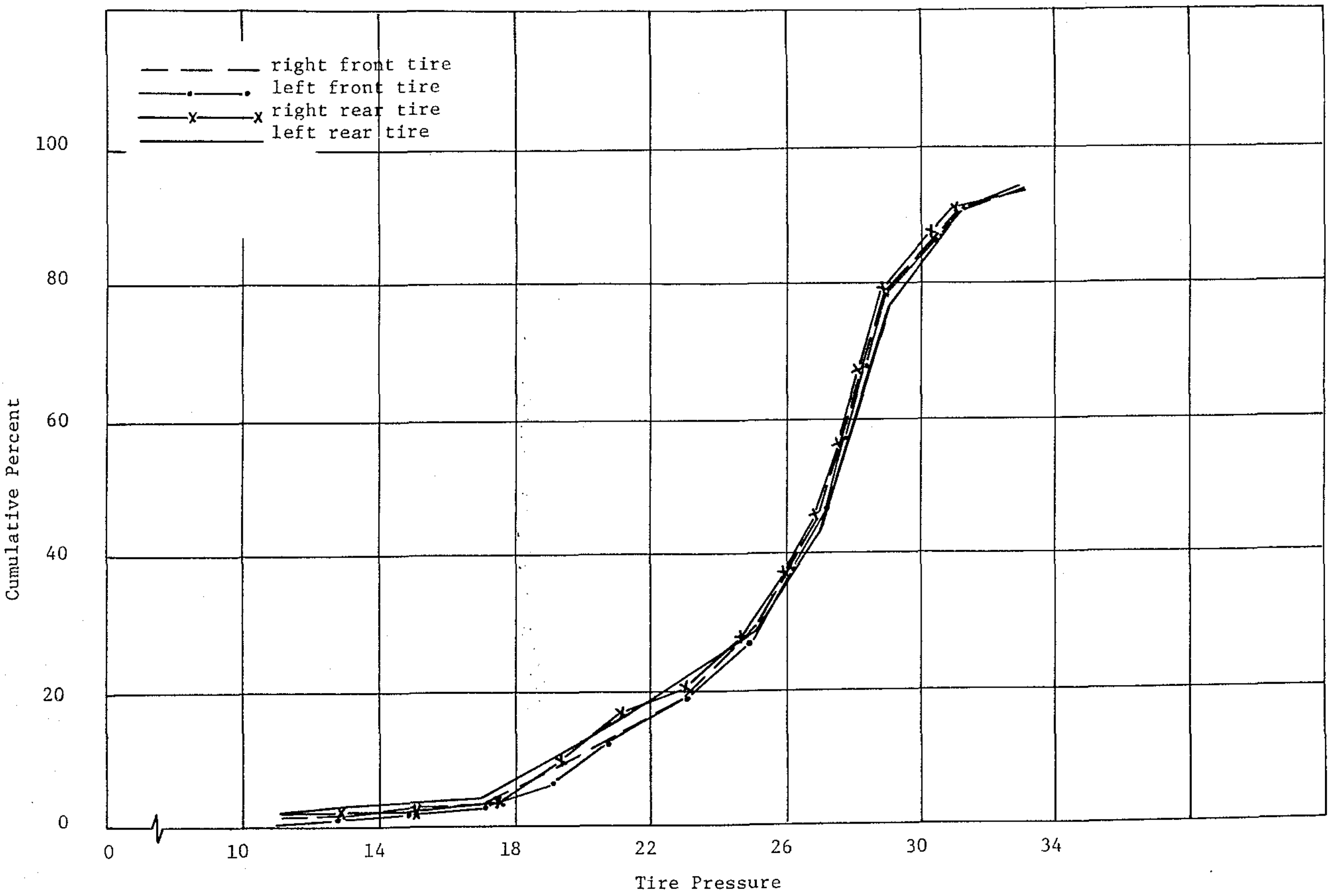


FIGURE 66. COMPARISON OF TIRE PRESSURES - ACCIDENT STUDY. (ref. 25)

FIGURE 66. COMPARISON OF TIRE PRESSURES - ACCIDENT STUDY. (ref. 25)

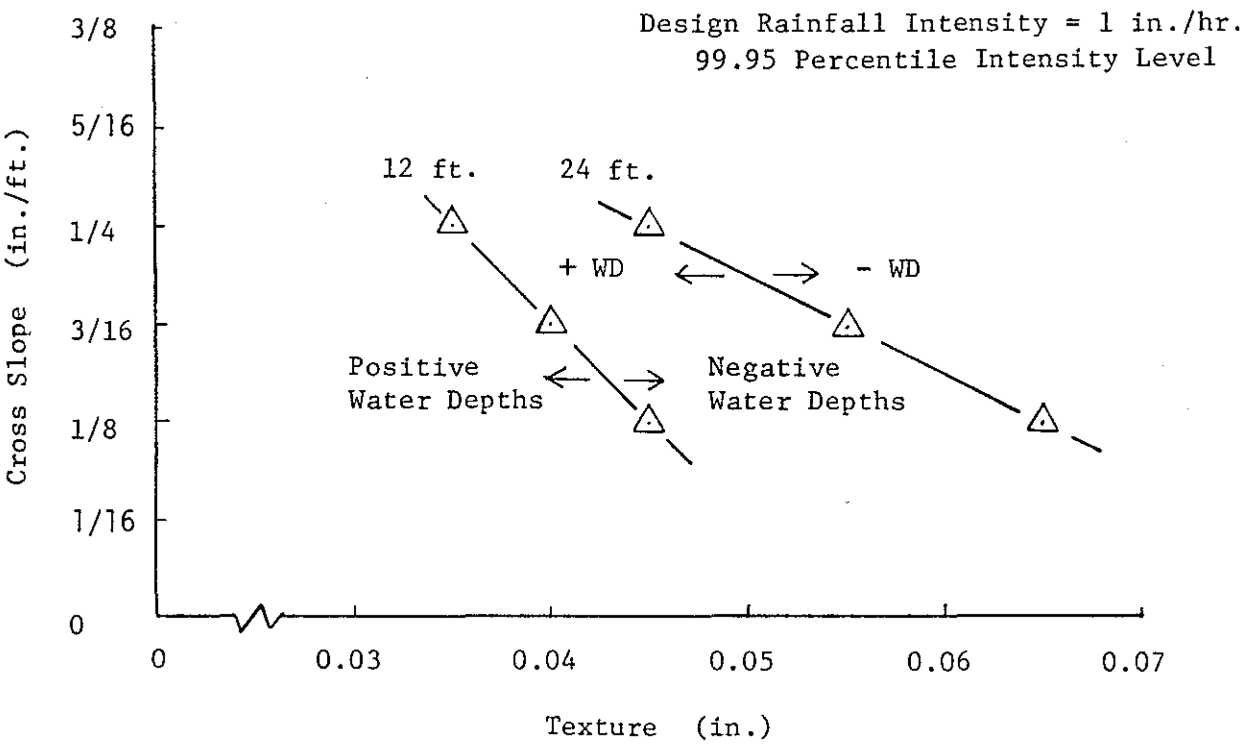


FIGURE 67. COMBINATIONS OF CROSS SLOPE AND TEXTURE REQUIRED TO PREVENT SIGNIFICANT WATER DEPTHS.