NASA CR-174,909

NASA-CR-174909
19850025178

NASA CR-174909

ROLLING, SLIP AND ENDURANCE TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS

By:
Joseph L. Tevaarwerk
Transmission Research Inc.

July 1985

LIBRARY COPY

MAY 2 4 1990

LANGLEY RESEARCH CENTER
LIBRARY NASA

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Centre
Cleveland OH 44135
Under Contract DEN 3-35

NF01216

ROLLING, SLIP AND ENDURANCE TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS.

By:
Joseph L. Tevaarwerk
Transmission Research Inc.
July 1985.

Prepared for:
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Centre
Cleveland, Ohio 44135

N 85- 33491 #

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-174909		

4. Title and Subtitle	5. Report Date
ROLLING, SLIP AND TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS.	July 1985.
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
J.L. Tevaarwerk, Applied Tribology RR3 Stokes Lane , Shelburne, VT 05482	
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No.
Transmission Research Inc. 10823 Magnolia Dr, Cleveland, OHIO 44106	DEN 3-35
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
NASA Lewis Research Center. Cleveland OH 44135	Contractor Report.
	14. Sponsoring Agency Code

15. Supplementary Notes

Third Interim Report:
Project Manager, D.A. Rohn, Advanced Concepts and Mechanisms Section, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

Traction and wear tests were performed on six Low Modulus Materials (LMM). Three different traction tests were performed to determine the suitability of the material for use as traction rollers. These were the rolling , slip and endurance traction tests. For each material the combination LMM on LMM and LMM on steel were evaluated.

Rolling traction test were conducted to determine the load - velocity limits, the rolling traction coefficient of the materials and to establish the type of failures that would result when loading beyond the limit. It was found that in general a simple constant rolling traction coefficient was enough to describe the results of all the test.

The slip traction tests revealed that the peak traction coefficients were considerably higher than for lubricated traction contacts. Typical values are in the .2 to .4 range. The elastic/plastic traction model that is used for the prediction of slip traction in lubricated contacts was also found to be applicable here.

The endurance traction tests were performed to establish the durability of the LMM under conditions of prolonged traction. Wear measurements were performed during and after the test. It was found that the application of prolonged slip traction tends to reduce the load - velocity limits for the LMM on LMM roller combinations more than for the LMM on Steel.

Energetic wear rates were determined from the wear measurements conducted in the endurance traction tests. These values show that the roller wear is not severe when reasonable levels of traction are transmitted.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Traction drives; Traction; Traction Polymers; Traction drive design; Polymer Rolling Traction Polymer Rolling Wear; Polymer Rolling Failures.	Unclassified. Unlimited. Star Category 37

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	IX + 107 pp	

*For sale by the National Technical Information Service, Springfield, Virginia 22161

ROLLING, SLIP AND ENDURANCE TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS.

By:
Joseph L. Tevaarwerk
Transmission Research Inc.
July 1985.

Prepared for:
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Centre
Cleveland, Ohio 44135

N 85-33491 #

1. Report No. NASA CR-174909	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle ROLLING, SLIP AND TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS.		5. Report Date July 1985.
		6. Performing Organization Code
7. Author(s) J.L. Tevaarwerk, Applied Tribology RR3 Stokes Lane , Shelburne, VT 05482		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address Transmission Research Inc. 10823 Magnolia Dr, Cleveland, OHIO 44106		11. Contract or Grant No. DEN 3-35
		13. Type of Report and Period Covered Contractor Report.
12. Sponsoring Agency Name and Address NASA Lewis Research Center. Cleveland OH 44135		14. Sponsoring Agency Code

15. Supplementary Notes

Third Interim Report:
Project Manager, D.A. Rohn, Advanced Concepts and Mechanisms Section, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

Traction and wear tests were performed on six Low Modulus Materials (LMM). Three different traction tests were performed to determine the suitability of the material for use as traction rollers. These were the rolling , slip and endurance traction tests. For each material the combination LMM on LMM and LMM on steel were evaluated.

Rolling traction test were conducted to determine the load - velocity limits, the rolling traction coefficient of the materials and to establish the type of failures that would result when loading beyond the limit. It was found that in general a simple constant rolling traction coefficient was enough to describe the results of all the test.

The slip traction tests revealed that the peak traction coefficients were considerably higher than for lubricated traction contacts. Typical values are in the .2 to .4 range. The elastic/plastic traction model that is used for the prediction of slip traction in lubricated contacts was also found to be applicable here.

The endurance traction tests were performed to establish the durability of the LMM under conditions of prolonged traction. Wear measurements were performed during and after the test. It was found that the application of prolonged slip traction tends to reduce the load - velocity limits for the LMM on LMM roller combinations more than for the LMM on Steel.

Energetic wear rates were determined from the wear measurements conducted in the endurance traction tests. These values show that the roller wear is not severe when reasonable levels of traction are transmitted.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Traction drives; Traction; Traction Polymers; Traction drive design; Polymer Rolling Traction Polymer Rolling Wear; Polymer Rolling Failures.	Unclassified. Unlimited. Star Category 37

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	IX + 107 pp	

*For sale by the National Technical Information Service, Springfield, Virginia 22161

SUMMARY.

Traction and wear tests were performed on six low modulus materials (LMM). Five of these were thermoplastic and the other thermosetting. Three different traction tests were performed to determine the suitability of the material for use as traction rollers. These were the rolling, slip and endurance traction tests. For each material the combination LMM on LMM and LMM on steel were evaluated.

Rolling traction test were conducted to determine the load - velocity limits and the rolling traction coefficient of the materials and to establish the type of failures that would result when loading beyond the limit. It was found that most of the thermoplastics failed by sub-surface melting. The thermosetting material tended to fail either by spall formation or by crushing. Two materials with the highest load - velocity limit and the lowest rolling traction coefficient were selected for further evaluation with the endurance traction test. It was found that in general a simple constant rolling traction coefficient was enough to describe the results of all the test.

The slip traction tests revealed that the peak traction coefficients were considerably higher than for lubricated traction contacts. Typical values are in the 20 to 40% range, which is about 3 to 5 times higher than for lubricated contacts. The elastic/plastic traction model that is used for the prediction of slip traction in lubricated contacts was also found to be applicable here. From the analysis of the traction coefficients it was found that the limiting shear strength of the material is somewhat sensitive to pressure, but the effect is less than that for lubricating fluids. Increasing temperatures tend to increase the traction coefficient. Some peculiar behaviour was observed during these tests in that two levels of traction appear to exist. What controls this particular behaviour is not known.

The endurance traction tests were performed to establish the durability of the LMM under conditions of prolonged traction. Wear measurements were performed during and after the test. It was found that the application of prolonged slip traction tends to reduce the load - velocity limits for the LMM on LMM roller combinations more than for the LMM on Steel. The reason for this lies in the ability of the steel roller to carry the heat away from the interface shear zone. The type of failures encountered during the endurance traction test for the LMM on Steel combinations were generally the same as those in the rolling traction tests. For the LMM on LMM combinations this however was quite different, and tended to show more surface related type failures such as delamination and blistering. This might be expected on the basis of the extra thermal load that occurs in these tests. From an analysis of the thermal load due to rolling traction and due to slip traction it was found that under normal operating conditions, using the LMM - Steel combinations, the rolling traction predominates and is 5 to 10 times larger than the slip traction heat load. This indicates that on a first design calculation the influence of the slip heat load may be neglected.

Energetic wear rates were determined from the wear measurements conducted in the endurance traction tests. These values show that the roller wear is not severe when reasonable levels of traction are transmitted.

TABLE OF CONTENTS

NOMENCLEATURE.

Below follows a list of the various symbols used in the text and their units.

Sym.	DESCRIPTION	Units
a	Semi Hertzian contact size in the x direction	[m]
A	Rolling friction coefficient	[*]
A	Area for convection heat transfer	[m^2]
B	Thermal resistance for endurance experiments	[*]
C	General purpose constant	[*]
D	Roller diameter	[m]
E'	Composite elastic modulus for the rollers	[Pa]
$F(\tau)$	Dissipative function for traction model	[sec^{-1}]
F_x	Traction force in the x direction	[N]
F_{xb}	Bearing friction force	[N]
F_z	Normal force on the contact	[N]
F_{zw}	Contact load per unit width (F_z/w)	[N/m]
G	Shear modulus	[Pa]
G_r	Grashof number	[-]
G_s	Shear modulus of the roller material	[Pa]
H	Auxiliary variable for traction calculation	[-]
h	Heat transfer coefficient	[N/m°Csec]
h	Thickness of strained layer	[m]
J	Thermal equipartition fraction	[-]
k	Thermal conductivity of air	[N/m°Csec]
k	General correlation constant	[*]
K_e	Energetic wear rate	[m^3/Nm]
L	Length of the wear path	[m]
m	Initial slope of the slip traction curve	[-]
n	Power law constant	[-]
P_o	Hertzian contact pressure	[Pa]
P_r	Prandtl number	[-]
q	Kalker coefficient	[-]
R_e	Equivalent radius for rollers	[m]
R	Roller radius	[m]
$R_{i,f}$	Initial and final roller radius	[m]
R_{ew}	Roller Reynolds number	[-]
S	Auxiliary variable used in elastic/plastic model	[-]
t	time	[sec]
U	Rolling speed of the rollers	[m/sec]
ΔU	Longitudinal slip velocity of the discs	[m/sec]
V_{or}	Volume of material worn away	[m^3]
W	Power dissipated	[Nm/sec]

w	Effective width of the roller	[m]
X	Heat load ratio	[-]

GREEK SYMBOLS.

θ	Temperature of the roller surface	[°C]
θ_a	Ambient temperature	[°C]
τ	Shear stress	[Pa]
τ_s	Non linear stress parameter for hyperbolic sine	[Pa]
τ_c	Limiting strength of material	[Pa]
$\dot{\gamma}$	Shear strain rate	[1/sec]
μ	Traction coefficient	[-]
μ_r	Rolling traction coefficient	[-]
μ_s	Slip traction coefficient	[-]
ξ	Slide to roll ratio (U/U)	[-]

ABBREVIATIONS.

LMM Low Modulus Material(s)

LIST OF FIGURES

1-0 INTRODUCTION

Traction or friction plays a mayor role in today's technological society in that it holds one of the keys to reduce our overall energy consumption, and thereby the dependence on unreliable sources of this energy. Friction and traction indicate the resistance to relative motion of two 'contacting' bodies. The term traction and friction have the same meaning in a tribological sense, however friction is used when this resistance is undesirable and traction is used when it is desirable.

The mechanical components in which friction and traction are important are rolling element bearings, gears, cam and tappets and traction drives. Because these devices almost always operate in a wet or fluid lubricated environment, the traction or friction is mostly governed by the particular fluid that is used. In the first three devices friction is the key source of inefficiency and because of the multitude of bearings and gears in service, a small reduction in these losses can amount to phenomenal savings in energy. Rolling element bearings actually have rather interesting requirement for friction or traction in that at low to medium speeds friction should be low, but at high speeds traction should be high to ensure that the rolling elements operate at the correct velocities.

Traction drives on the other hand rely on the transmittal of tractive forces for power transmission purposes and they require high traction at all times. With variable speed traction drives it is possible to allow prime movers to operate at their most efficient power point, almost independent of the load requirements. It is by these means that traction drives can indirectly be looked upon as potential energy savers. Fuel consumption reductions of 25 to 40 % are believed possible with the use of variable speed traction drives in automobiles.

Traditionally the materials that were used for the power transmission rollers were leather, rubber and phenolic. These all gave high traction, did not require very high precision in the manufacture of the components and could be operated in a dry environment. The manufacturing of these components was by the conventional metal working techniques. The operational lives of the drives with these materials was however quite short so that metallic elements were soon introduced to replace the traction rollers. With metallic traction rollers one does require a lubricant so as to prevent direct metal to metal contact and the consequent adhesive wear. The introduction of a lubricating fluid drastically reduces the amount of available traction coefficient and in order to maintain this as high as possible special fluids are used that have shear strengths about twice as high as conventional mineral lubricants. The introduction of the lubricant now also requires the use of a totally sealed operating environment, thereby further adding to the cost and complexity of the system. Also the manufacturing techniques for the traction elements is akin to that used in the roller bearing industry although perhaps not as stringent a requirement is placed upon the surface finish.

It seems however that this form of traction drives certainly provides a very viable solution to the transmission of high levels of power.

Several novel and new forms of traction drives along these lines have recently been developed and tested by Loewenthal et al [1978] and Kemper [1979] and McCoin et al. [1981].

However for the transmission of low levels of power these devices are too costly in their present form. Metallic traction drives in the low power spectrum are typically 4 to 5 times as costly as simple variable speed belt drives and therefore not very attractive for large scale industrial use.

In order to reduce the cost of the low power drives several of the requirements of metallic traction drives would have to be relaxed without impeding on the functionality. In point form these objectives are;

1) less precise manufacturing techniques
2) avoid the use of lubricating fluids
3) design for higher traction density
4) use of improved traction materials

From this list it is clear that early traction drives clearly satisfy these requirements better, with perhaps the exception of item 3). The use of non-metallic materials in a traction drive will facilitate items 1) and 2) and with the proper selection of materials will lead to improved traction. The employment of polymeric materials suitable for injection moulding or die casting techniques will permit the simple manufacture of the components. If this material can at the same time be used to transmit the traction then the design is at the same time greatly simplified. Also a number of new polymeric materials have been developed that exhibit excellent wear and friction characteristics for traction purposes. In regards to item 3) in this list, there have been several new designs recently that employ a very high density of traction contacts in a given space, see Loewenthal [1981].

The aim of this investigation is to identify and evaluate possible materials that may be used in the design of traction drives so as to simplify their design, and to develop the required traction models so as to predict the traction characteristics of these materials under various conditions.

1-2 PRIOR INVESTIGATIONS

When we speak of traction of polymeric or low modulus materials (LMM) we should distinguish between the two principal forms. These are the rolling traction and the slip traction. The rolling traction is the resistance encountered when rolling one member over another and results from the hysteresis losses of the material under the contact zone. For steel rollers this traction is very low and only of secondary importance in the design of traction drives. For LMM however it can be quite large and it has to be taken into account both from a traction point of view and also as far as the thermal effects are concerned.

The slip traction is the resistance that is encountered when attempting to slip one roller relative to the other roller when they are in <u>rolling</u> contact. This is different from the sliding traction or friction encountered when sliding one member over another.

Experimental investigations on the rolling traction of LMM were conducted by Flom [1960] for spheres, and Greenwood et al [1960] on spheres and line contacts of varying lengths. Theoretical developments were performed by Greenwood et al[1960] who tried to relate the rolling traction to hysteresis losses of the material, by Flom and Bueche [1959] for the simple rolling of spheres and by May et al [1959] for the rolling friction of hard cylinders rolling over a viscoelastic material. From simple experiments Greenwood and Tabor [1957] showed that the sliding friction of rubber is identical to the rolling friction provided that the surfaces are well lubricated so that no tangential interface stresses occur. This experiment exemplified the fact that rolling friction is only related to the subsurface stress distribution and not to the surface tangential tractions or any other surface effects.

Slip traction research is a good deal scarcer in the literature. The only work directly related to traction drives was done by the Braunschweig group in Germany. Notable among the experimental contributions from there are the work by Bauerfeind [1966] and Sackmann [1980] on the slip traction of rubber covered wheels. No attempt was made by either of these researchers to develop any theoretical models to explain and predict the slip traction behaviour.

1-2 TRACTION DATA RESEARCH PROGRAM

For purposes of design of traction drives employing LMM as their principal traction elements, it is important that suitable materials be investigated for both their rolling traction and slip traction characteristics. Adequate data is needed to establish the range of operating speeds, pressures and temperatures encountered in industrial environments. Additionally, the data could be tested against proposed rolling traction and slip traction models to investigate how well they predict the observed tractions.

A program was undertaken whereby six commercially available LMM were evaluated for their rolling traction characteristics and their associated load/speed/temperature limits. From these six materials two were selected for further evaluation of their slip traction characteristics and their slip traction endurance.

This work was performed by Transmission Research Incorporated of Cleveland Ohio under contract to the NASA Lewis Research Center, Cleveland, Ohio. The NASA technical project manager was Mr. D. A. Rohn from the Advanced Concepts and Mechanisms Section at the NASA Lewis Research Center.

2-0 EXPERIMENTS

In order to examine the potential of various candidate traction materials a test program was developed that would allow evaluation of their performance under the following conditions;

1) conditions of pure rolling to evaluate the rolling losses,
2) variable slip conditions to establish the traction slip characteristics of the material,
3) fixed values of slip to evaluate the performance under steady conditions of traction and the consequent heat input.

Each test material was to be evaluated on the basis of LMM in contact with the same LMM, and also the LMM in contact with a steel roller so as to observe the differences in behaviour for the two conditions. From the test series conducted under 1) the speed/load/temperature limits for the material were established. Based upon the best performance criterion a selection of two candidate materials was made that were to be used for the evaluation under 2) and 3).

2-1 TEST MATERIALS.

Test materials were selected based upon the likelihood of meeting the objectives as outlined in 1-0. A choice was made to include both thermoplastic LMM and thermosetting LMM in view of their different thermal characteristics.

The six materials evaluated for their speed/load/temperature performance under rolling conditions only were;

a) Nylon 6-6 (referred to as Nylon)
b) Monocast Nylon (referred to as Mononylon)
c) Acetal
d) Torlon* (Polyamide-imide) unfilled. (referred to as Torlon)
e) Torlon with fluorocarbon and graphite. (referred to as FTorlon)
f) Phenolic, cotton fabric filled

With the exception of material e) all materials were cast or manufactured in cylindrical form. The test rollers were cut off to dimensions of nominally 50 mm diameter by 20 mm wide and a bore of 25 mm.

Based upon the results from the speed/load/temperature rolling test performance two materials were selected for the evaluation of items 2) and 3). These materials were;

d) Torlon
f) Phenolic

* Torlon is a registered trademark of Amoco Chemicals Corp.

2-2 DESCRIPTION OF TWIN DISC MACHINE.

The various traction experiments were carried out on an existing twin disc test facility, shown in Fig. 2-1 and 2-2. This test facility was modified such that it would be capable of rolling and slip traction measurements. These measurements were all performed in the longitudinal or running direction of the rollers. In order to conserve the power of the motor and to be able to test beyond the power capacity of the motor use was made of a bicoupled transmission system torque loop . This system consisted of a planetary differential coupled to the test rollers through timing belts and pulleys. The sun gear was coupled to the bottom roller shaft while the top roller shaft was connected through belts to the ring gear of the planetary. The ring gear was also at the same time connected to the variable speed motor to replace the power lost in the system. The planet carrier was used to control the amount of differential velocity between the top and bottom roller. The hardware details of this setup are shown in Fig. 2-4. This method only requires that the slip and torque losses in the system be replaced but does not require a large capacity motor generator set. With the ratios for the differential and the timing belts as employed in this setup a maximum slip of 4% could be obtained when using equal diameter rollers. From preliminary slip traction tests this was found to be more than sufficient to obtain the entire traction curves under all the conditions.

In order to be able to perform the rolling traction measurements the Nylon spline coupling between the fixed top shaft and the floating top shaft was removed, see Fig. 2-2. In this way the top shaft could idle along and the forces measured by the loadcell dynamometer would be due to the rolling traction and a certain amount of bearing drag. At the same time the planet carrier was held stationary.

Slip traction curves were obtained by inserting the spline coupling between the two top shafts. This would then complete the torque loop through the rollers and the differential drive. Now by using a hydraulic pump as a drag brake the torque in this loop could be controlled merely by restricting the flow from the pump. With the increasing amount of torque in the loop a gradual increase in the slip between the rollers took place depending on the roller material and kinematic conditions. This slip was measured by the pulse counters on each shaft and the traction force at the top test roller was measured by a ring dynamometer as shown in Fig. 2-3. A cross over valve was used in the hydraulic circuit so that both forward and reverse slip traction curves could be obtained.

The same configuration was used for the endurance traction tests but now the flow from the hydraulic pump was fully blocked. In this way the amount of slip in the system was fixed for the duration of the test. It was found that this method of traction control for the endurance test was best. Straight traction control was found to be very difficult because of the peculiar influence that temperature has on the traction coefficient of some of the material combinations.

2-3 INSTRUMENTATION OF THE TRACTION TESTER.

By suitably instrumenting the disc machine the relevant experimental parameters can be measured. In the experiments reported here the slip, longitudinal traction force, roller surface temperature and rolling velocity were measured. The technique of measuring each of these variables will be discussed next.

2-3-1 THE MEASUREMENT OF THE TRACTION FORCE.

The top shaft was mounted in a self aligning bearing at the rear support while at the roller end no direct constraint was provided for. The shaft could move in the vertical plane and two freely rotating pulleys were mounted on the shaft. Over these two pulleys the loading cables from the deadweight loading system provided for the normal loads on the roller assembly, see Fig. 2-1. A third bearing was mounted on the shaft and connected through a gimbal arrangement to a ring dynamometer so as to restrain the roller movement in the horizontal direction. With this arrangement it is possible to measure the tangential traction force at the roller contact without having to make use of torque transducers and slip rings to obtain the signal. There is however the drawback that some of the bearing frictional torque is reflected in the traction signal and this will have to be corrected for in the calculation of the results.

A ring dynamometer type load cell was used to measure the horizontal force on the upper roller assembly. It was found necessary that the ring dynamometer load cell be thermally isolated from the machine because temperature variations tended to introduce drift into the signal. The electrical signal from the load cell was conditioned for noise and amplified using common mode rejection techniques. The gain on the amplifier was adjusted so that a good range on the signal was measured for each test. Calibration of the load cell was done in situ by dead loading, see Fig. 2-1 and 2-2. This calibration was checked periodically but never was there any need for recalibration.

The influence of the bearing friction in the signal was measured by using steel rollers as the test rollers and then recording the horizontal forces. This was done for a number of load and operating speeds, as well as for the rolling traction and the slip and endurance traction configuration. The bearing frictional forces were then calculated on the basis that the rolling resistance of steel rollers is negligibly small. From these test the following bearing friction forces were deduced;

(2-1) For the rolling traction; $F_{xb} = 1.7 + .0015\ F_z$ [N]

(2-2) For the slip & endurance; $F_{xb} = 9.75 + .25\ U$ [N]

where F_{xb} = bearing frictional force [N]
F_z = roller normal load [N]
U = rolling speed [m/sec]

2-3-2 THE MEASUREMENT OF SLIP.

The rotational velocity of both the top and bottom shaft were measured by using a MC 6840 frequency counter. The proximity probes for the control of the counters were mounted near the rear bearings, see Fig. 2-3. Each shaft had a simple protrusion on it that would produce a pulse once per revolution. This pulse was used to turn count down counters on when controlled to do so. The next successive pulse from the proximity probe would stop the countdown. When each of the two counters had completed their cycle a flag was set and the register contents were read. From the difference between the original and the final contents of the registers the amount of time for a single revolution of each shaft was calculated. From this the angular speed for each shaft was calculated, and hence the peripheral velocity of each roller can be calculated if the roller radius is known. The countdown frequency on the counters was selected such that an accuracy of at least 1 : 10000 was obtained. By employing this method the slip of the rollers could be measured every 5 or six revolutions of the shafts. From the count down and the undeformed roller radii the slip is calculated as follows;

$$(2\text{-}3) \quad S = 2\,\frac{(U2 - U1)}{(U2 + U1)} = 2\left(\frac{R2}{R1} - \frac{C2}{C1}\right) / \left(\frac{R2}{R1} + \frac{C2}{C1}\right) \qquad [-]$$

This can be approximated if the amount of slip is small by the following;

$$(2\text{-}4) \qquad S = \left(\frac{R2}{R1} - \frac{C2}{C1}\right)$$

where S = roller slip [-]
U = rolling velocity [m/sec]
C = number of count down pulses [-]
R = undeformed roller radius [m]

Suffix 1 denotes the top roller and suffix 2 denotes the bottom roller.
It should be stressed that the actual amount of slip will be somewhat different when two different roller materials are in contact because of the deformation of the rollers themselves. Also as the temperature of the rollers rise there will be an influence in the actual slip that does not reflect in the calculated slip. For the slip traction experiments these errors can be removed by obtaining the traction in both the forward and reverse rolling direction. In the rolling traction measurements the actual slip is not of great significance to us so the error introduced by the effects mentioned is not very important.

2-3-3 THE MEASUREMENT OF THE ROLLER TEMPERATURE.

In the analysis and reduction of the test data it is important that the roller temperature be known as accurately as possible. This temperature can be measured by embedding a thermocouple directly below the surface of the disc and then to take this signal out through mercury slip rings. This method is however not very practical when a large number of different rollers are involved and is also very costly from an installation point of view. Furthermore when dealing with viscoelastic materials the temperature distribution in the roller material will be a strong position of location because of the effect of hysteresis heating and the poor thermal properties of the materials. It is therefore better to content oneselves with the roller surface temperature.

With care the surface temperature can be measured by using a trailing thermocouple that rides on the roller surface. The disadvantage of this technique is that it can be speed sensitive in its response because of frictional heating.

The latter technique was employed here and care was taken to ensure that the contact force on the thermocouple was not excessive. The use of a reference junction ensures that the same reference level for the thermocouple is used at all times. The signal from the thermocouple is amplified using common mode rejection techniques to minimize the influence of electrical noise and other disturbances. Calibration was done by the boiling water method adjusted for sea level differences. This calibration was checked periodically. Only slight deviations were encountered. Because of the frictional heating at the junction/toroid interface a variation of about 2 °C was found in the signal between stationary rollers and those rotating at a surface velocity of 20 m/s. The overall reproducibility of the temperature measurement is better than 2 °C.

2-3-4 MEASUREMENT OF THE ROLLER SPEED.

The rotational velocity of the top roller was measured indirectly through the use of a tachometer on the top shaft. Knowledge of the roller diameter permitted the calculation of the surface velocity of the roller. The electrical signal from the tachometer was scaled by using a divider circuit and filtered by using a low pass R-C filter with a 2 sec time constant. This method of velocity measurement is often used to give both magnitude and direction indication. Calibration of the system was performed on a periodic basis for both the forward and reverse signal. No major adjustment were ever required for the speed measurements

2-3-5 MEASUREMENT OF THE ROLLER WEAR.

During the endurance testing the amount of roller material that was removed or displaced was to be measured. The technique that was employed on the traction tester is a simple shaft height measurement with a micrometer as shown in Fig. 2-3. This will allow the height to be measured prior to a test and after the completion of the particular endurance test. By simple trigonometry the difference in the readings from before and after the test can then be related to the reduction in the test roller diameter. The resolution on the readings were about 1 : 20000 based upon the roller diameter.

From the wear data taken during the endurance test it became clear that this method of wear measurement sometimes gave negative wear of the rollers. This was caused by the fact that the thermal expansion of the rollers during the tests more than offset the encountered wear. Since it was not practical during the test to allow the rollers to obtain the same temperature from before and after the test it was decided that the readings from the wear measurement would only be used as a global wear indicator.

3-0 TRACTION MEASUREMENTS.

With the traction tester in the above described configuration the various traction test were carried out. The signals from the force, temperature and speed transducers were fed into a digitizer from where they were led into an Apple II+ computer for plotting and storage on magnetic media for future use. The slip measurement was performed on a separate board that fitted directly into the computer. No digitization of this signal was required therefore.

In order to select the materials for further evaluation the rolling traction experiments were performed first. After these tests the slip traction curves were obtained for a number of contact loadings. Upon selection of the candidate materials for further study the endurance traction experiments were conducted.

3-1 ROLLING TRACTION MEASUREMENTS.

The objectives of the rolling traction experiments were to obtain data on the rolling traction coefficient and to determine the limit of operation for the material combination. Rolling traction measurements were conducted with the top shaft of the machine in the idling mode so that no slip traction would exist in the system. The method of conducting this experiment was essentially one whereby the machine was operated for a fixed period of time under steady conditions of normal load and speed. During this time the amount of slip, roller surface temperature and the rolling traction force were measured continually. The results from these measurements were averaged over a small time period and plotted directly on the screen of the computer as a function of time. Depending on the test duration and the operating speed for the test anywhere between 100 to 400 such measurements per time period were averaged to form a single data point. Each completed test would consist of 240 equally spaced data points of all the major variables.

Initial and final traction force measurement were taken in both directions to be able to zero the traction trace so as to remove any offset in the signal. At the end of each test the data was stored on a floppy disc for future storage and manipulation. If the specimen rollers were intact then the load or speeds were increased and the whole process was repeated until failure occurred. At the point of failure the recorded portion of the data was saved to disc and a new set of test rollers was installed so as to start the next test sequence. If the failure of a set of rollers could not be effected within the time period for a given single test, and when operating at the maximum conditions of speed or load, then the test rollers were removed and their width was reduced so as to obtain a higher specific loading.

Upon completion of the test series on a particular roller combination the data was recalled into the memory of the computer and further manipulated. This manipulation of the data consisted of the correct positioning of the rolling traction trace and the correction of this force for the bearing frictional drag. The data was then plotted and summarized for further analysis and study. In total about 200 rolling traction tests were conducted on the six material combinations.

3-1-1 ROLLING TRACTION RESULTS.

Typical rolling traction traces are shown in Fig. 3-1 to 3-6. These curves represent the rolling traction measurements of LMM in contact with a steel roller. The results of the LMM in contact with LMM are very similar in nature with minor deviations in the scale of the surface temperature. The three vertical axis represent the rolling traction coefficient F_X/F_Z in percent, the rolling slip as defined by equation (2-4) in percent, and the roller surface temperature in °C. The horizontal axis is the test time in seconds. In the test the rolling traction coefficient and the rolling slip would normally stay fairly constant. The roller surface temperature on the other hand would gradually rise from the starting temperature to some stable value. When the temperature had stabilized at the end of the test time of 1800 seconds the load on the rollers would be increased for the next tests. The peculiar shape of the rolling slip and roller temperature trace as seen in Fig 3-1 and Fig 3-2. occurred only with the two nylons in the rolling traction measurements. A similar behaviour was also observed for the endurance traction measurements on Torlon and Phenolic. The cause of this behaviour is not fully understood at the moment.

The entire test results of all the rolling traction test are also summarized in Appendix I. Here additional details are given regarding the roller dimensions and test data. For the last three columns the rolling traction, rolling slip and temperature are indicated as existed at the end of the test. For most experiments this indicates the steady state operation conditions.

3-2 SLIP TRACTION MEASUREMENTS

Slip traction curves were obtained with the machine in the torque loop operation mode. Increasing amounts of torque were generated in this loop by slowly restricting the fluid flow through the hydraulic pump that was coupled to the planet carrier in the planetary differential. The slip, traction force , speed and roller temperature were all measured on a continues basis and digitized for use in the computer. About 10 readings of each measurement would be summed and their average would constitute one data point to be stored and used for further processing.

From this data the computer would automatically trace the force versus slip curve on the screen while the data was taken. By reversing the direction of rotation of the machine, a mirror imaged set of curves can be obtained. For each experiment 500 data points were taken at fixed time periods of 1 second. Multiple data data points would be stored as separate entries.

After the completion of a test series the data would be recalled into memory of the computer and further manipulated. This manipulation consisted of the averaging of the multiple entries, the filling in of any gaps in the data through forward and backward interpolation, the comparison of the traces for the forward and reverse rolling direction and the centering of the traces about the center lines. After the centering operation the data would be smoothed by a 'N' point averaging technique for traction points after the peak traction points. For storage a geometric series was used so that the total traction trace was now represented by 40 data points for each measured variable. These traces were then stored on magnetic media and used for further manipulation and data extraction at a later point.

3-2-1 SLIP TRACTION RESULTS.

Typical slip traction traces for the LMM materials are shown in Fig. 3-7 to Fig. 3-12. These results are for the LMM in contact with the steel rollers only. Very similar results were obtained from the slip traction measurements on the LMM in contact with the same LMM. The results as plotted have been corrected for the frictional drag due to the bearings as indicated in equation (2-2). In the worst case, i.e. when the load was lowest and the speed highest this correction amounted to about 5% on the total traction coefficient. The tests were conducted for the contact loading in three steps up to 90% of the maximum rolling traction loads that were found in the load/speed/temperature tests. Also the speeds were 10 and 20 m/sec, to coincide with the rolling traction speeds. It was found impossible to perform good slip traction test at the highest speed because of the very high amount of heat that was produced due to the slip traction. This tended to cause very rapid roller failure.

It should be pointed out here that these slip traction curves were obtained on the fly. Hence it is not a true reflection of the traction capacity of the material under conditions of continued slip. However because of the observed fact that slip traction tends to <u>increase</u> with <u>increasing</u> roller temperature these slip traction results can be thought of as the minimum traction that will exist under the given conditions. Similar to the rolling traction results we will see that there appear to be two levels of traction at which some of these materials operate at. Also the results from the endurance traction test are more indicative of the maximum possible traction that can be obtained for long periods of time. The results of all the slip traction experiments are summarized in Appendix II together with some additional information. Indicated under the column 'Mu' are the peak traction coefficient, under Temp the mean temperature of the slip traction experiment in the linear range and under 'Slope' the slope in the linear traction region is indicated. Both these traction parameters are indicated under the two headings 'calculated' and 'fitted'. The difference between the two sets of parameters will be explained in chapter 5.

3-3 ENDURANCE TRACTION MEASUREMENTS.

The endurance traction measurements were carried out with the same machine configuration as that used for the slip traction measurements. The method of testing however was in line with the rolling traction measurements except that a fixed amount of slip was introduced into the system and this was held constant during the duration of the test. The amount of slip was selected based upon the previous results from the slip traction experiments such that the operation occurred at the point of maximum slip traction or at a slip somewhat higher. In order to gather data on the wear of the LMM under traction the inter roller distance was monitored during each test.

The purpose of the endurance traction tests was to see how much traction can be transmitted on a continues basis through the material without failure of the rollers. The endurance traction test were only performed on the two materials that were thought most suitable for further analysis. These were materials d) and f).

3-3-1 RESULTS FROM THE ENDURANCE TESTS.

Typical endurance traction traces for materials d) and f) are shown in Fig. 3-13 to Fig. 3-23. These are for both the LMM in contact with steel and in contact with itself. The plot is very similar to that used for the rolling traction results with the exception of the first plot. This plot now shows the slip traction as a function of time. Also the test duration was shortened to 600 seconds because once the steady state had been reached the traces did not change for the remainder of the test.

The traces shown were selected on the basis that they show the very divergent behaviour that is typical of all the endurance traction tests. For example for the Phenolic on steel results (Fig 3-13 and 3-14) we see that the traction coefficient increases drastically as we go from 5 m/sec to 10 m/sec. At a yet higher load and higher speed (Fig 3-15) we notice however that the traction is initially high but then drops off as the test progresses. In Fig. 3-16 we see the peculiar two level traction behaviour of the LMM. The case shown is for a nominal elliptical contact, however it also did occur on the line contact configurations, see for example Fig. 3-19. The roller surface temperature has a similar double level to it because of the extra heat generated by the additional traction. The as calculated slip remained constant. It was thought that this behaviour may be caused by the initial layer of contaminant on the surface of the LMM. This however does not appear to be the case as may be seen from Fig. 3-21 to 3-23. With this experiment it was noticed that the onset of the traction rise occurred just at the end of the selected time period of the test. The test was continued under the same conditions but for a longer period of time, Fig 3-22. The traction kept on rising and headed towards to the new plateau. The temperature trace during this experiment was extremely erratic. In order to test the hypotheses of the initial contaminant on the rollers they were allowed to cool to room temperature during a waiting period. The next test, Fig 3-23. again at the same conditions shows that the same two level traction behaviour is still present. This seems to indicate that the two level traction behaviour is fundamental to the traction of LMM. The behaviour was more prevalent on the LMM in contact with LMM than in the tests of LMM in contact with steel.

The data from all the endurance traction experiments on the two materials is summarized in Appendix III. The slip traction and temperature indicated are those values that existed at the end of the test, and therefore not representative of the entire test curve. They merely indicate the value of the traction coefficient at that instant. The traction data in the appendix has been corrected for the bearing friction. Appendix IV contains the data on the inter roller measurements made to determine the wear rate of the material.

3-4 FAILURE MODES.

During all the tests performed the loads or speeds were increased until a physical failure of the roller occurred. These failures took on several forms and are given in Appendix V for each failure that was observed. The terminology used under the heading 'failure mode' is explained below. Figures 3-24 to 3-32 show photographs of some of these failure modes on the test specimen.

3-4-1 EXPLANATION OF FAILURE MODES.

Blistered, Thermal blistering: The formation of local high spots on the running surface of the specimen due to the excessive heat. Failure is detected by the rapid increase in the noise level during the test. The time between the onset of failure and the termination of the test was about 3 seconds, see Fig. 3-24.

Crushing: Sudden loss of structural strength of the material due to high loads or high temperature. No material was lost during this mode of failure, however the failure zone showed cracks in the material, see Fig. 3-25 and 3-26.

Delamination: Layer by layer of material were removed or worn away from the surface of the rollers. This mode of failure only occurred with the composite materials. The test were terminated either due to high wear or noise level, see Fig. 3-27.

Inc. Delamination: This is an early form of the Delamination mode of failure except that the noise level was high enough to warrant the termination of the test. Only local patches of material had been removed, see Fig. 3-28.

Spalling: Sudden removal of a section of material from the running surface very much like the spalling as observed in metallic rolling elements. The pit of the spall had typically a depth of 1/2 the track width. Failure was detected by a moderate increase in the noise, see Fig. 3-29 and 3-30.

Glazing: Highly polishing of the surfaces due to the differential slip velocity on the rollers. Hairline cracks, perpendicular to the rolling direction, could often be observed. Termination of test was determined by visual means. After glazing of the surfaces no real traction would develop.

Burning: Darkening of the entire roller surface in the contact track. Sometimes a light blue smoke would rise from the specimen. Termination of the test was based upon either smoke detection or rapid increase in the noise level. Some burning may be seen in Fig. 3-28.

Plastic flow: Gradual creep of the roller material to conform to the mating roller. Caused by high loads or high temperatures. This mode of failure was not catastrophic but did result in a dimensional change of the roller curvatures especially for the non conforming roller tests.

Subsurface melting: Thermal softening of the roller material due to subsurface hysteresis losses. Because of the low thermal conductivity of plastic this softening would result in a zone of liquid polymer melt below the surface that eventually would leak out through a crack that developed the the surface. Failure mode is very gradual with a sudden noise increase when the fluid melt breaks through to the surface of the roller and then resolidifies due to the colder environment. Figure 3-31 shows the onset of a failure due to subsurface melting while Figure 3-32 shows an advanced state of the same. The time elapsed between onset on gross failure was about 5 sec.

Gauged: Local removal of roller material due to adhesive wear; Occurred only with some slip traction test.

4-0 ANALYSIS OF THE ROLLING TRACTION RESULTS.

The primary objective of the rolling traction measurements were to obtain the material limits on the combination of speed,load and temperatures in the rolling contact mode. These were the first test results obtained and they are detailed in Appendix I. All these results are also plotted in Fig. 4-1 to 4-6. in the load versus speed fashion using logarithmic scales for both axes. This method of presenting the data is quite commonly used for the LMM wear characteristics, and leads to the establishment of the so-called PV (pressure-velocity) limits of the material combination. The crossed symbols in the figures indicate that the test at that combination of load and speed passed without failure of the rollers and that steady state operating conditions were obtained. The test load would be increased and the test repeated. An open symbol represents a failed test where the rollers showed some kind of surface damage.

From the figures 4-1 to 4-6 it may be observed that in many cases a simple imaginary straight line can be drawn through the failed /unfailed results. (note : the actual lines shown will be explained in the next section) The equation for such a line would be of the following form;

$$f(F_{zw},U) = F_{zw} \times U^n = \text{Constant} \qquad (4\text{-}1)$$

where n = power law coefficient

When n is unity then we do have indeed have the constant PV relationship. In our case however the coefficients n is generally not unity. For the two materials that will be used in the endurance traction testing the constants n and C are given in Table 4-1 below.

Material combination	C	n
Torlon-Torlon	795	.49
Torlon Steel	445	.40
Phenolic-Phenolic	2300	1.03
Phenolic-Steel	1225	.92

Table 4-1: Experimental constants for the PV equation.

In using equation (4-1) with these constant the correct units have to be used for both the variables in order to get the correct answer. Also it should be remembered that this equation is only valid at one ambient temperature, in this case about 25 °C. With the new model that will be developed below we hope to remove this restriction.

When sliding LMM on each other the product PV is directly related to the amount of power that is generated and hence the temperature that results from this. Here the temperature is controlled by the amount of natural convection that takes place. In the case of the rolling traction tests the actual amount that is taken away by convection and therefore the temperature rise will not be strictly proportional to the PV product.

The product of rolling speed and the rolling traction results in a certain amount of energy dissipation on the rollers. The energy is dissipated due to hysteresis losses in the roller material, so the source of heat due to this dissipation of energy is a certain distance below the surface of the rollers. The heat conducts to the surface and from there is convected away by virtue of the motion of the rollers. The resulting temperature may or may not influence the rolling traction coefficient but in general a stable operating temperature results for a given test condition. If no stable condition develops than generally the rollers fail due to thermal softening for the thermoplastics or else due to collapse in strength due to the temperature. The mechanism that determines to velocity - load limit is therefore one of heat generation and the resulting cooling due to the motion. Here we are dealing only with the heat due to the rolling traction but the argument applies equally well to a temperature rise due to any source of heat.

4-1 TEMPERATURE RISE DUE TO ROLLING FRICTION.

The amount of power that is dissipated due to the rolling traction is given by;

(4-2) $$W = U\,F_x \qquad [\mathrm{Nm/sec}]$$

Or in terms of the rolling traction coefficient μ_r this may be written as;

$$W = U\,\mu_r\,F_z$$

This is to be dissipated away and will lead to a temperature rise of the rollers. In general terms the roller temperature may be written as ;

(4-3) $$\theta = \theta_a + \frac{W}{\tilde{A}\,\tilde{h}} \qquad [^\circ\mathrm{C}]$$

where θ_a = ambient temperature [°C]
$\tilde{h}$ = heat transfer coefficient [N/m°Csec]
$\tilde{A}$ = convection area [m^2]

The heat transfer coefficient for the combination of rollers as used in the experiment is not known exactly, however we may take the expression as developed for single cylinders rotating in still air by Etemad [1955]. His experimental determination of the heat transfer coefficient led to the following expression;

(4-4) $$\frac{\tilde{h}\,D}{k} = .11\ [\ .5\ (\ R_{ew.}^{2} + G_r\ )\ P_r\ ]^{.35}$$

where : D = roller diameter [m]
k = thermal conductivity for air [N/°Cm²sec]
R_{ew}= roller Reynolds number [-]
G_r = Grashof number [-]
P_r = Prandtl number [-]

For the conditions prevailing in our tests the free convection term indicated by the magnitude of the Grashof number is very much smaller than the forced convection term. This will allow us to reduce equation (4-4) quite considerable. Also if we make the valid assumption that the properties of air are reasonable constant over the temperature range as observed, then equation (4-4) may be reduced to the following;

(4-5) $$\tilde{h} = .1311\ U^{.7}\ D^{-.3} \quad [\mathrm{N/m^{o}Csec}]$$

This is the heat transfer coefficient for a single cylinder rotating in dry air. In the experiment we had two cylinders in close contact so that the airflow around these would be quite different. We will however use (4-5) for lack of a better expression. The area of convection that is used in equation (4-3) could be taken as the banded area formed by the rolling contact. Also since we have two rollers in contact we should say;

(4-6) $$\tilde{A} = 2\pi w D \quad [\mathrm{m^2}]$$

where : w = effective width of the roller [m]

Substitution of equations (4-3), (4-5) and (4-6) into (4-2) and rearranging to obtain an expression for the rolling traction coefficient gives;

(4-7) $$\mu_r = .0506\ \frac{\theta - \theta_a}{F_{zw}}\ U^{-.3}$$

This expression directly relates the rolling traction coefficient to the temperature rise of the roller. There is however a problem here in that we only have the surface temperature of the roller and this, while being a direct indication of a local temperature, does not tell us much about the temperature distribution around the roller. It would be tied to the geometry of the rollers and the test configuration so that at least the trends of the temperature rise with load and speed should be correct for a given material combination. So if we plot the temperature rise against the contact load at constant velocity then we should be able to extract the rolling velocity from this plot. Note that the implicit assumption has been made that the rolling traction coefficient is not a function of the contact load, something that is reasonably true for most of the materials tested. Because of the uncertainty involved in the exact numerical value of the constant we may write equation (4-7) in a somewhat different way to test its validity by using the experimental results. This form relates the temperature rise above ambient to the contact load as follows;

$$\theta - \theta_a = A\, F_{zw}\, U^{.3} \quad [°C] \tag{4-8}$$
$$\text{where } A = \mu_r/.0506$$

The experimental data on temperature rise under various conditions of speed and load may now be used to obtain the experimental value for 'A'. Figures 4-7 to 4-12 show the results of the correlation of temperature rise as predicted by equation (4-8) and that actually measured in the experiments. The degree of correspondence is very good for most of the materials. Also indicated on the plots is the single constant 'A' that was derived from the correlation to tie all the data together.

Assuming that the roller surface temperature is tied to the rolling traction coefficient as indicated in equation (4-7) then we may calculate the actual rolling traction coefficient for the experiments. The results from such a calculation are shown in Table 4-2. Comparing the rolling traction coefficient thus obtained with the measured values as reported in Appendix I shows that the degree of correspondence is very good overall and extremely good for the unfilled Torlon. The possible explanation for this is that the internal heat dissipation for the unfilled torlon does indeed occur very close to the surface and so is the closest in its behaviour to the modelling that we have done here.

4-2 PREDICTION OF THE CONSTANT FAILURE TEMPERATURE.

With the above analysis it is now possible to test the validity of the constancy of the temperature at which the rollers tend to fail. This test is of course subject to all the assumptions that have gone into the derivation of the the equation that relates the temperature rise to the rolling friction coefficient. In fact in its simplest form we could say that it is constant for the particular roller material combination and this is not unreasonable for some of the materials. This could be extended to include even the combinations of LMM against LMM and against steel. The value for the rolling traction coefficient for this simple model of the temperature rise could be the mean value as indicated in Table 4-2. If we use this value then according to the hypothesis that the roller failures occurred at constant temperature it should be possible to plot a constant temperature line through the results. These lines were added to Fig. 4-1 to 4-4 by assuming that the failure load was half way between the failed and the next passed load, and by using equation (4-8) to obtain the predicted failure temperature rise. The rolling traction coefficient that was used is the mean coefficient as indicated in Table 4-2. A good prediction of the constant failure temperature would result in a straight line that would lie directly in between the passed and failed results, as for example is the case with Fig.4-4 . In examining the degree of fit for all the material combinations tested it may be said that the degree of adherence to the constant failure temperature hypothesis is fair for most materials and very good for some. It is most likely that a better adherence could have been obtained if the rolling traction coefficient would have been made speed dependent. From the calculations shown in Table 4-2 this is borne out. It must be kept in mind however that we are trying to establish simple equations for the calculation of the speed - load limits of these materials and that better predictability could only lead to more complexity in the calculation. Also for at least one of the materials (Torlon) the model predicts the failure limits very well indeed.

The failure temperature is calculated as the difference between ambient and the roller temperature. The actual temperature of the rollers is about 25 °C higher because of the ambient conditions and the heating due to the thermocouple.

RESULTS FROM THE ROLLING TRACTION ANALYSIS OF LOW MODULUS MATERIALS				
Torlon-Torlon	U=10.0	dT/dFz= .20	Reg.Coeff= .979	Muroll=.0025
Torlon-Torlon	U=20.0	dT/dFz= .24	Reg.Coeff= .974	Muroll=.0025
Torlon-Torlon	U=30.0	dT/dFz= .25	Reg.Coeff= .980	Muroll=.0023
Torlon-Steel	U=20.0	dT/dFz= .25	Reg.Coeff= .955	Muroll=.0025
Torlon-Steel	U=30.0	dT/dFz= .28	Reg.Coeff= .925	Muroll=.0026
Mean value for Mur=.0025				
Phenolic-Phenolic	U=10.0	dT/dFz= .61	Reg.Coeff= .999	Muroll=.0078
Phenolic-Phenolic	U=20.0	dT/dFz= .60	Reg.Coeff= .982	Muroll=.0062
Phenolic-Steel	U=10.0	dT/dFz= .36	Reg.Coeff= .849	Muroll=.0045
Phenolic-Steel	U=10.0	dT/dFz= .52	Reg.Coeff= .997	Muroll=.0066
Phenolic-Steel	U=20.0	dT/dFz= .82	Reg.Coeff= .980	Muroll=.0084
Phenolic-Steel	U=30.0	dT/dFz= .55	Reg.Coeff= .910	Muroll=.0050
Mean value for Mur=.0065				
Nylon-Nylon	U=10.0	dT/dFz= 1.31	Reg.Coeff= .989	Muroll=.0167
Nylon-Nylon	U=20.0	dT/dFz= 2.35	Reg.Coeff= .975	Muroll=.0242
Nylon-Nylon	U=30.0	dT/dFz= 2.08	Reg.Coeff=1.000	Muroll=.0189
Nylon-Steel	U=10.0	dT/dFz= 1.21	Reg.Coeff= .926	Muroll=.0153
Nylon-Steel	U=20.0	dT/dFz= 1.40	Reg.Coeff=1.000	Muroll=.0144
Nylon-Steel	U=30.0	dT/dFz= 2.47	Reg.Coeff= .871	Muroll=.0225
Mean value for Mur=.0186				
Acetal-Acetal	U=10.0	dT/dFz= 1.02	Reg.Coeff= .950	Muroll=.0129
Acetal-Acetal	U=20.0	dT/dFz= 1.10	Reg.Coeff=1.000	Muroll=.0113
Acetal-Acetal	U=30.0	dT/dFz= 3.89	Reg.Coeff= .998	Muroll=.0355
Acetal-Steel	U=10.0	dT/dFz= .52	Reg.Coeff= .980	Muroll=.0066
Acetal-Steel	U=20.0	dT/dFz= .90	Reg.Coeff=1.000	Muroll=.0093
Acetal-Steel	U=30.0	dT/dFz= .70	Reg.Coeff= .998	Muroll=.0064
Mean value for Mur=.0137				
Mononylon-Mononylon	U=10.0	dT/dFz= 2.46	Reg.Coeff= .982	Muroll=.0312
Mononylon-Steel	U=10.0	dT/dFz= 1.52	Reg.Coeff= .969	Muroll=.0193
Mononylon-Steel	U=20.0	dT/dFz= 1.40	Reg.Coeff=1.000	Muroll=.0144
Mean value for Mur=.0216				
FTorlon-FTorlon	U=10.0	dT/dFz= .64	Reg.Coeff= .979	Muroll=.0081
FTorlon-FTorlon	U=20.0	dT/dFz= .99	Reg.Coeff= .951	Muroll=.0102
FTorlon-FTorlon	U=30.0	dT/dFz= 1.30	Reg.Coeff= .969	Muroll=.0119
FTorlon-Steel	U=10.0	dT/dFz= .62	Reg.Coeff= .961	Muroll=.0079
FTorlon-Steel	U=10.0	dT/dFz= .53	Reg.Coeff= .993	Muroll=.0067
FTorlon-Steel	U=20.0	dT/dFz= .78	Reg.Coeff= .985	Muroll=.0080
FTorlon-Steel	U=30.0	dT/dFz= 1.08	Reg.Coeff= .870	Muroll=.0098
Mean value for Mur=.0089				

Table 4-2: Summary of the rolling traction coefficient analysis for the various roller combinations.

5-0 ANALYSIS OF THE SLIP TRACTION RESULTS.

In order to understand the required analysis of the experimental slip traction data it will be helpful to consider the following discussion of traction. This discussion is based upon the traction behaviour of steel rollers in contact with a film of oil trapped in between the rollers and subjected to the high contact pressure. The influence of pressure on the fluid in the contact is one of solidification, in other words the fluid behaves like a solid under conditions of shear. The degree of solidification depends entirely upon the contact pressure and the fluid itself. Generally however the shear response of the fluid is found to be solid like in nature when the effective viscosity of the material in the contact has reached about .1 MPa.s . This corresponds to about the viscosity of low density polyethylene at 100 °C and at atmospheric pressure, see for example Meissner [1963]. This material is about the lowest density for LMM and generally the higher density materials have higher corresponding viscosities. It may therefore be expected that all the LMM investigated here well exceed the viscosity that is normally considered to be the minimum for solid like behaviour for traction purposes. The influence of pressure on the viscosity will no doubt increase the viscosity of the material in the contact, however the actual pressures reached in the contact of LMM rollers is much less than that for steel rollers in contact so this effect is expected to be minimal. Based upon the viscosity concept the traction behaviour of LMM should therefore be similar to that for liquid lubricated contacts with the exception that we will most likely not be able to observe any Newtonian behaviour under the current experimental conditions.

5-1 TRACTION IN HERTZIAN CONTACTS.

The ability of a material, trapped under pressure in the elastically deformed region of two loaded curved elements, to transmit a tangential force from one element to the other, is commonly referred to as friction or traction. The magnitude of this force depends on several variables such as :1) the contact kinematic conditions of slip, spin and sideslip, 2)the material present, 3) temperature, pressure and operating speeds. Here we will examine the traction behaviour under simple slip only.

Under conditions of increasing slip between the two elements an increasing traction force is transmitted up to a certain limit at which point it will decrease with further slip. See Fig. 5-1

There are three regions identified on this traction curve and the behaviour in each of these regions can best be described by the Deborah number. For a simple Maxwell viscoelastic model this number is the ratio of the relaxation time and the mean transit time, see Johnson and Tevaarwerk [1977].

(A) The linear low slip region. Thought to be isothermal in nature, it is caused by the shearing of a linear viscous fluid (low De) or that of a linear elastic solid (high De). For the LMM tested here this region is expected to be elastic.

(B) The nonlinear region. Still isothermal in nature but now the viscous element responds nonlinearly. At low De this portion of the traction curve can be described by a suitable nonlinear viscous function alone, while at high De a linear elastic element interacts with the nonlinear viscous element.

(C) At yet higher values of slip the traction decreases with increasing slip and it is no longer possible to ignore the dissipative shearing and the heat that it generates in the film. Johnson and Cameron [1967] showed that the shear plane hypothesis advanced by Smith [1965] does account for most of their experimental observations in this region. More recently Conry et al [1979] and Tevaarwerk [1983] have shown that a nonlinear viscous element together with a simple thermal correction can also describe this region.

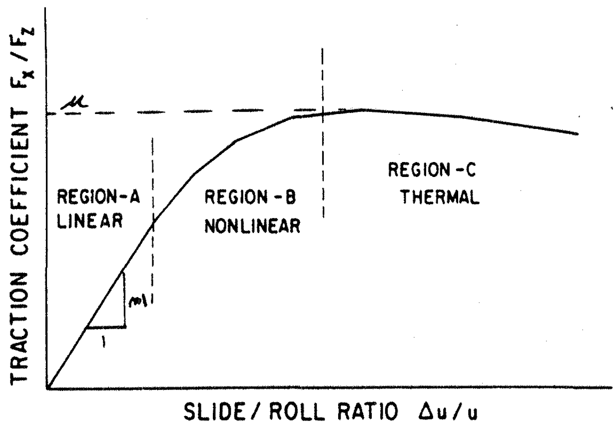


Fig. 5-1 Typical slip traction curve for liquid lubricated contact.

5-2 ISOTHERMAL SLIP TRACTION ANALYSIS.

The rheological model that describes the traction under simple slip in the three regions of operation fairly well is the traction model as developed by Johnson and Tevaarwerk [1977];

$$(5\text{-}1) \qquad \frac{1}{G}\frac{d\tau}{dt} + F(\tau) = \dot{\gamma}$$

The dissipative function $F(\tau)$ is open to the choice of the researcher to fit the observed traction but Johnson and Tevaarwerk [1977] found that the hyperbolic sine;

$$(5\text{-}2) \qquad F(\tau) = \frac{\tau_s}{\eta} \sinh\,(\tau/\tau_s)$$

described all of their experimental results in regions (A) and (B) very well. At higher pressures and for materials with high traction coefficients this dissipative function may be replaced by the purely plastic behaviour of the material;

$$(5\text{-}3) \qquad F(\tau) = 0 \text{ for } \tau < \tau_c \ ; \ F(\tau) = \dot{\gamma} \text{ for } \tau = \tau_c$$

Whether the perfectly plastic behaviour of the material is intrinsic is not clear.

Recent work by Johnson and Greenwood [1980] suggests that it is possibly the result of thermal behaviour of the sinh model, however for many applications the elastic/plastic form of the J&T model is adequate and certainly for the traction of LMM it is expected to be adequate.

5-2-1 VARIATION OF THE RHEOLOGICAL PROPERTIES.

The slip traction of the material under shear may be obtained by solving for the local shear stress using equation (5-1) and than integrating these stresses over the contact area. Before this is possible however something should be said about the variation of the properties with pressure and temperature in the contact.

The shear modulus G as used in equation (5-1) reflects the elastic response of the material in the contact zone to the application of strain. This strain is reasonably local to the contact area but it does extend down into the material for a certain distance. The stress resulting from this strain is therefore governed by the elastic properties of the bulk material and the contact material properties itself. In the case of lubricated contacts the shear stiffness of the film will therefore only contribute a portion to the actual initial small strain response. For the unlubricated contact, as we are dealing with here, it is only the substrate material that is strained. This means that the shear modulus should be taken as that for the substrate. Hence we may write;

(5-4) $$G = G_S$$

The value of G_S may be calculated from the initial traction region slope 'm' through the following expression;

(5-5) $$G_S = \frac{\pi}{4} m\, q\, P_o$$

where q = shape coefficient = h/a
h = nominal depth of the strain influence region
a = semi contact dimension in the rolling direction.

The depth of the strain influence region is given the symbol h here because when dealing with lubricated contacts it is taken to be the thickness of the central film in the contact. The shape factor is sometimes referred to as the Kalker coefficient and are given in Kalker [1967]. There is a slight influence of the contact aspect ratio on the shape factor.

The variation of the limiting shear strength of the material over the contact area is more governed by the conditions at the interface between the rollers, so we might expect a somewhat different behaviour. From the results presented in Chapter 3 it seems that to a very reasonable degree the large slip region on the traction curves behaves in an isothermal manner. That is to say that the traction does not decay rapidly with increasing slip. This is not necessarily an indication that the temperature of the rollers is constant in this region, but rather that the limiting shear strength is not greatly influenced by the increasing temperature. It should therefore be possible to be able to analyze the traction results on the basis of an isothermal properties within the contact. Similarly from the traction results it is seen that the peak traction coefficient increases with increasing contact load. As will be seen later on this increase is not quite proportional to the contact pressure but neither is it independent of the pressure. For the analysis of the results and the calculation of the slip traction curves we will assume however that the limiting shear strength of the material in the contact is proportional to the contact pressure. We may therefore write the following;

$$\tau_c = \mu \, P_o \sqrt{1 - X^2 - Y^2} \tag{5-6}$$

where μ = peak traction coefficient $(F_X/F_Z)_{max}$

5-2-2 SLIP TRACTION EQUATION.

In order to solve for the slip traction equation we shall use (5-1) and (5-3) as our starting points, that is we will use the elastic plastic form of the Jonhson and Tevaarwerk model. Also we will use (5-5) and (5-6) as the variation of the modulus and the limiting shear strength over the area of the contact. This very same form was used by Tevaarwerk and Johnson [1979] and Tevaarwerk [1979] to predict fluid traction under various conditions of slip and spin. For longitudinal slip only the traction can be calculated analytically and it is given by;

$$\frac{F_X}{\mu \, F_Z} = \frac{2}{\pi} \left[\tan^{-1} S + \frac{S}{(1 + S^2)} \right] \tag{5-7}$$

where $S = \dfrac{\pi}{4} \dfrac{m}{\mu} \dfrac{\Delta U}{U}$

This expression is completely independent of the contact aspect ratio and is therefore equally valid for elliptical as well as line contacts. In the case of line contacts it may be better to use the load per unit length rather than the contact load itself, but this will not alter the form or the result of the equation. Also the expression is valid for the conditions where a contact is under side slip and combinations of side slip and longitudinal slip.

It is also possible to perform the integration under the assumption that the limiting shear strength is constant over the contact area, see Tevaarwerk [1976].

The solution for that model is as follows;

$$(5\text{-}8a) \quad \text{for } S \leqslant \frac{1}{3} \qquad \frac{F_x}{\mu\, F_z} = \frac{4}{\pi} S$$

and

$$(5\text{-}8b) \quad \text{for } S \geqslant \frac{1}{3} \qquad \frac{F_x}{\mu\, F_z} = \frac{1}{3\pi} [\ 12S + 6H - 4\tan(H) - \sin(2H)\ ]$$

where $H = \cos^{-1}(1/3S)$

To see the influence on the traction for the two different distributions of the limiting shear strength equations (5-7) and (5-8a,b) are plotted in Fig. 5-2 below.

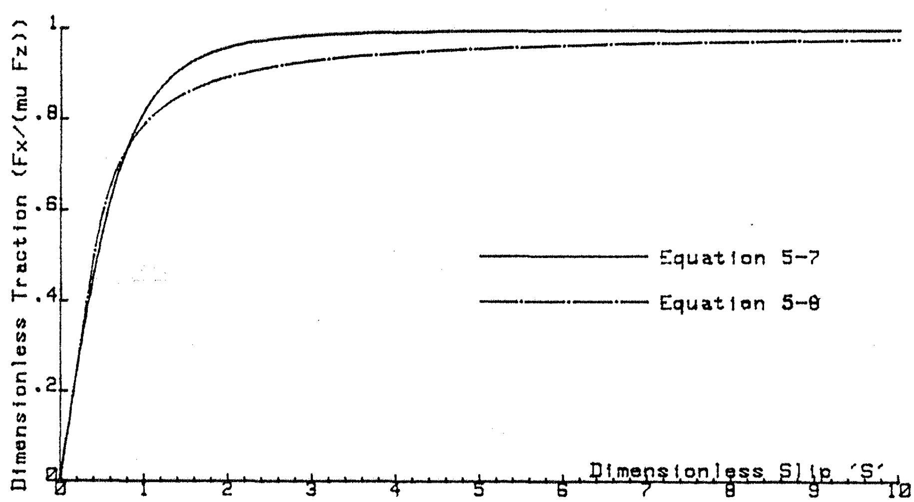


Fig. 5-2: Comparison between the traction behaviour of equation (5-7) and (5-8).

As may be observed from this figure there are small but subtle differences in the slip traction behaviour of the two models. The most observable one is the fact that the increase in traction with increasing slip is much slower for equation (5-8) than for (5-7). This appears to correspond somewhat better with the result that were obtained experimentally. However the drawback of equation (5-8) is that it demands no influence of contact pressure on any of the properties in the contact. This does not correspond to the observed influence of contact load on the traction coefficient for example which is certainly increasing with load for some of the materials tested. The real traction behaviour probably lies somewhere in between that indicated by the two equations.

5-3 COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS.

In the summary of the slip traction data in Appendix II the traction data was reduced to just two parameters. These were the initial traction slope 'm' and the peak traction coefficient 'μ' and they are indicated in the fourth and third last columns under the heading 'calculated'. Calculated here means that the results were obtained by a simple arithmetic technique in the data reduction program. This is without regard to any particular traction model that we may wish to examine the results against for their overall behaviour with increasing slip.

In order to measure the performance of the traction models against the experimental data an interactive fitting technique was used whereby the experimental data was superimposed on the theoretical traction curve. A 'good fit' value for the slope 'm' and peak traction coefficient 'μ' may then be found. This procedure was followed for all the traction results on the materials. For the theoretical slip traction prediction the constant modulus but pressure dependent limiting shear strength model according to equation (5-7) was used. The resulting initial traction slope and the peak traction coefficient thus obtained are given in Appendix II in the last two columns. A comparison between the predicted and the experimental data for the LMM against steel results is shown in Fig. 5-3 to 5-8. Overall the degree of fit of the results is very good over a very broad range of slip ,speed and contact normal load. There is some deviation in the slip range where the two traction models differ the most, that is in the $1<S<3$ range for the dimensionless slip. This is the region that is strongly influenced by the distribution of the limiting shear strength over the contact area. The results tend to indicate that a somewhat less dependence of the limiting shear strength on pressure would give a better fit. As we will see however in the next two sections the dependence of the limiting shear strength on the contact pressure is neither directly proportional nor is it totally independent, so the degree of fit on the basis of constant shear strength over the contact area would have yielded about the same result.

5-4 VARIATION OF SLOPE WITH PEAK TRACTION COEFFICIENT.

An examination of the results in Appendix II shows that there appears to be a strong correlation between the fitted traction slope 'm' and the peak traction coefficient 'μ'. This is perhaps not surprising in view of the fact that both the interface properties and the substrate properties are for one and the same material. The influence of temperature might be expected to be the same on both of these. It was decided that a simple correlation of the traction slope on the basis of the peak traction coefficient would be performed. This was done for the results from the fitted traction experiments and only for the LMM that were used in the endurance traction test. Similar correlations could be performed on the other results and they would give similar results. The correlations that were found to be the best were of the following form;

(5-9) $$m = c + d\mu$$

where c,d experimental constants

in other words simple linear correlations. Comparison of the experimental results and the correlation are shown in Fig. 5-9 and 5-10 for both LMM against steel and against itself. The data for both types of tests were combined. There appears to be a definite correlation between the two parameters but it is not a simple proportional dependence in either case. This would tend to show that the influence of contact load is different on the two traction properties.

5-5 VARIATION OF TRACTION COEFFICIENT WITH CONTACT LOAD.

In order to examine the influence of contact pressure and contact load in somewhat more detail the traction data as obtained in the endurance traction test will be analyzed now. The reason that the endurance traction results are selected for this purpose is that they are definitely more isothermal in nature than the slip traction test results. As was already mentioned in Chapter 3, there is a peculiar transition in the traction coefficient with temperature. This is true for both the Phenolic and Torlon traction results, and is more pronounced with the LMM on LMM traction results. We will therefore only use the LMM on steel traction results in this analysis. Also it is clear from the summary on the traction results that this combination has a higher traction capacity than the LMM on LMM combination.

The Hertz pressure in a line contact varies with load as follows;

$$(5\text{-}10) \qquad Po = \sqrt{\frac{E' \; F_{zw}}{2 \pi R_e}}$$

where E' = composite elastic modulus of the rollers [Pa]
F_{zw} = load per unit length (F_z/w) [N/m]
R_e = equivalent radius of the rollers [m]
w = contact width [m]

The variation of the contact area with increasing load is the same as that for pressure. Now if we take the limiting shear strength to be independent of the contact pressure than it follows that the traction coefficient should decrease with increasing contact load. The exact variation for this condition should be as follows;

$$(5\text{-}11) \qquad \mu = \frac{F_x}{F_z} = \frac{2aw\tau_c}{F_z} = \frac{k\sqrt{F_{zw}}}{F_{zw}} = k/\sqrt{F_{zw}}$$

where k = proportionality constant

A similar argument could be invoked if the contact were one formed by general curved rollers with the exception that the variation would be to the -1/3 power on load.

If it is assumed that the limiting shear stress varies directly as the contact pressure then it follows that for line contacts;

$$(5\text{-}12) \qquad \mu = \frac{F_X}{F_{ZW}} = k'$$

where k' would be independent of load. The same would be true for elliptical contacts. In summary we may correlate the peak traction coefficient with the following expression;

$$(5\text{-}13) \qquad \mu = K\ (F_{ZW})^n$$

where the following observations on 'n' apply,

1) for the case where the limiting shear strength is independent of the contact pressure,
   $n = -.5$ for the line contact case
   $n = -.33$ for the elliptical contact case

2) for the case where the limiting shear strength is directly proportional to the contact pressure,
   $n = 0$ for both line contact and elliptical contact.

3) for the case where the limiting shear strength increases more rapidly than the contact pressure,
   n = positive for both cases on contact shape.

The traction coefficient as measured during the endurance traction test were plotted as $\log(F_{ZW})$ against $\log(\mu)$ for all the tests performed on Torlon against steel and Phenolic against steel. The traction coefficients for Phenolic were found to be speed dependent in a very predictable manner and decreased with increasing speed. This is perhaps caused by the viscoelastic nature of the material. The Torlon results were found to be speed independant. See Fig. 5-11 and 5-12. There were some data points that were excluded from the analysis as indicated. These were the freshly installed rollers for the Phenolic - Steel test and one very low contact load series from the Torlon - Steel results. As may be observed from the correlation equation on Figures 5-11 and 5-12 the exponent 'n' on this equation is about -.25 . This would tend to indicate that there is some influence of contact pressure on the limiting shear strength of the LMM but not as much as a direct proportionality. This same observation may be made from some traction results taken by Bauerfeind [1966].

It is possible that in assuming E' independent of the contact load we may have made an error. A general softening of the modulus E' with load would have resulted in the same final observation.

6-0 ANALYSIS OF THE ENDURANCE TRACTION RESULTS.

The results from the traction endurance tests as outlined and presented in Chapter 3 are plotted in the same fashion as the rolling traction speed - load test results, see Fig 6-1 and 6-2 . Added to these plots are the PV lines according to equation (4-1) and the constants given in Table 4-1.

Observation of these results shows that the slip traction generally reduces the speed - load limits for the material combinations, especially the LMM against LMM combinations. For the LMM against steel combinations there is a much lesser effect of the slip traction for the Phenolic - Steel combination, and for the Torlon - Steel it appears that the influence of traction actually increases the speed - load limit. This is of course highly unlikely and the reason for the apparent contradiction lies in the fact that the PV limit as obtained from the rolling traction data is tied to a given ambient temperature. The ambient temperature conditions for the endurance traction test was on average a good 20 °C less than that for the rolling traction tests.

A more plausible explanation for the influence of slip traction on the load - speed limits may be found from the thermal analysis of the test data.

6-1 TEMPERATURE ANALYSIS OF ENDURANCE TRACTION RESULTS.

The constant temperature failure hypothesis for the load speed limits as developed and tested against the rolling traction results will be extended here to include the effects of slip traction. The amount of power that is dissipated due to the rolling and slip traction is given by;

(6-1) $$W = (\mu_r + \xi \mu_s)\, U\, F_z \qquad [\text{Nm/sec}]$$

where : μ_r = rolling traction coefficient [-]
μ_s = slip traction coefficient [-]
U = rolling velocity [m/sec]
F_z = total contact normal load [N]
ξ = the slide to roll ratio [-]

This is to be dissipated away and will lead to a temperature rise of the rollers. In this case there are two sources of heat and they generate a temperature in two different locations. The rolling traction component generates heat at a certain distance below the surface. This heat then conducts to the surface and from there is convected away by the surrounding air. In the case of the LMM on LMM the amount generated is the same for each roller. For the LMM in contact with steel all the heat is generated in the one roller and then some of this may conduct into the steel roller.

The slip traction component on the other hand generates the heat at the interface between the two rollers. At the contact site this heat conducts into the surface and then convects away to the surrounding air. In the case of the LMM in contact with LMM the amount of heat that will conduct into each surface will be about half of the heat generated due to the slip traction. For the LMM in contact with the steel roller however there will be disproportional amount of heat going into the steel surface because of its superior thermal properties relative to the LMM roller.

6-1-1 HEAT EQUIPARTITION.

In general the surface temperature rise for a given roller may be written as ;

$$\theta = \theta_a + \frac{W\,J}{\tilde{A}\,\tilde{h}} \qquad [^\circ C] \tag{6-2}$$

where θ_a = ambient temperature. [°C]
$\tilde{h}$ = heat transfer coefficient [N/m°Csec]
$\tilde{A}$ = convection area [m²]
J = fraction of the total heat generated. [-]

The value of J may be calculated from the equipartition rule based upon the ratio of the thermal diffusivity. This rule may be stated as follows;

$$J_1 = \frac{(k/C\rho)_1}{(k/C\rho)_1 + (k/C\rho)_2} \tag{6-3}$$

where : $(k/C\rho)_1$ = thermal diffusivity of roller #1
$(k/C\rho)_2$ = thermal diffusivity of roller #2

The fraction of heat into the second surface is then calculated by a simple rotation of the subscripts in equation (6-3).

When both rollers are identical then J=.5 and the same amount of heat goes into each surface. For the case of the LMM in contact with the steel roller the value of J is very close to unity for the steel roller and zero for the LMM roller. The exact values are subject to the various thermal values that may be found for the materials involved. By using the variously published data on the thermal properties of LMM one finds that $.98<J<1.0$. Hence for all practical purposes it may be assumed that the steel roller absorbs all the slip traction heat and that the LMM roller only needs to convect the heat generated due to rolling traction.

The heat transfer coefficient for either the steel or the LMM roller is still expected to be given by equation (4-5);

$$\tilde{h} = .1311\, U^{.7}\, D^{-.3} \qquad [N/m^\circ C sec] \tag{4-5}$$

however the area involved in convection of the heat is expected to be very much different for the steel roller than for the LMM roller. This results from the fact that the thermal conductivity for steel is so high compared to that for LMM and the heat transfer coefficient. The exact area however is difficult to establish as well as the exact heat transfer coefficient because of the shape of the rollers. They resemble discs more closely rather than the long cylinders that equation (4-5) was based upon.

6-2-2 TEMPERATURE OF THE ROLLER SURFACE.

One method that may be used to circumvent the difficulties involved with establishing the exact area for the heat transfer and the equipartition fraction is to set up an equation that is based upon above formulated concept, but that uses some experimentally determined constants. Such an equation may be derived by combining equations (6-1), (6-2) and (4-5) as follows;

$$\theta - \theta_a = (A F_{zw} + B \mu_s F_z \gamma) U^{.3} \quad [^\circ C] \tag{6-4}$$

where A = rolling traction coefficient
B = thermal resistance for slip traction heat

The values for the rolling traction coefficient were determined in Chapter 4, so it remains to find the values for B. These may be obtained by fitting the actual measured temperature difference between the roller surface and ambient to equation (6-4). The results from this type of a correlation are shown in Fig. 6-3 to 6-6 for the two materials that were used in the endurance tests. The degree of fit is very good for most of the experimental results and the values of B, shown in Table 6-1 below, correspond roughly to what would have been expected.

Roller combination	"B"
Torlon-Torlon	20
Phenolic-Phenolic	12.5
Torlon-Steel	2.3
Phenolic-Steel	2.3

Table 6-1 : Values of the constant 'B' from the experimental data on the material combinations.

With these constants it should now be possible to predict the roller temperature under any combination of load, speed and slip so that the failure hypothesis can be tested under conditions of slip traction.

It is interesting to note that about 5 to 9 times more heat goes into the LMM rollers when they are in contact with each other than when in contact with the steel roller. In fact it might be instructive to look at the ratio of the heat contributed due to rolling traction and due to the slip traction.

6-2-3 ROLLER HEAT LOADS.

The ratio of the amount of heat to be convected away from the rollers due to rolling traction and that due to the slip traction will be calculated here. From equation (6-4) it follows that this is given by;

$$X = (B/A)\ \mu_s\ \gamma\ w \tag{6-5}$$

This may be calculated as a function of the product $\mu_s \gamma w$ for the various material combinations tested here. Typical values for this variable grouping range from .02 to .05 for the experiments conducted here. In a practical situation the slide to roll ratio would not be higher than 1%, so we could expect values of about .005 to .015 for this grouping. Table 6-2 below shows the magnitude of X for these typical values of the slip group,

Roller combination	(B/A)		Value of the slip group $\mu_S \xi w$		
		Normal operation		Test range	
		.005	.015	.02	.05
Torlon - Torlon	204	X = 1	3	4	10
Phenolic - Phenolic	48	X = .25	.75	1	2.5
Torlon - Steel	23	X = .11	.35	.5	1.2
Phenolic - Steel	9	X = .05	.14	.2	.5

Table 6-2: Typical ratios of the heat into the LMM due to the slip and rolling traction.

This table clearly shows that under normal operating conditions, that is in the linear region of the slip traction curve, the largest amount of heat convected from the LMM roller is generated due to the rolling traction component. For the two LMM - Steel combinations only about 10 % of the heat results from the slip traction. In the real case this may even be less because the initial linear region on the traction curve is mostly elastic in its response and so the amount of slip heat will be less than the simple product of traction and slip velocity.

6-3 ROLLER SURFACE TEMPERATURE CALCULATION.

By using equation (6-4) it is now possible to calculate the roller surface temperature for the various conditions of rolling speeds and slip. This calculation may then reveal whether there is any constant temperature that may be used in the calculations to determine the load - speed limits for the material.

Figure 6-7 shows the roller temperature as calculated due to the rolling and slip traction for the LMM on steel combination. For the slip traction coefficient μ_S the values as calculated by equation (5-13), with the values as shown in Fig 5-11 and 5-12. It is clear from these results that there indeed appears to be an upper limit to the temperature above which failures will take place. This seems to be more clearly defined for the Torlon than for the Phenolic test case. It should be pointed out that the type of failures with the Torlon were very distinct and sudden, while the Phenolic failures were more subject to human judgement and therefore might show a bit more randomness. Also the rolling friction coefficient for Torlon corresponded much better to the model than did the Phenolic results.

In view of the lower amount of thermal loading when using these materials in the proper operating range of the traction curve it is tempting to make the failure prediction simply on the basis of the rolling traction component only. These results are shown in Fig. 6-8 and it is seen that the order of the results has not really been altered. This failure temperature calculation however would only predict the type of failures as observed under the conditions of rolling traction only.

7-0 THE WEAR OF LMM UNDER TRACTION.

During the endurance testing of the LMM material combinations the wear of the rollers was measured as explained in 2-3-5. This method of wear measurement was found to be of limited value because of the thermal expansion coefficients of the roller material. It was found that quite often the wear of the rollers was negative when determined by this method, see Appendix IV.

In order to get a measure of the wear that is encountered when transmitting traction accross the LMM roller combinations it was decided to measure the roller diameter before and after the total experimental tests on the rollers and then to use these results, together with a wear model, to obtain some indication of the wear rates on LMM.

7-1 WEAR MODEL FOR LMM ROLLERS.

The type of wear that will be considered here as acceptable wear is termed 'mild' or 'continues' wear. This then excludes all the other forms of wear such as galling, pitting, plastic flow and fatigue. In this investigation we have termed those forms of wear as failures because they tended to make the rollers inoperative. Mild or continues wear on polymers is thought to take place by the so called 'roll formation' process. In this process a rolling-up of the surface material takes place due to the traction and the interface slip. Eventually, after enough rolling of the fragment has taken place, it will tear away from the surface and cause a weight loss to the specimen. In cases where the wear due to this form of debris formation is high, it should in theory at least influence the traction or frictional aspects of the polymers.

It is clear that the mild wear is in fact a very inefficient form of machining of the surfaces and it should therefore be dependent on the interface power dissipation. In other words the total wear that is encountered on the rollers should be a function of the total frictional work that has gone into the surface. To be sure only a fraction of this work will go into the removal process, with the rest being dissipated as heat. We could therefore formulate a so called 'energetic' wear rate for the LMM.

The energetic wear rate may be calculated from the following;

$$K_e = \frac{\text{Volume of material removed}}{\text{Work of friction}} = \frac{V_{or}}{F_x\, L} \qquad (7\text{-}1)$$

This parameter is sometimes used as a measure of the efficiency of a cutting operation. When dealing with abrasive wear of surfaces it is sometimes referred to as the abradibility. The reciprical of K_e is then called the coefficient of abrasion resistance. The energetic wear rate K_e for the LMM endurance test may be calculated by evaluating the individual terms in the expression. The volume of material removed is calculated from the following;

(7-2) $$V_{or} = \pi w [Ri^2 - Rf^2] \qquad [m^3]$$

where : w = width of the wear track [m]
Ri= initial radius of the roller at wear zone [m]
Rf= final radius of the roller wear zone [m]

when both the top and bottom rollers are involved in the wear process then the sum of the wear volume of both of them should be taken. The work of friction is given by the inefficiency in the traction process and may be calculated from;

(7-3) $$F_x L = \mu_s F_z U \gamma t \qquad [Nm]$$

where : μs = slip traction coefficient [-]
Fz = total contact load [N]
U = rolling velocity [m/sec]
γ = slide to roll ratio [-]
t = duration of the test [sec]

Since the individual wear measurements taken during the endurance tests suffer from the thermal expansion of the rollers, we can only use the total wear volume and the total frictional work into the roller to evaluate the energetic wear rate. This assumes that K_e is independent of speed, surface temperature and load, something which is very unlikely. This means that the values of K_e thus calculated will be averages for a number of test conditions. In some cases the test duration was on the order of 2-3 hours while in others it was only 20 minutes before failure occurred. The range of K_e obtained from the various experiments will help in selecting an appropriate wear rate factor for a given design.

7-2 EXPERIMENTAL ENERGETIC WEAR RATES.

The total wear volume and the total frictional work was calculated for each of the endurance experiments as carried out. The summary results of these experiments are given in Appendix III. The resulting wear volume and frictional work into the rollers for each of these, together with the calculated values for K_e are given in Table 7-1 below.
The results from this table clearly show the influence that test time can have on the determination of K_e with a variation by a factor of 5 for the LMM-Steel results. Also the influence of the mating roller can clearly be observed. The higher wear rates with the LMM in contact with LMM is expected on the basis of the higher interface temperatures of the combinations.

Roller combination --- ---	Test duration [sec]	V_{or} [mm3]	Frict. Work [MNm]	K_e [mm^3/MNm]
Torlon - Steel	13784	39.6	.51	77
Torlon - Steel	1038	13.0	.03	410
Torlon - Steel	1285	10.6	.03	399
Torlon - Torlon	4290	62.2	.09	717
Torlon - Torlon	4778	67.7	.09	754
Phenolic - Steel	5963	28.1	.26	106
Phenolic - Steel	1308	37.7	.04	948
Phenolic - Steel	1765	32.7	.07	479
Phenolic - Steel	1800	51.0	.05	1020
Phenolic - Steel	1523	48.4	.04	1305
Phenolic - Phenolic	2400	118.2	.04	3314
Phenolic - Phenolic	745	53.7	.01	5994
Phenolic - Phenolic	1345	89.5	.02	5008

Table 7-1: The wear volumes and frictional work for the various material combinations tested under endurance conditions.

7-3 ENERGETIC WEAR RATES FOR INITIAL DESIGN.

It is probably satisfactory from an initial design point of view to use the lowest values of K_e since they were obtained under more variable load conditions, like the ones that would be expected in a real application. In the determination of the energetic wear rate for these specimen it may have been that not all of the material was in fact worn away. Some of it may simply have been displaced sideways due to initial plastic flow. This could have been determined simply by weighing the specimen before and after the tests , however in some cases there was some material loss due to the failure itself.

To calculate the wear of the LMM roller combination under a given variable load and speed condition we simply could write the following;

$$V_{or} = K_e \int F_x \; U \; dt \qquad (7\text{-}4)$$

This will give a very reasonable indication of the maximum wear that will take place for a given set of rollers. The actual wear will almost certainly be less because of the more favourable conditions in the actual operation than those that were used in the endurance tests.

For the determination of more precise wear, a specific test procedure using constant load, speed and temperature should be used.

8-0 REFERENCES

Bauerfeind, E., "Untersuchungen an Zylindrischen Gummywaelzreadern". Doctoral Thesis of the University of Braunschweig, (1966).

Conry,T.F., Johnson,K.L. and Owen,S. "Viscosity in the Thermal Regime of Traction". Proc. of the Leeds-Lyon Conference, Lyon 1979, Paper VIII (i).

Etemad,G.A., "Free Convection Heat Transfer From a Rotating Horizontal Cylinder to Ambient Air with Interferometric Study of Flow". Trans. A.S.M.E , Nov (1955), pp. 1283-1289.

Flom,D.G., "Rolling Friction of Polymeric Material. I. Elastomers". Journal of Applied Physics, 31 , #2, (1960), pp. 306-314.

Flom,D.G. and Bueche,A.M., "Theory of Rolling Friction for Spheres". Journal of Applied Physics, 30 , #11, (1959), pp. 1725-1730.

Greenwood,J.A. and Tabor,D., "The Friction of Hard Sliders on Lubricated Rubber: The Importance of Deformation Losses". Proc. Phys. Soc., 71 , (1957), pp. 989-1001.

Greenwood,J.A., Minshall,H. and Tabor,D., "Hysteresis losses in rolling and sliding friction". Proc. Roy. Soc. (London), Series A, 259 , (1960), pp. 480-507.

Johnson, K.L. and Cameron, R. "Shear Behaviour of Elastohydrodynamic Oil Films at High Rolling Contact Pressures". Proc. Inst. Mech. Eng. (London), 182 , pt. I, no. 14, (1967), pp. 307-319.

Johnson, K.L. and Tevaarwerk, J.L. "Shear behaviour of Elastohydrodynamic Oil Films". Proc. Roy. Soc. (London), Series A, 356 , (1977), pp. 215-236.

Johnson,K.L., and Greenwood, J.A. "Thermal Analysis of an Eyring fluid in EHL Traction", Wear, 61 (1980), p353

Kalker, J.J. "On the Rolling Contact of Two Elastic Bodies in the Presence of Dry Friction". Ph.D. Dissertation, Technische Hogeschool, Delft, 1967

Kemper, Y. "A High Power Density Traction Drive", SAE Paper 790849, 1979.

Loewenthal, S,H., Anderson, N.H. and Nasvytis, A.A. "Performance of a Nasvytis Multiroller Traction Drive." NASA TP 1378. (1978).

Loewenthal, S. H., " A Historical Perspective of Traction Drives and Related Technology ". Advanced Power Transmission Technology. G.K. Fisher, ed., NASA CP-2210, 1983.

May,W.D., Morris,E.L. and Atack,D., "Rolling Friction of a Hard Cylinder over a Viscoelastic Material". Journal of Applied Physics, 30 , #11, (1959), pp. 1713-1724.

McCoin, D.K. and Walker, R.D. "Design study of continuously variable roller cone traction CVT for Electric Vehicles", NASA CR-159841, Sept., 1980.

Meissner,J., "The Effect of Temperature on the Flow Properties of the Low Density Polyethylene Melt". Fourth International Congress on Rheology, Part III. (1963), pp. 437-453.

Sackmann, F. W., "Die Lebensdauer von Waelzraedern mit weichelastischem Belag bei Uebertragung von Tangentialkraft". Doctoral Thesis of the University of Braunschweig, (1980).

Smith, F.W. "Rolling Contact Lubrication-The Application of Elasto hydrodynamic Theory". Trans . Am. Soc. Mech. Engrs. 87 , Series D. p. 170 (1965)

Tevaarwerk,J.L., "The Shear of Elastohydrodynamic Oil Films". Doctoral Thesis of the University of Cambridge, (1976).

Tevaarwerk, J.L. "Thermal Traction Contact Performance Evaluation under Fully Flooded and Starved Conditions". NASA CR-168173, May 1985.

Tevaarwerk, J.L. and Johnson, K.L. "The Influence of Fluid Rheology on the Performance of Traction Drives", Trans. A.S.M.E. Jolt , 101 , p 266, (1979)

Tevaarwerk, J.L. "Traction Drive Performance Prediction for the Johnson and Tevaarwerk Traction Model". NASA TP-1530 (1979)

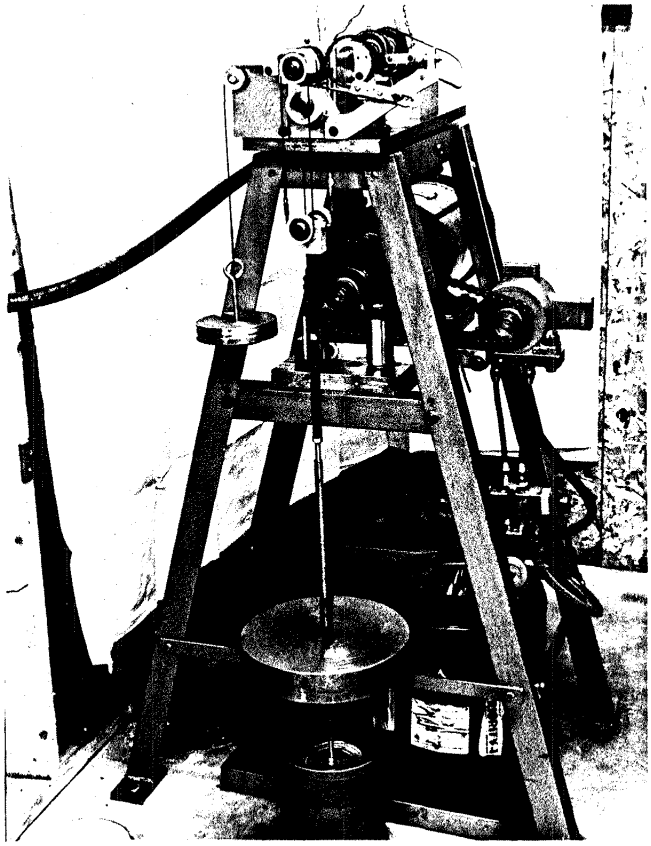


Figure 2-1 : Overview of the traction test facility.

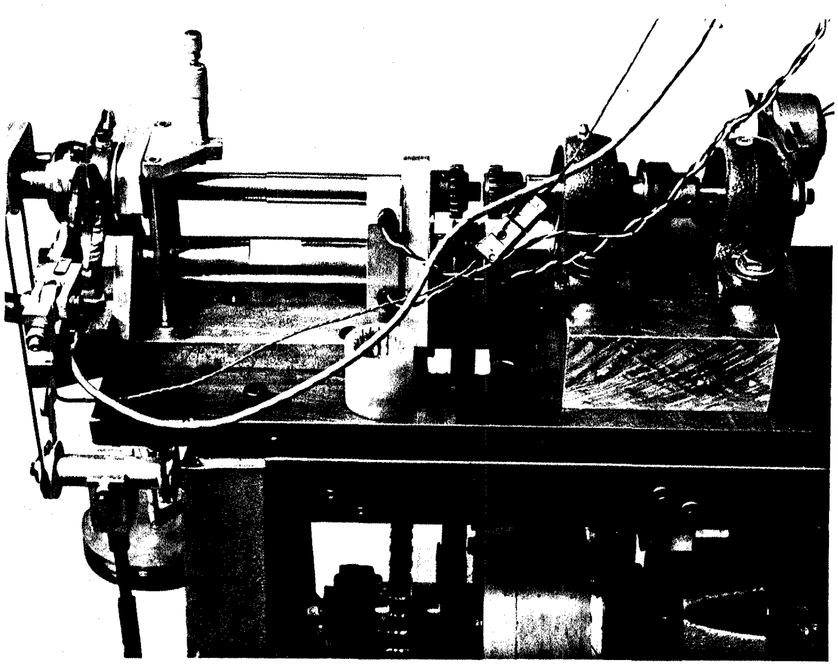


Figure 2-2: Details of the layout of the traction test facility showing the partial drive system.

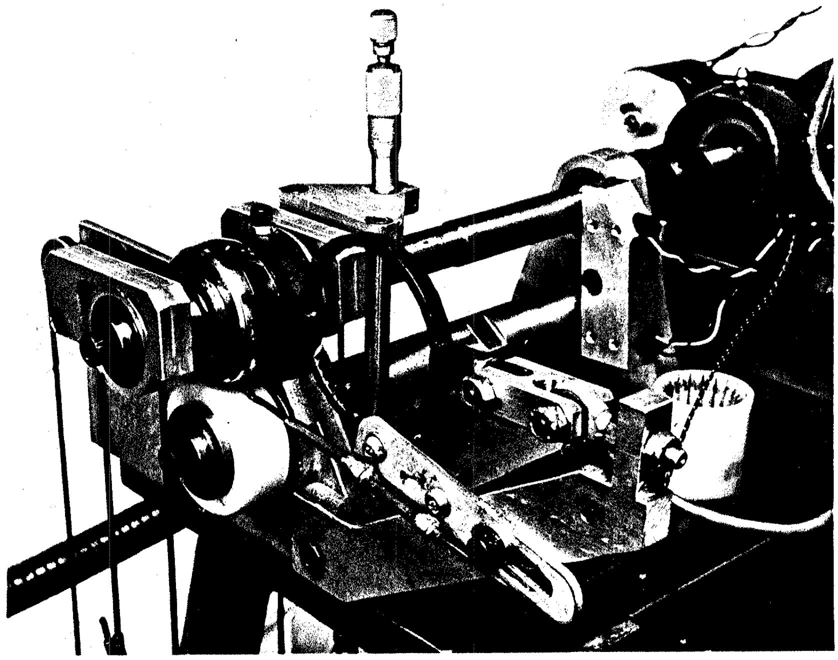


Figure 2-3: Details of the instrumentation on the traction test facility. Shown are the test rollers,thermocouple, loadcell and the velocity pick-ups.

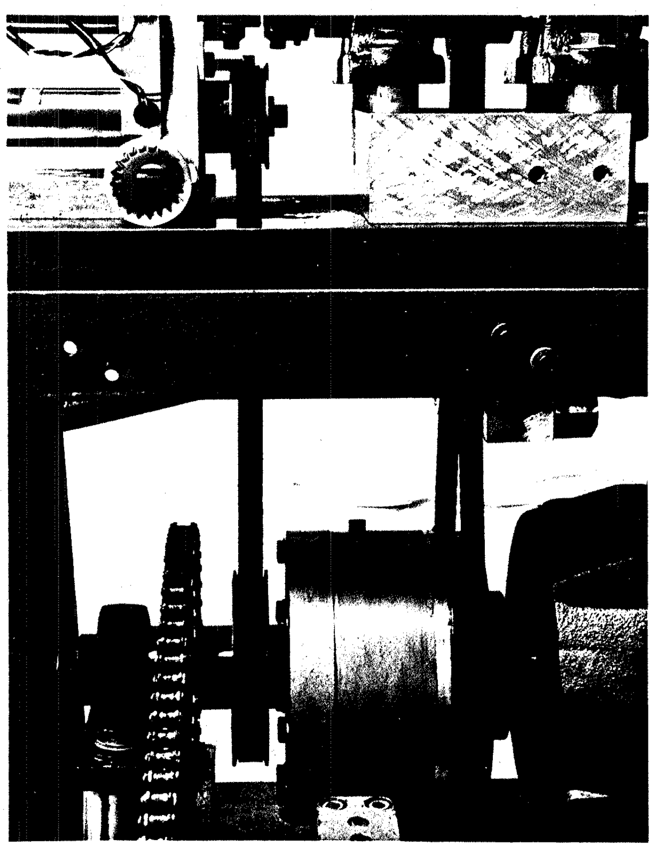


Figure 2-4: Details of the drive system used, showing the planetary differential and the drive belts.

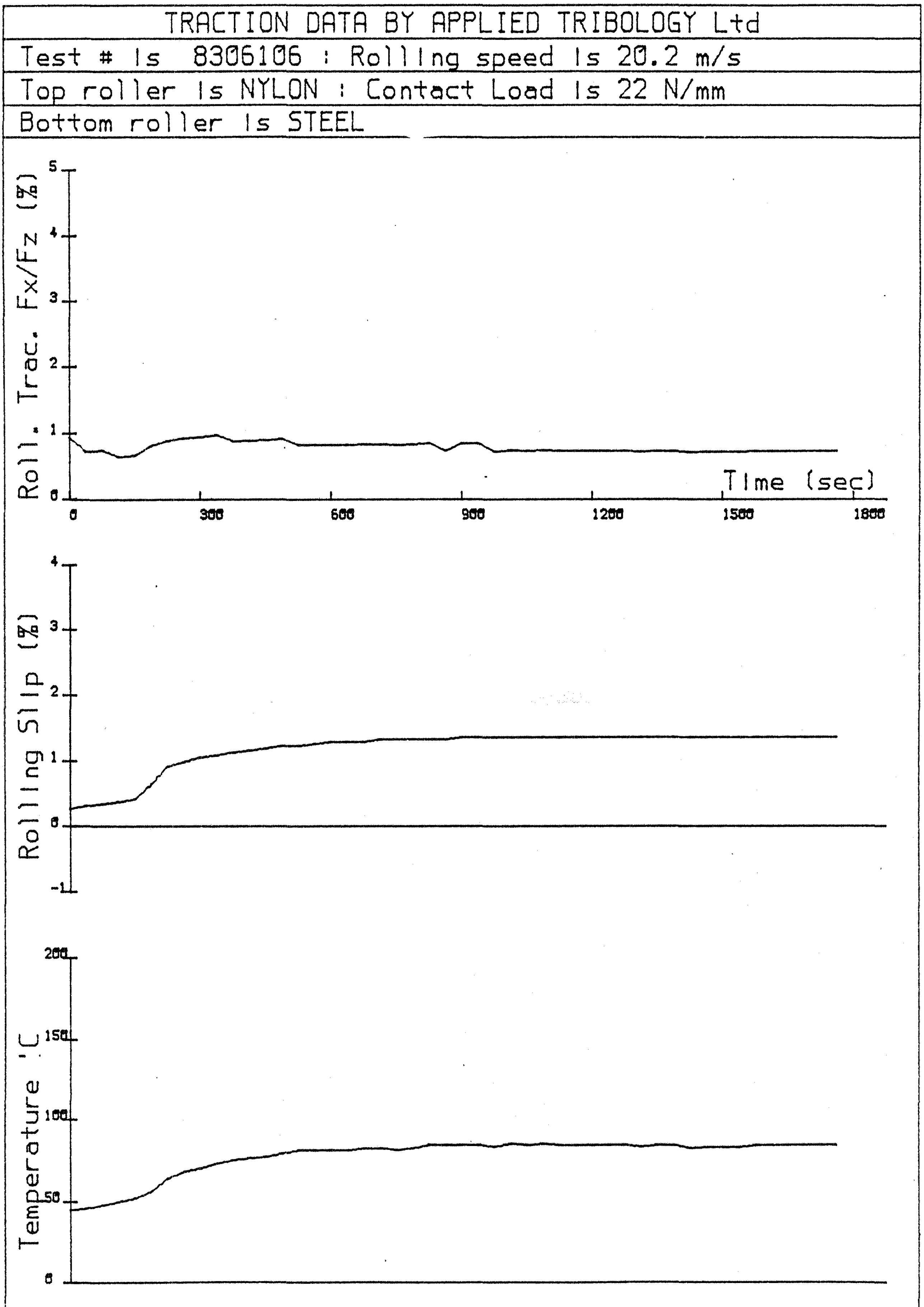


Figure 3-1: Typical rolling traction test result on the Nylon - Steel combination. Note the transitions in the rolling slip and the temperature trace.

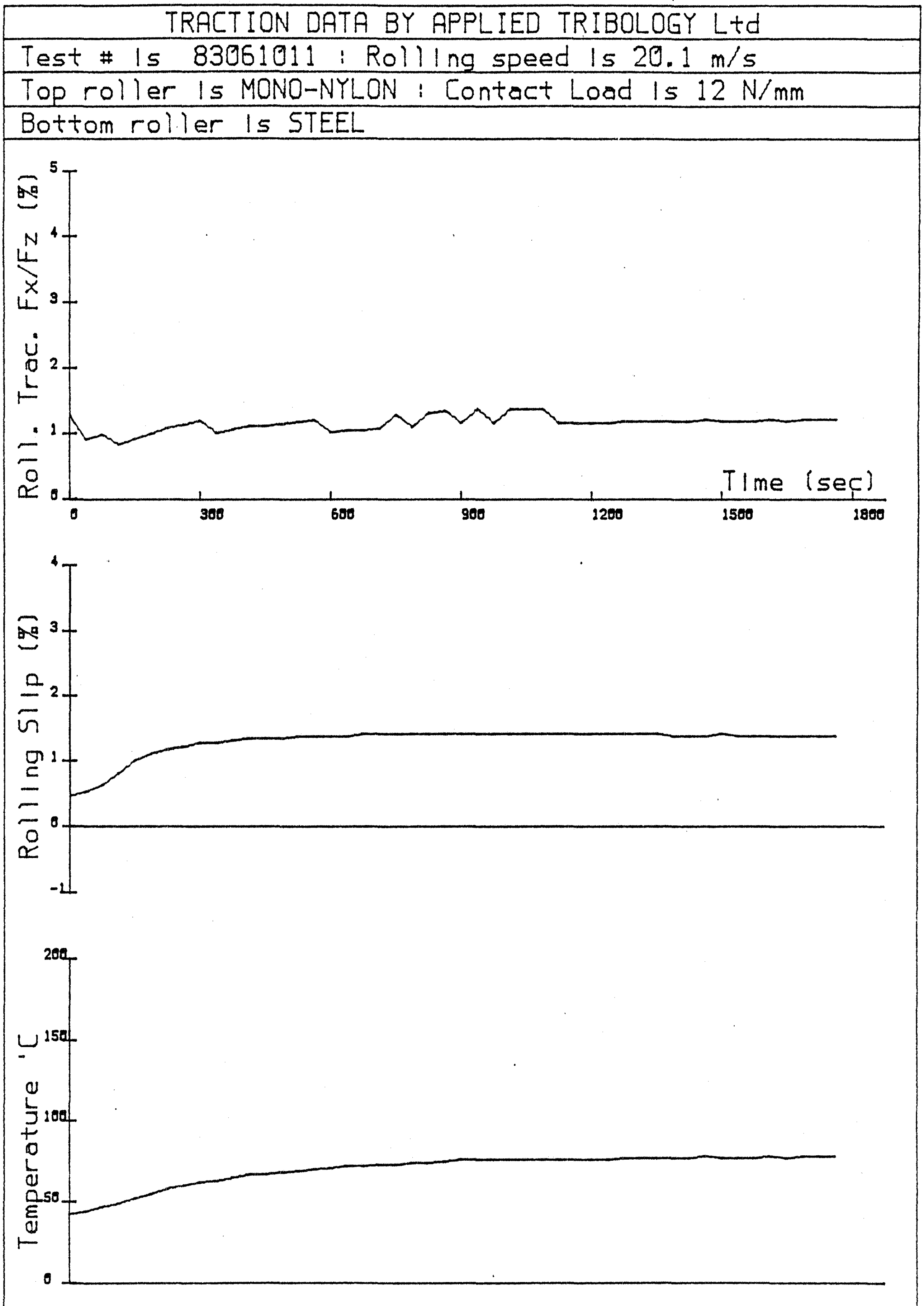


Figure 3-2: Typical rolling traction test result on the Mono-Nylon - Steel combination. Note the transitions in the rolling slip and the temperature trace.

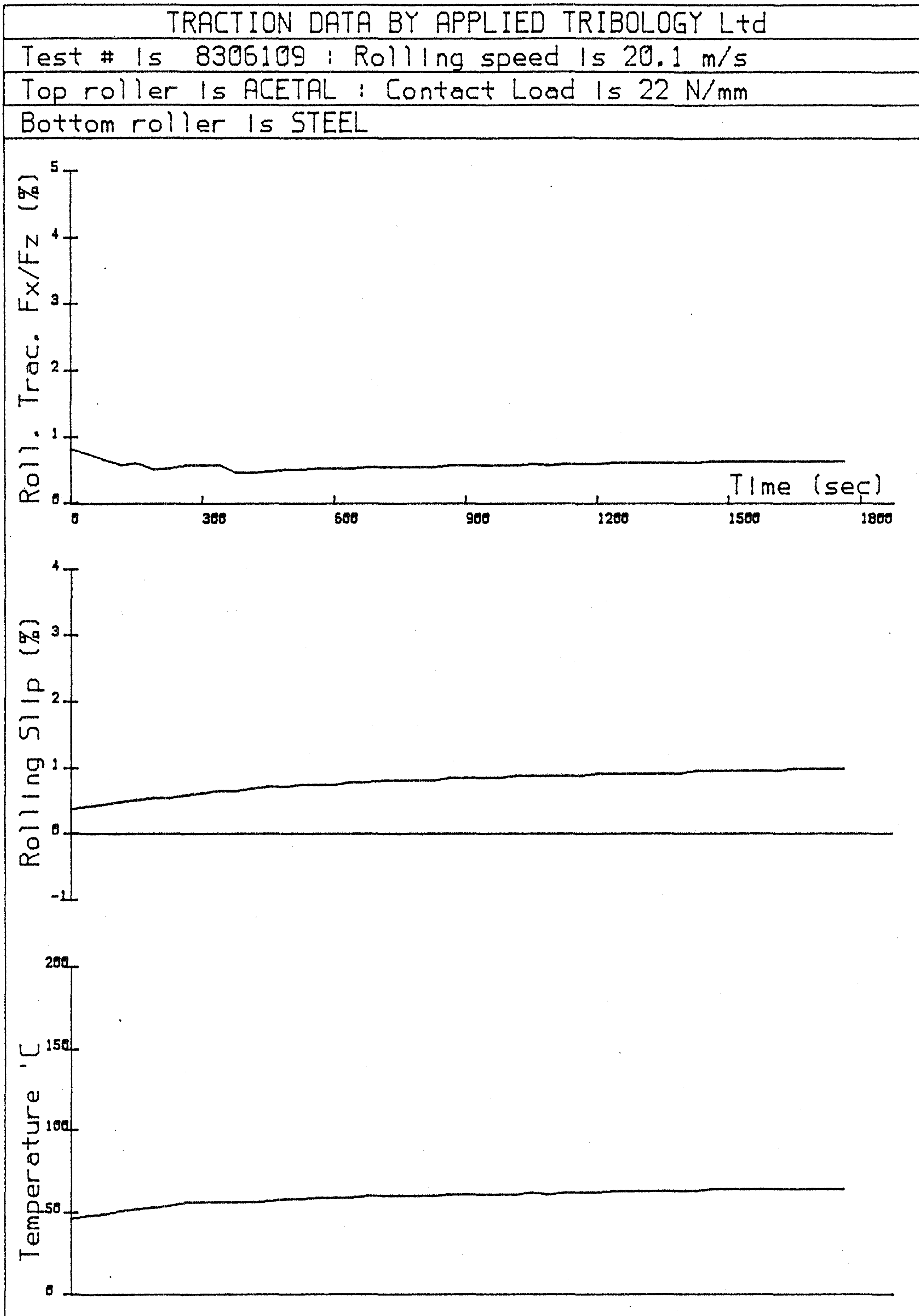


Figure 3-3: Typical rolling traction test result on the Acetal - Steel combination.

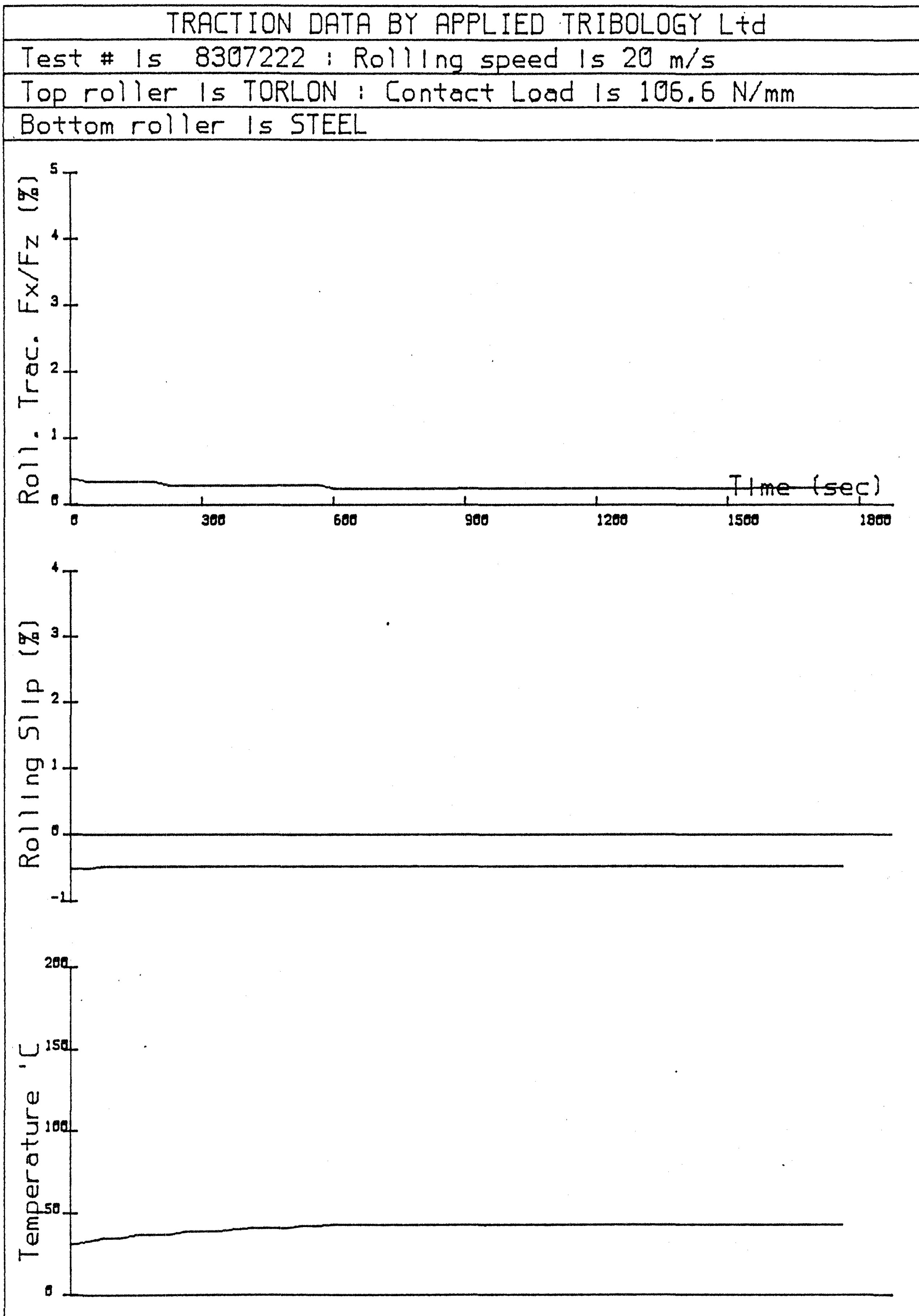


Figure 3-4: Typical rolling traction test results on the Torlon - Steel combination.

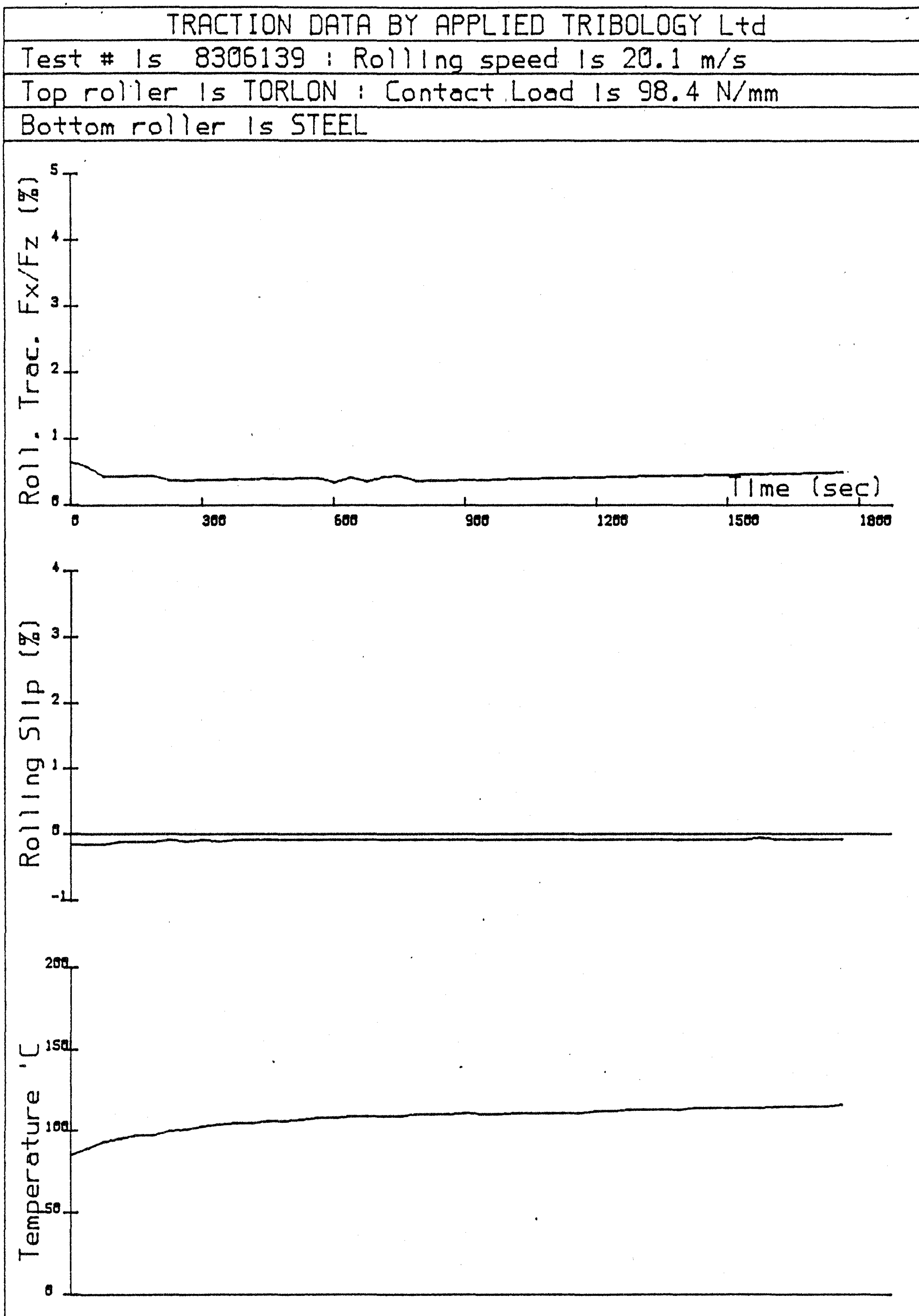


Figure 3-5: Typical rolling traction test resulst on the FTorlon - Steel combination.
Note that the rolling traction and the temperature are much higher.

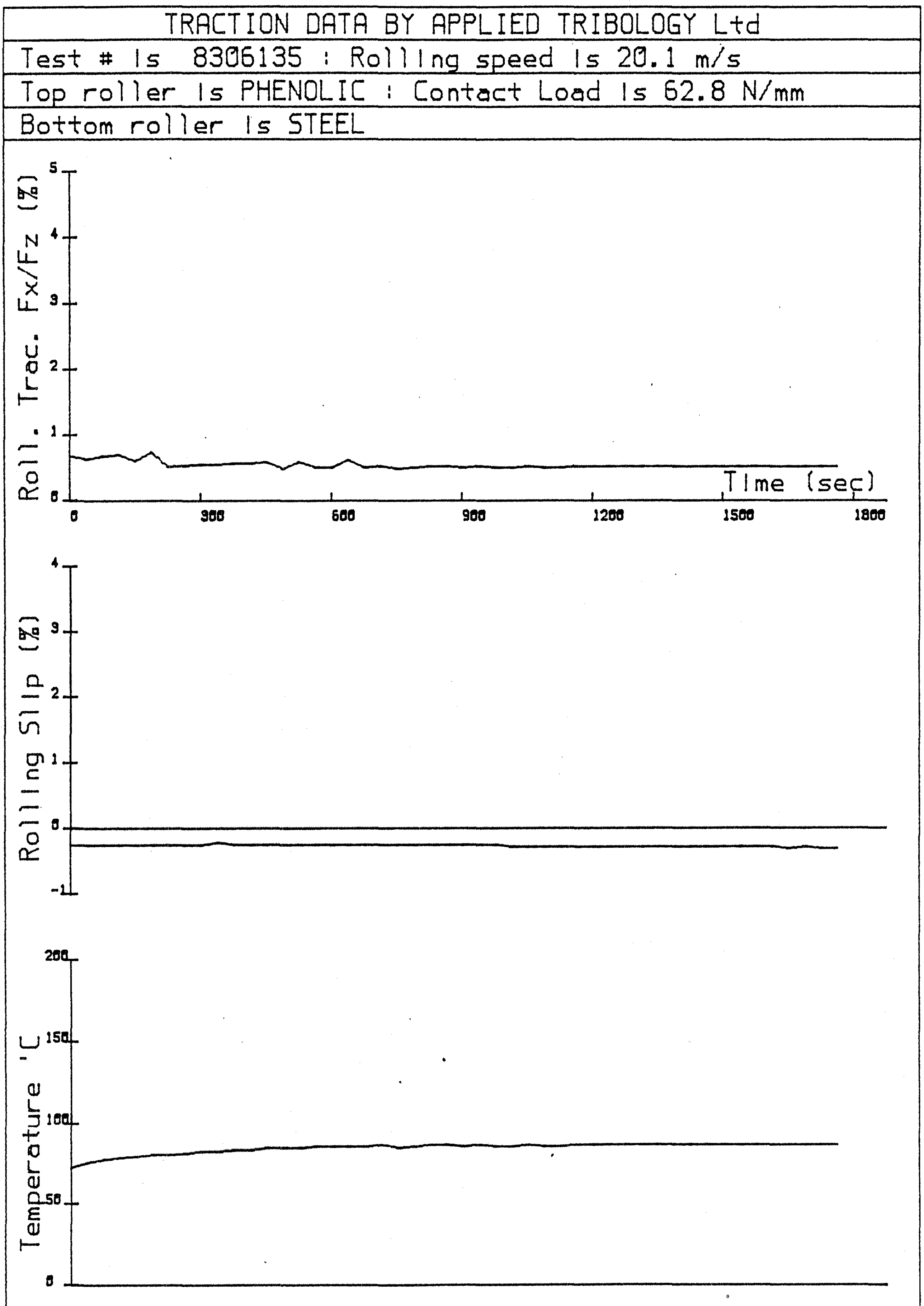


Figure 3-6: Typical rolling traction test results on the Phenolic - Steel combination.

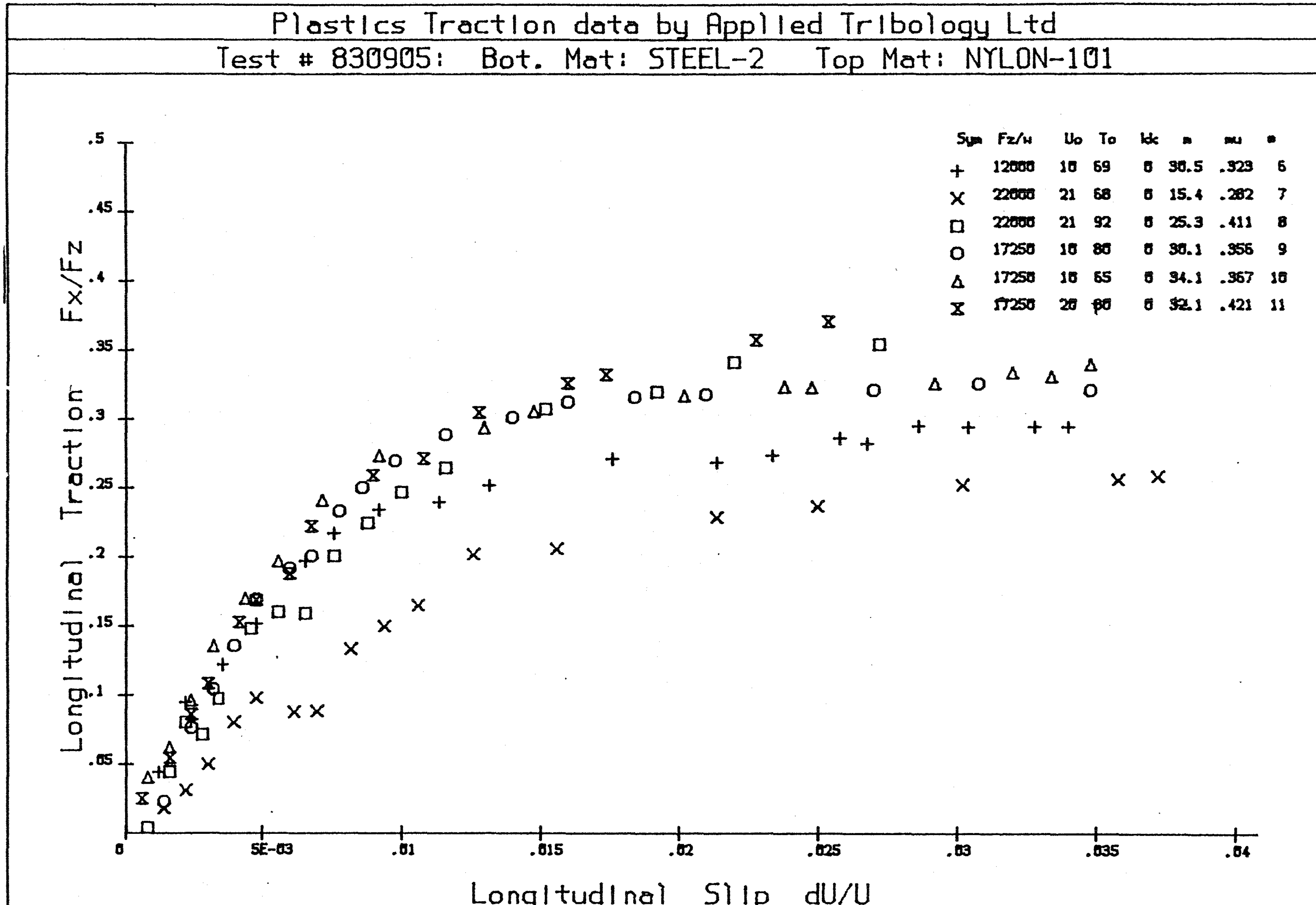


Figure 3-7: Slip traction test results for the Nylon - Steel roller combination for a range of conditions.

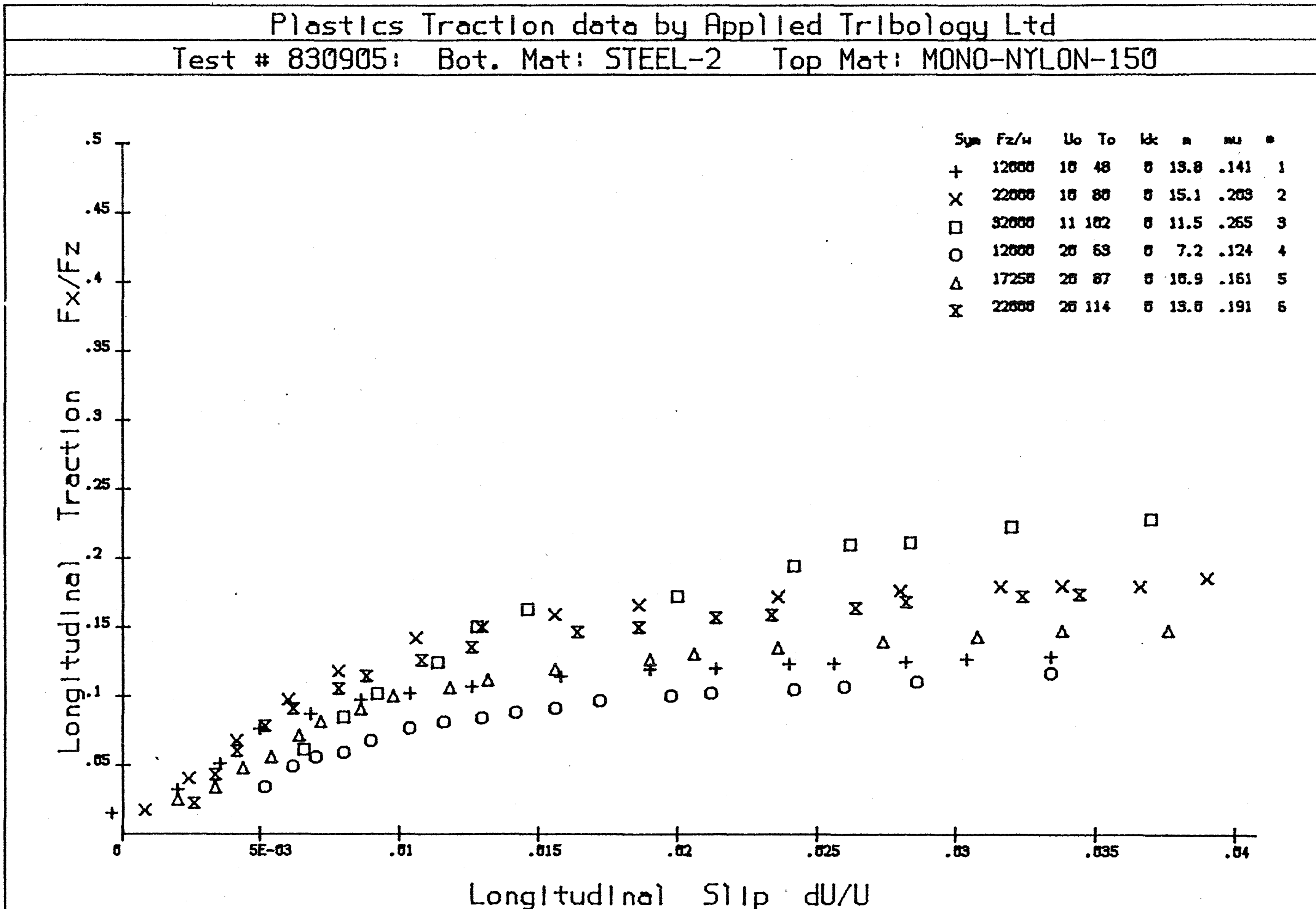


Figure 3-8: Slip traction test results for the Mono-Nylon - Steel roller combination for a range of conditions.

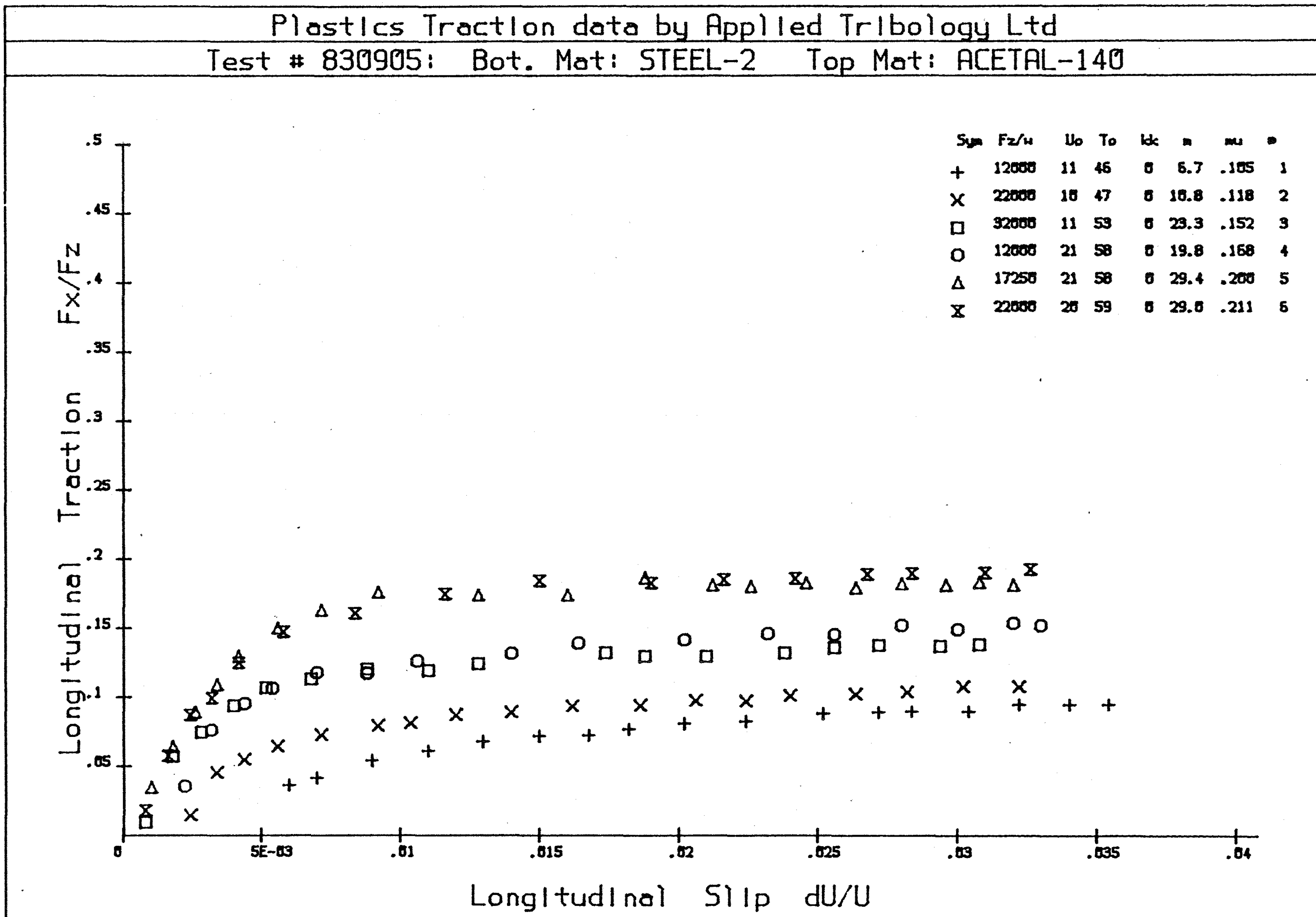


Figure 3-9: Slip traction test results for the Acetal – Steel roller combination for a range of conditions.

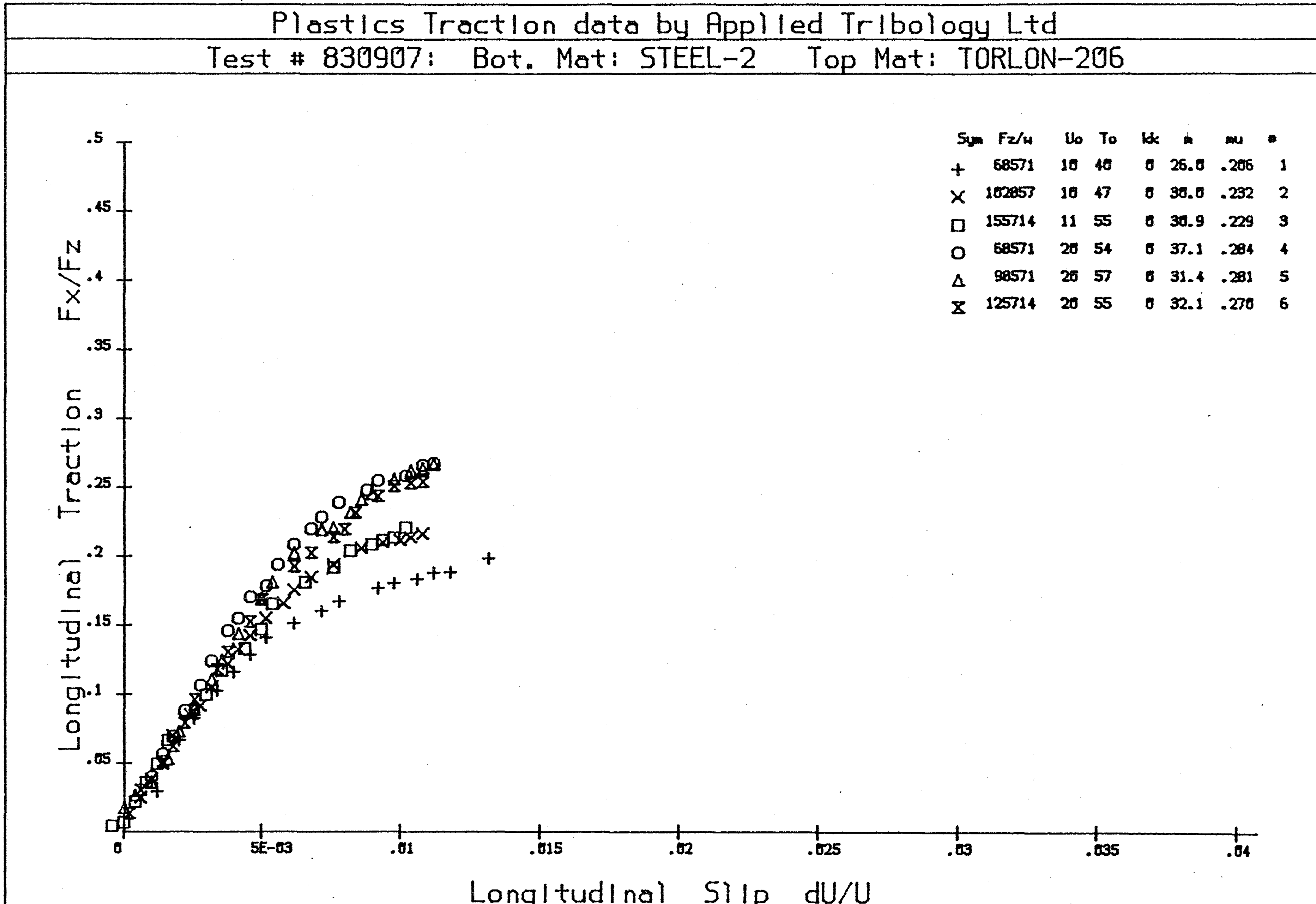


Figure 3-10: Slip traction test results for the Torlon - Steel roller combination for a range of conditions.

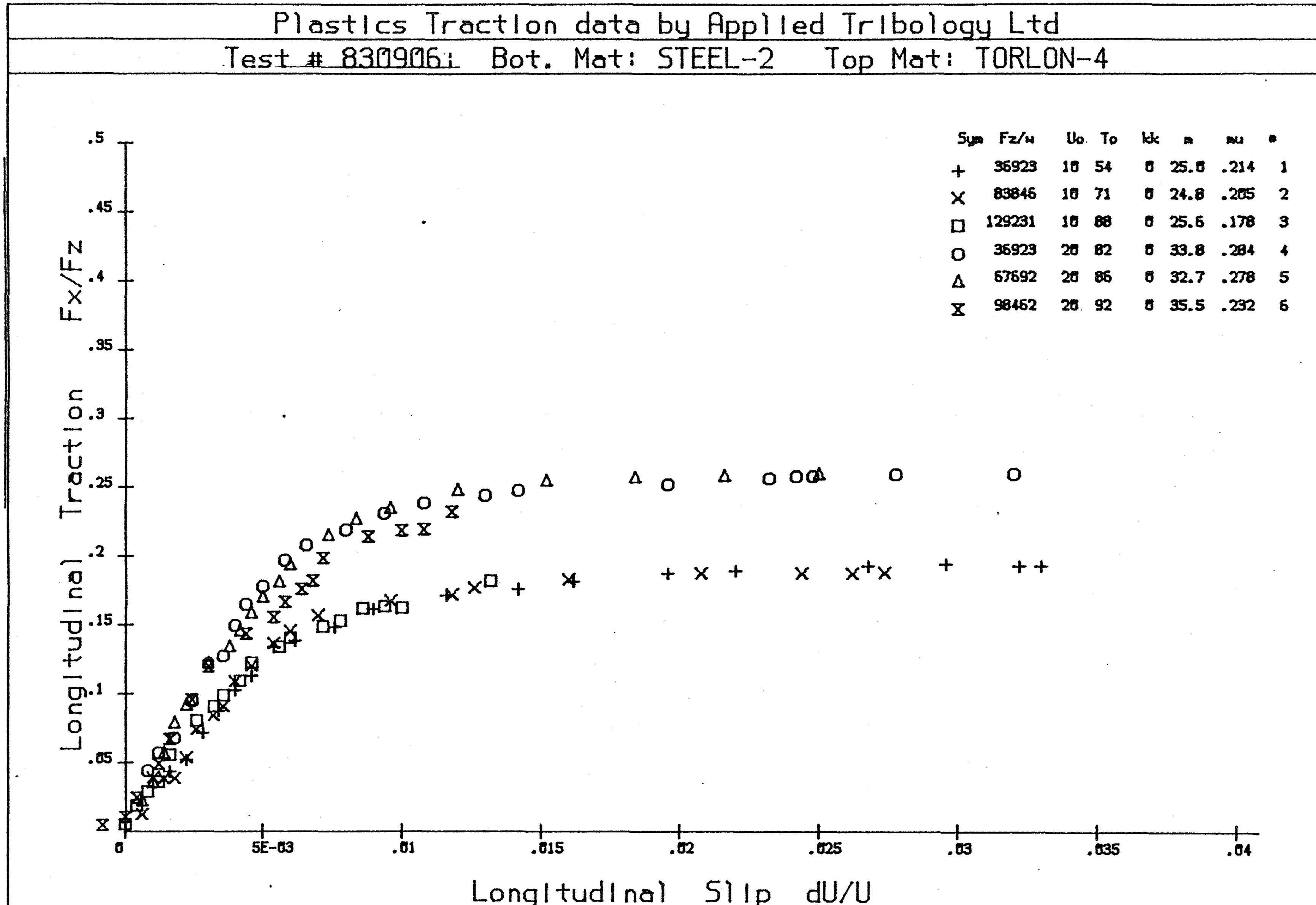


Figure 3-11: Slip traction test results for the FTorlon - Steel roller combination for a range of conditions.

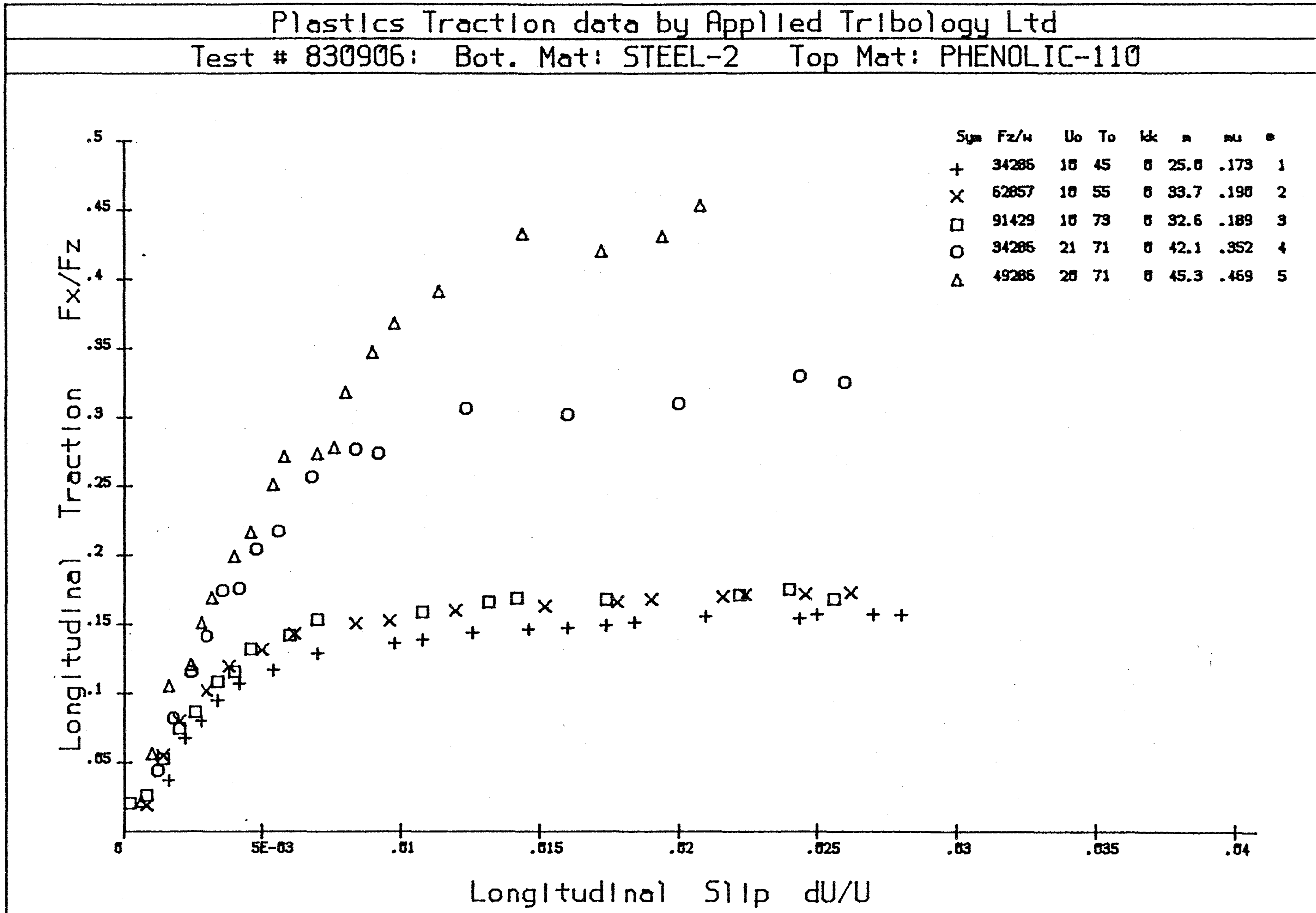


Figure 3-12: Slip traction test results for the Phenolic - Steel roller combination for a range of conditions.

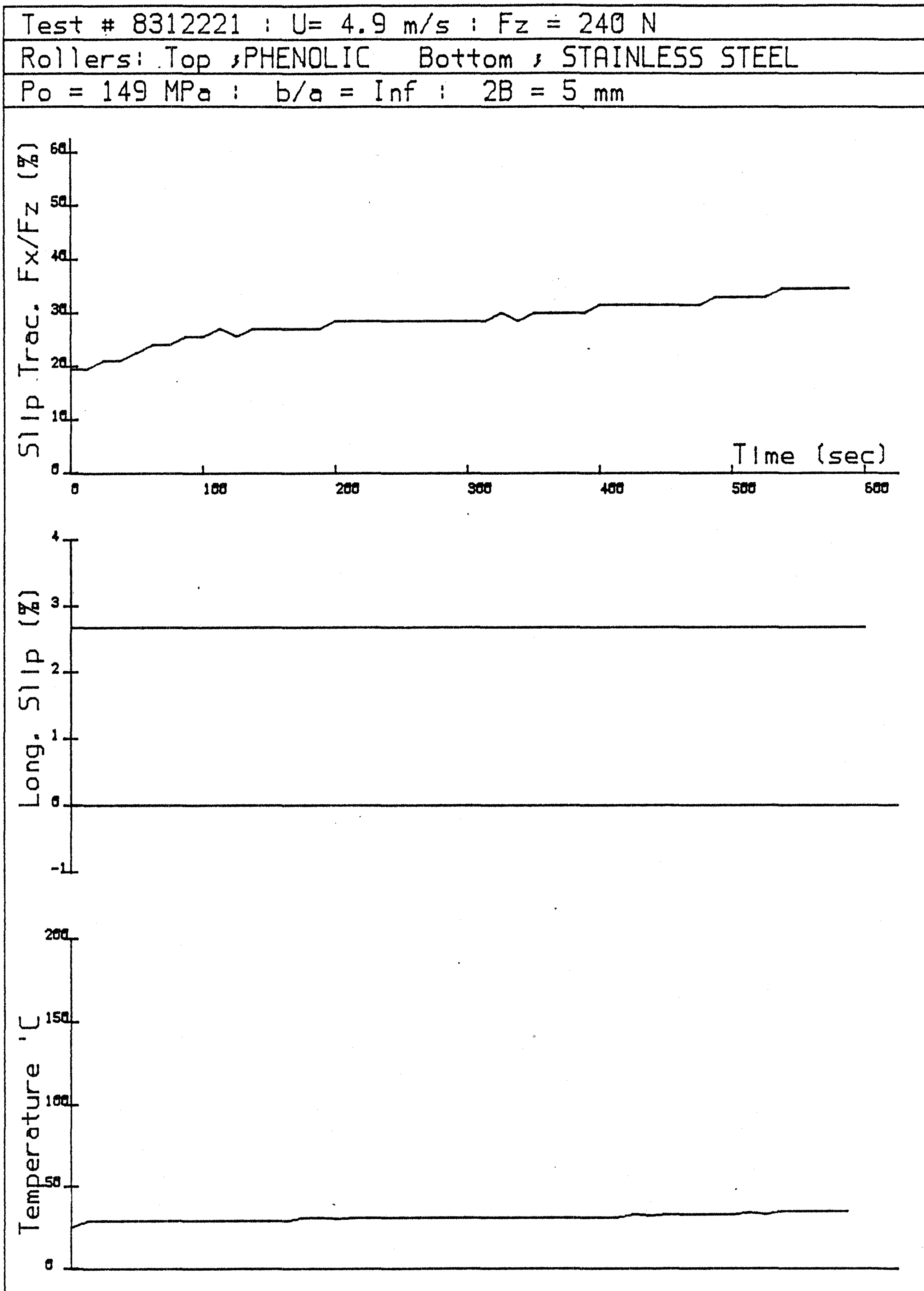


Figure 3-13: Endurance traction test results for the Phenolic - Steel roller combination. Speed U=4.9 m/sec.

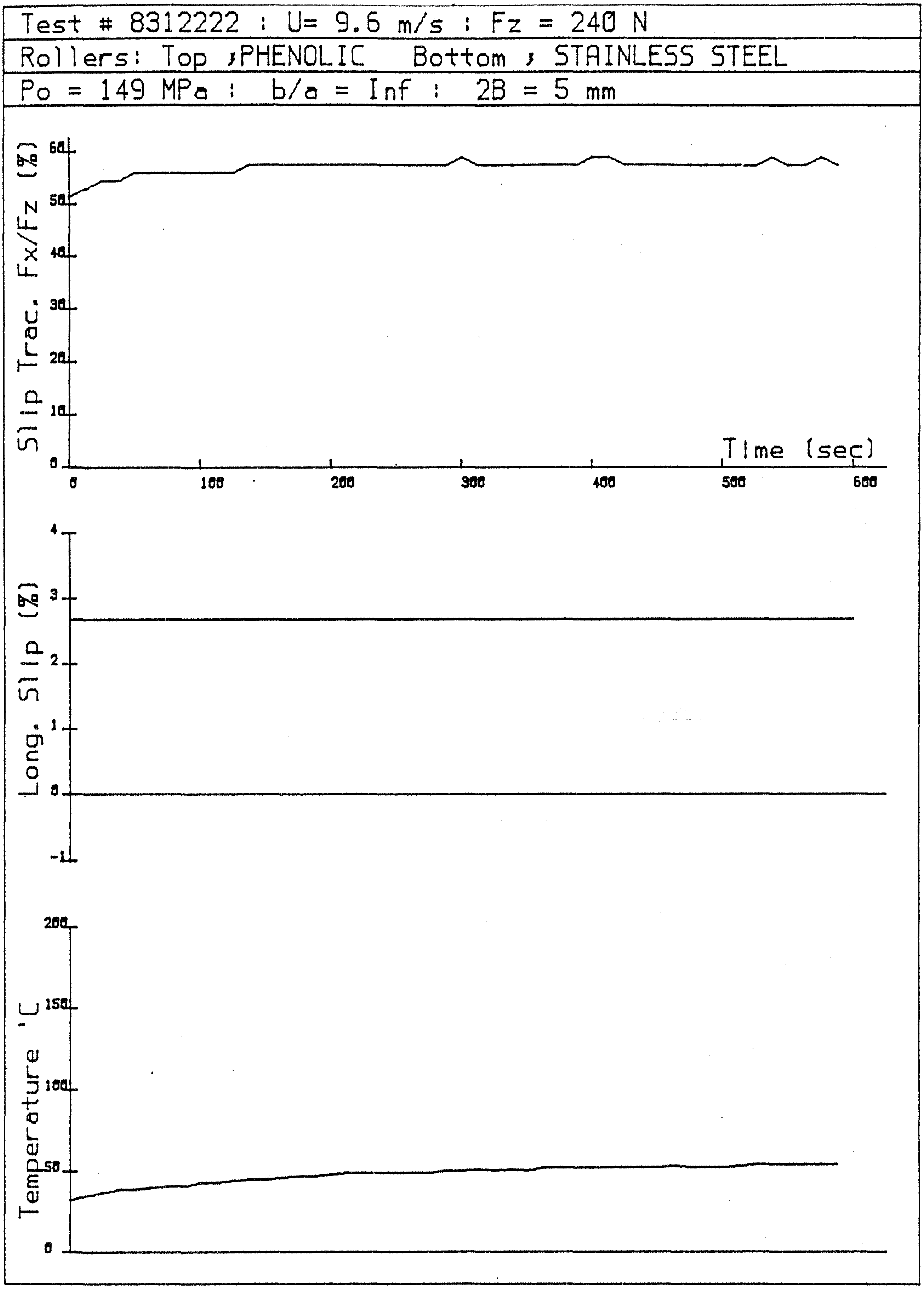


Figure 3-14: Endurance traction test results for the Phenolic - Steel roller combination. Same conditions as in Fig.3-13 but at higher speed. U=9.6 m/sec.

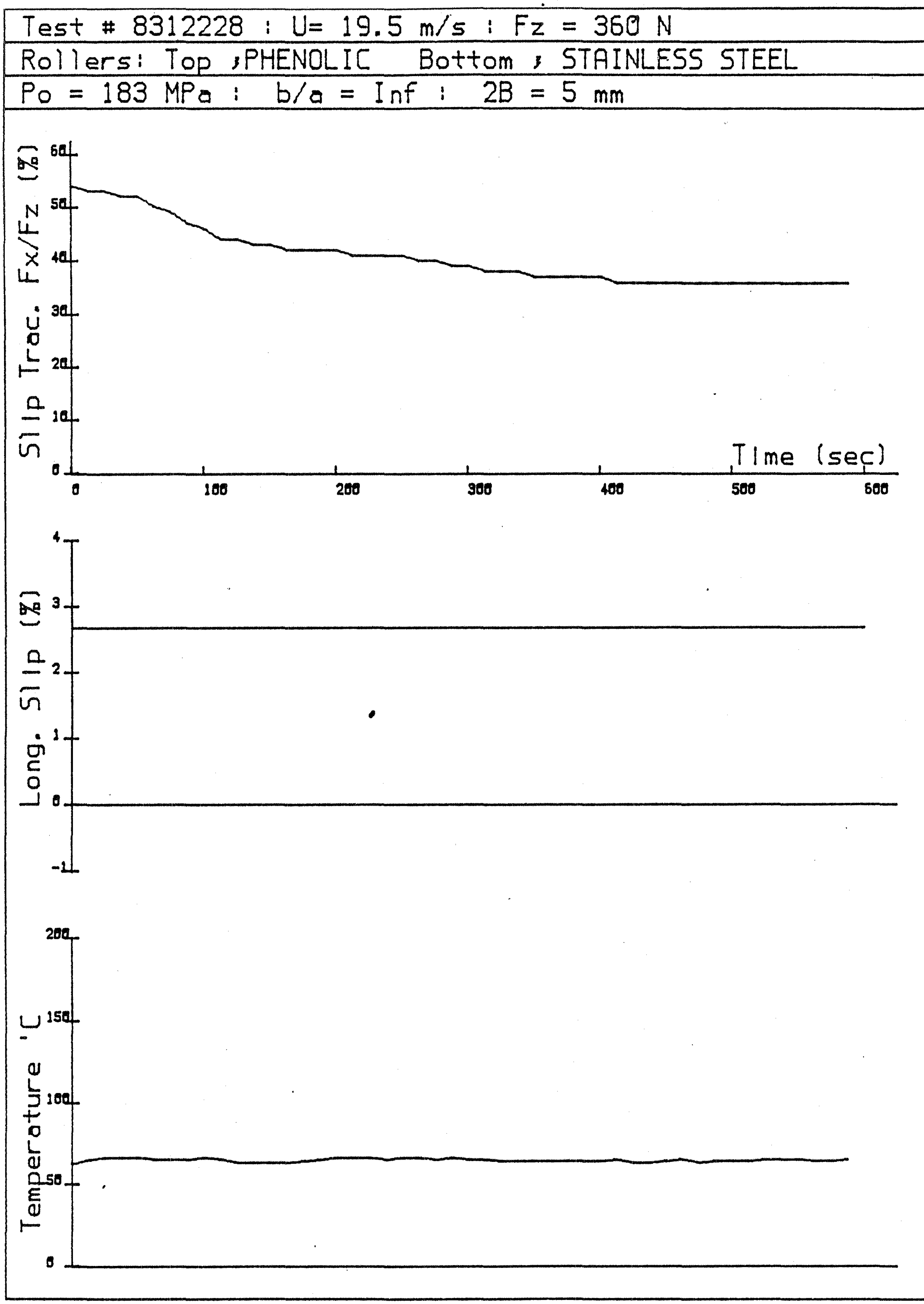


Figure 3-15: Endurance traction test results for the Phenolic - Steel roller combination. Higher speed and lower load condition than in Fig. 3-13. Note the gradual loss of traction.

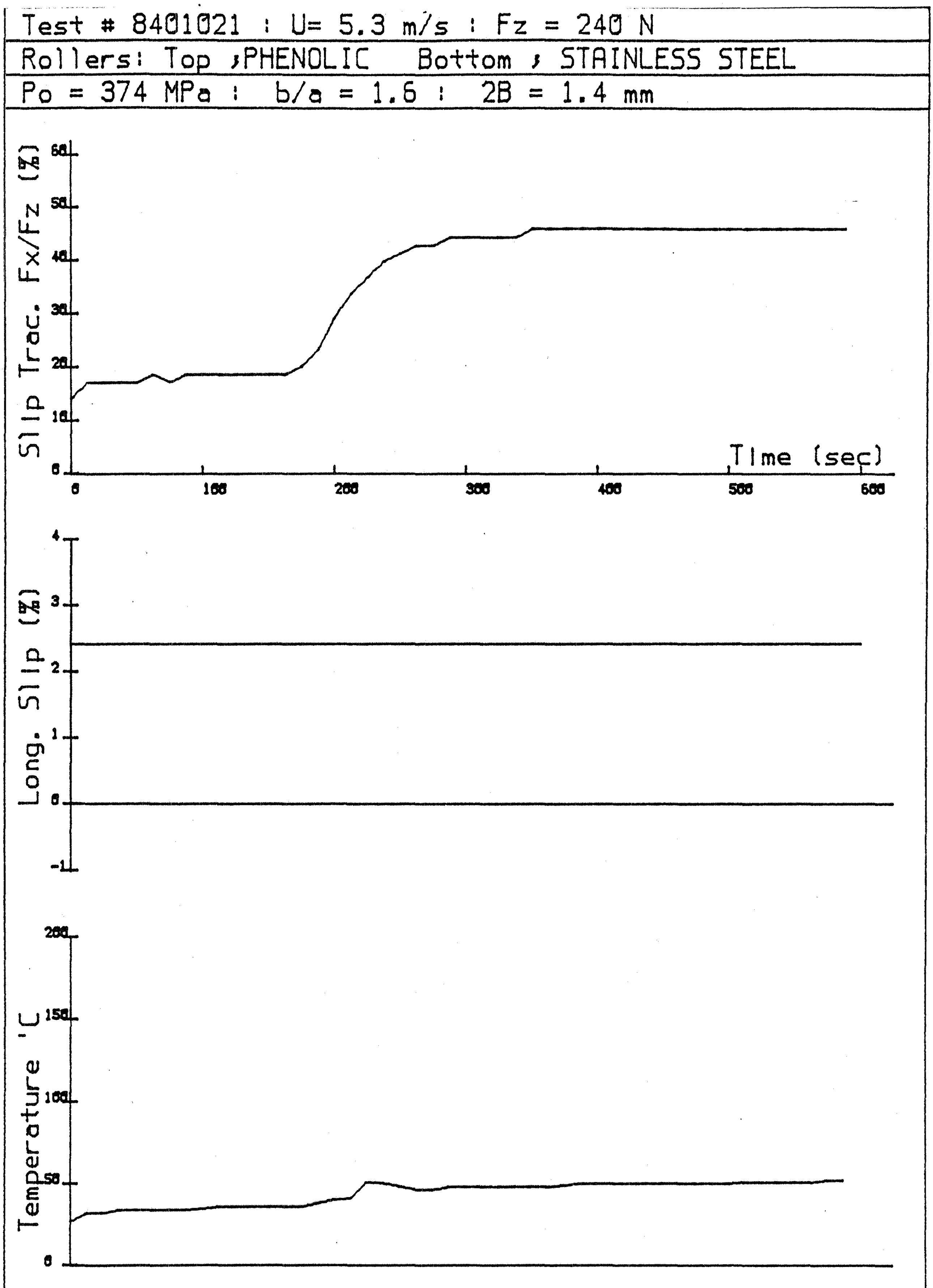


Figure 3-16: Endurance traction test results for the Phenolic - Steel roller combination with an elliptical contact. Note the sudden dramatic increase in the traction.

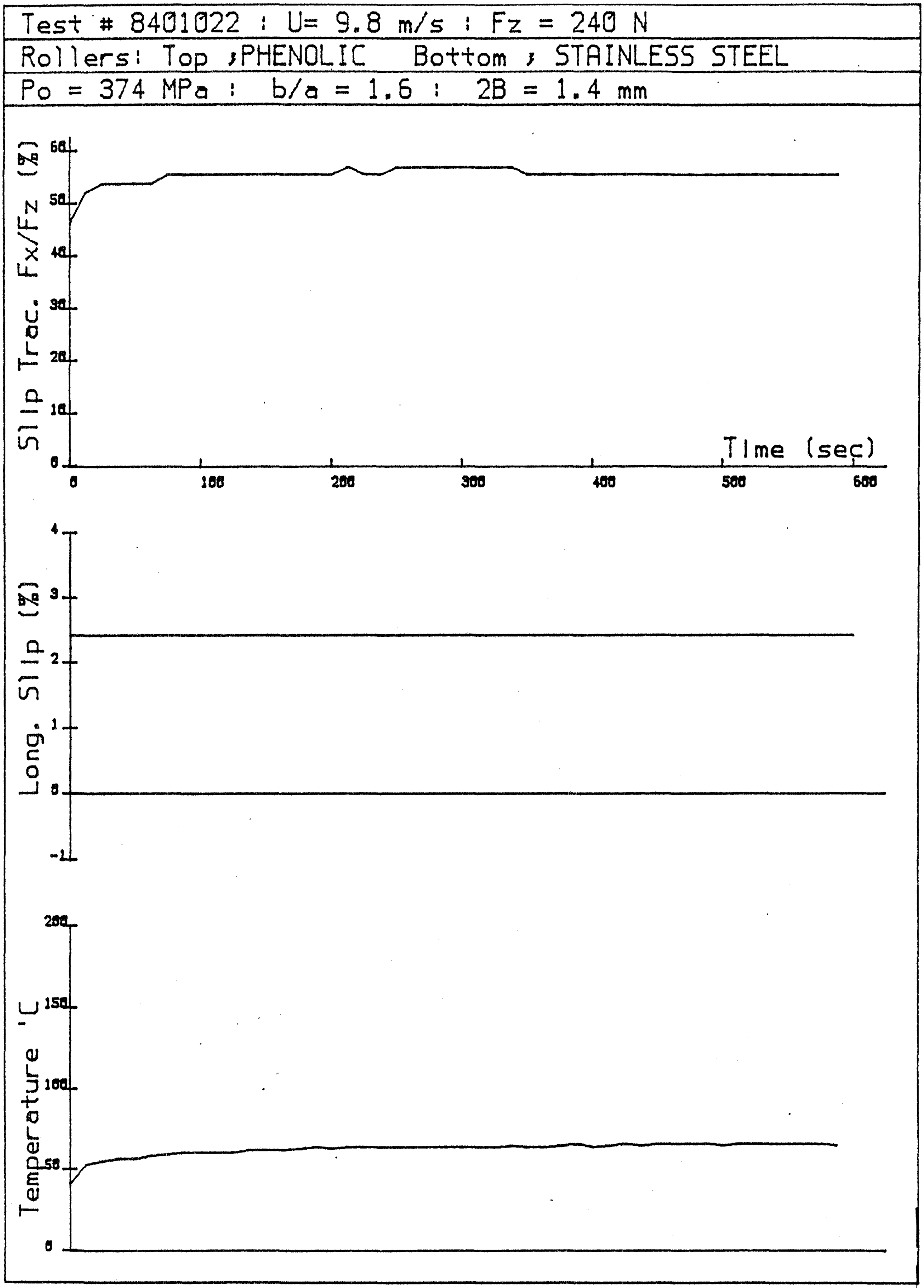


Figure 3-17: Endurance traction test results for the Phenolic - Steel roller combination with an elliptical contact configuration. Conditions are the same as in Fig. 3-16 but at a higher speed.

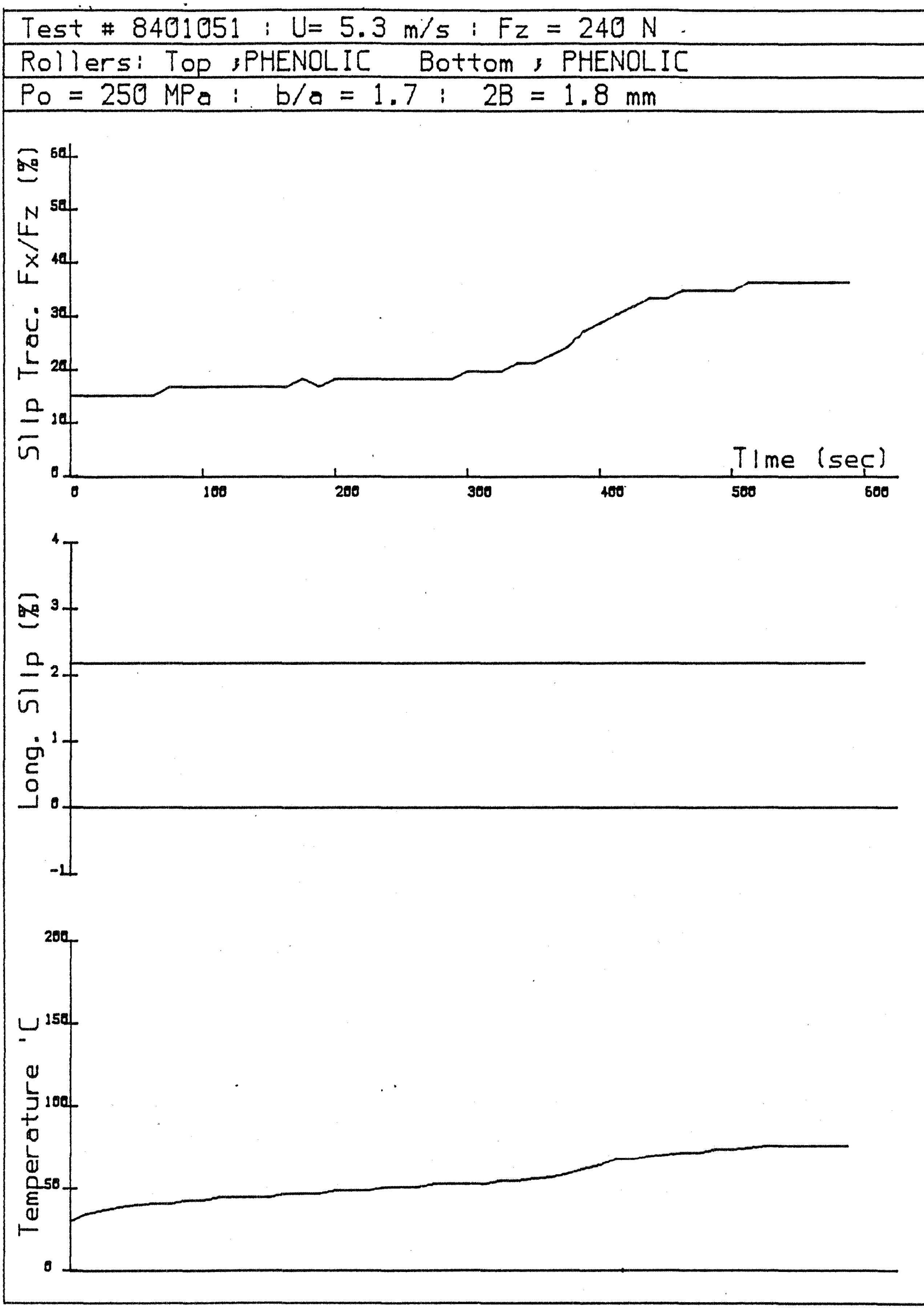


Figure 3-18: Endurance traction test results for the Phenolic - Phenolic roller combination with an elliptical contact. Note the transition in the traction and temperature trace.

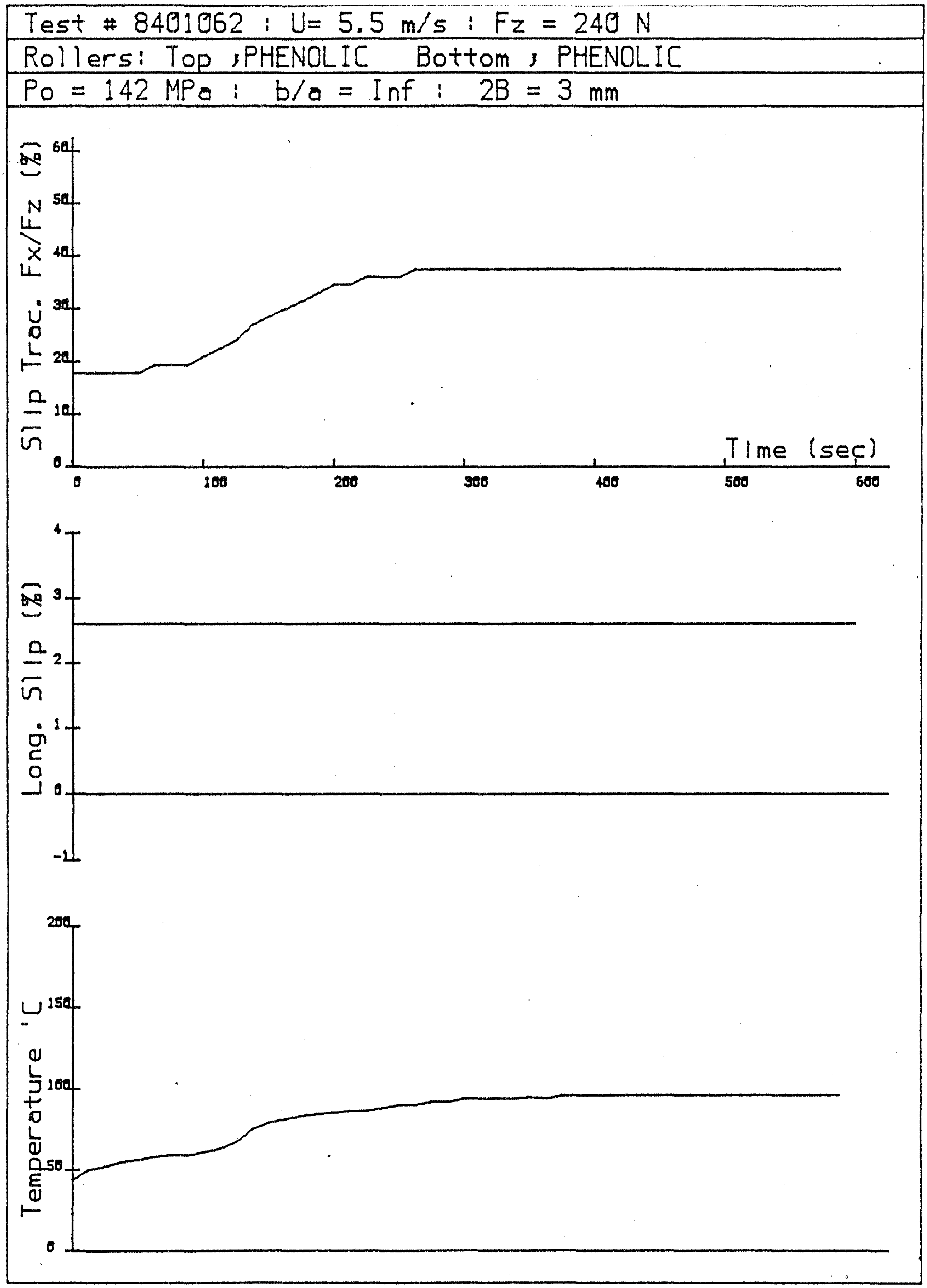


Figure 3-19: Endurance traction test results for the Phenolic - Phenolic roller combination. Conditions the same as in Fig. 3-18 but at a lower load.

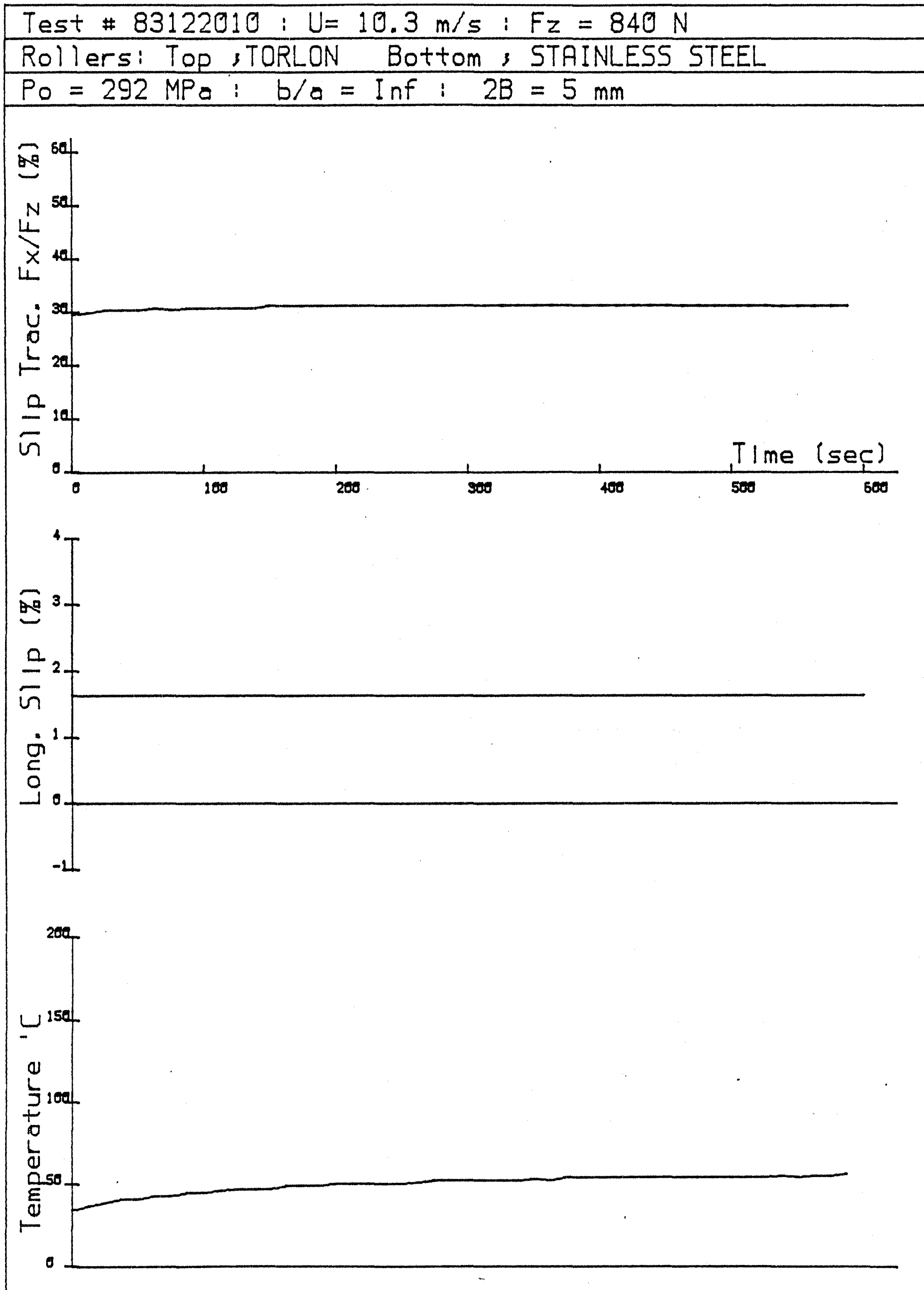


Figure 3-20: Endurance traction test results for the Torlon - Steel roller combination with a line contact.

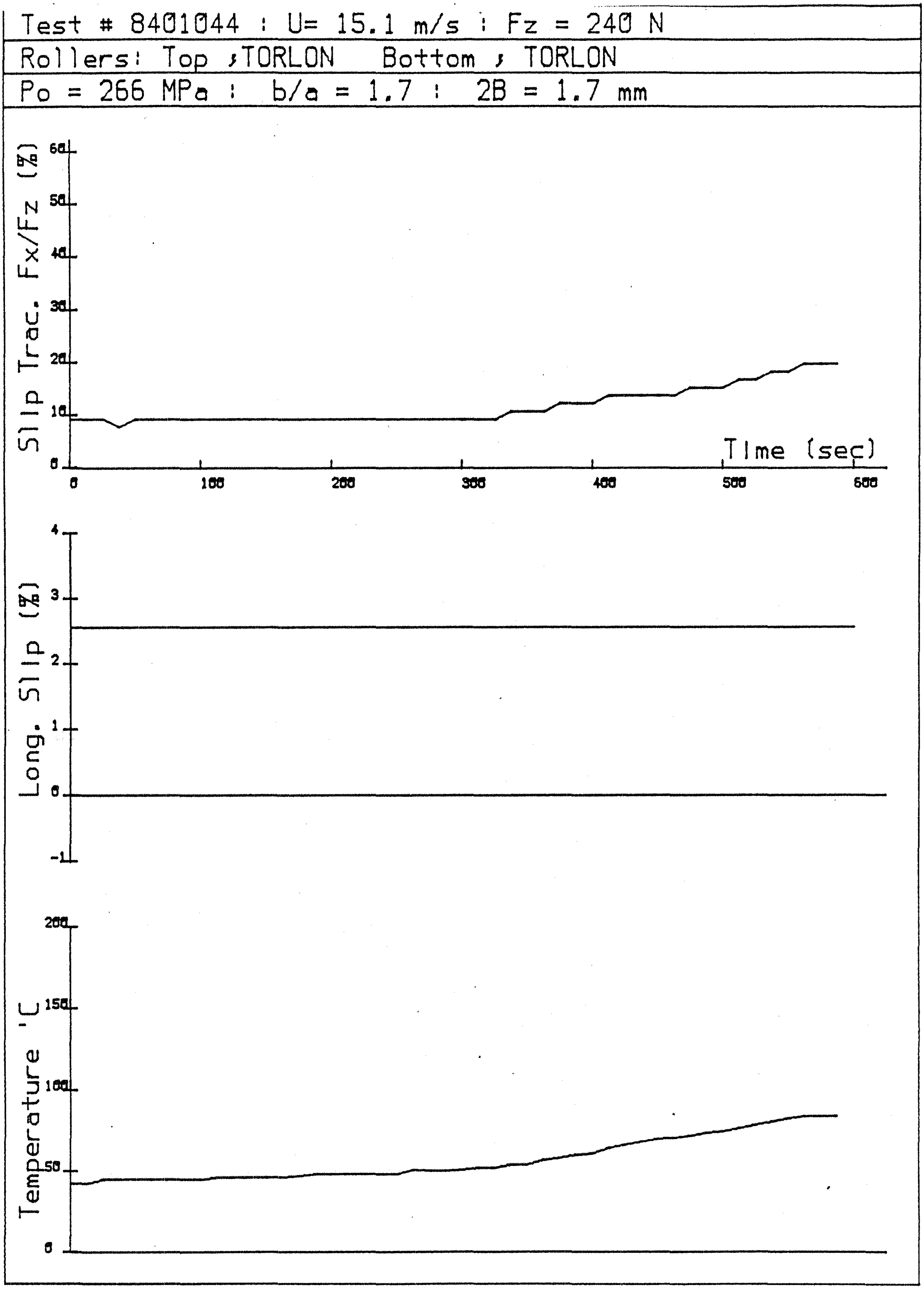


Figure 3-21: Endurance traction test results for the Torlon - Torlon roller combination with elliptical contacts. Note the rise in the traction and temperature traces.

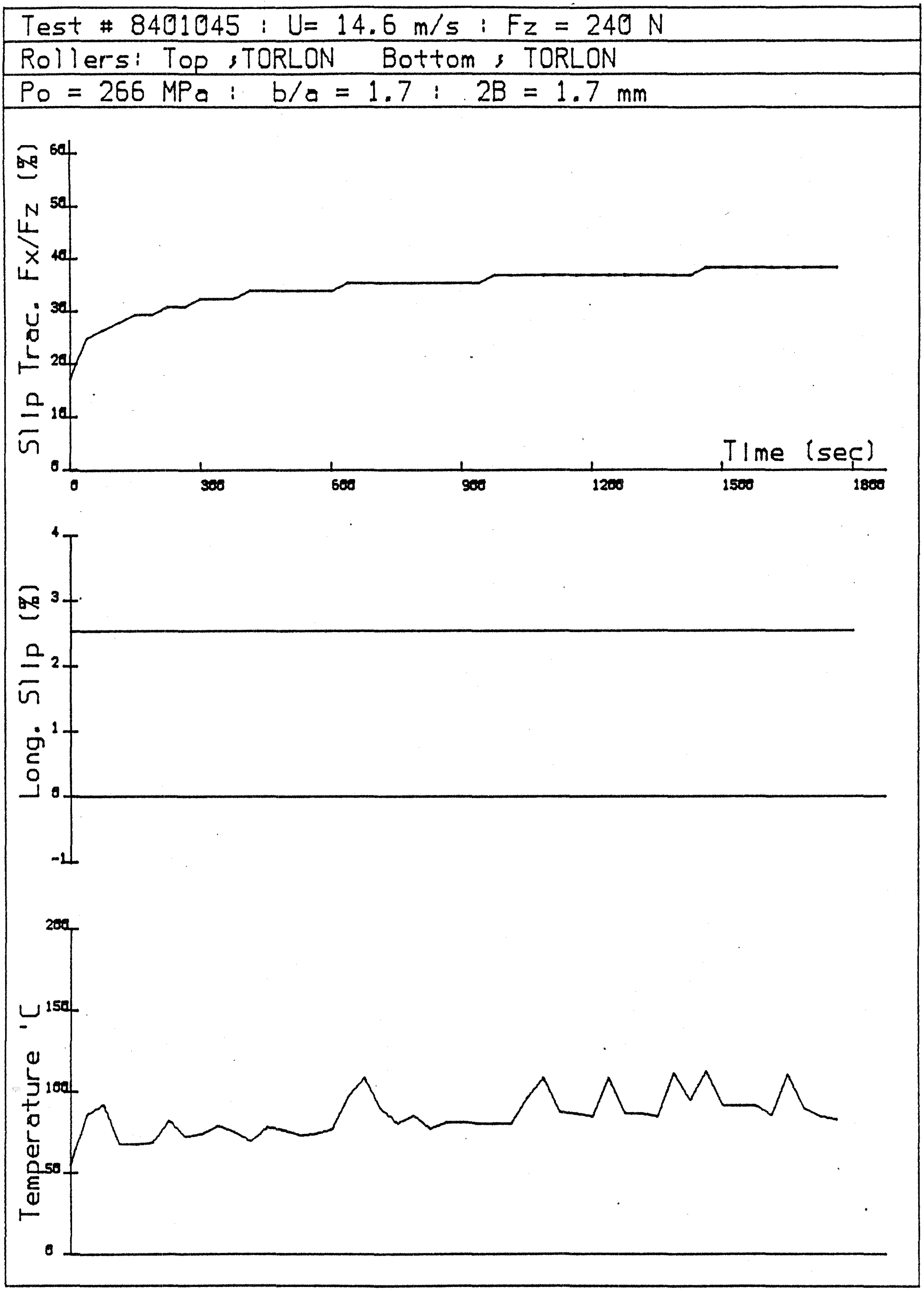


Figure 3-22: Endurance traction test results for the Torlon - Torlon combination. The conditions are the same as in Fig 3-21 but the test duration was increased. Rollers were warm at the start of the test.

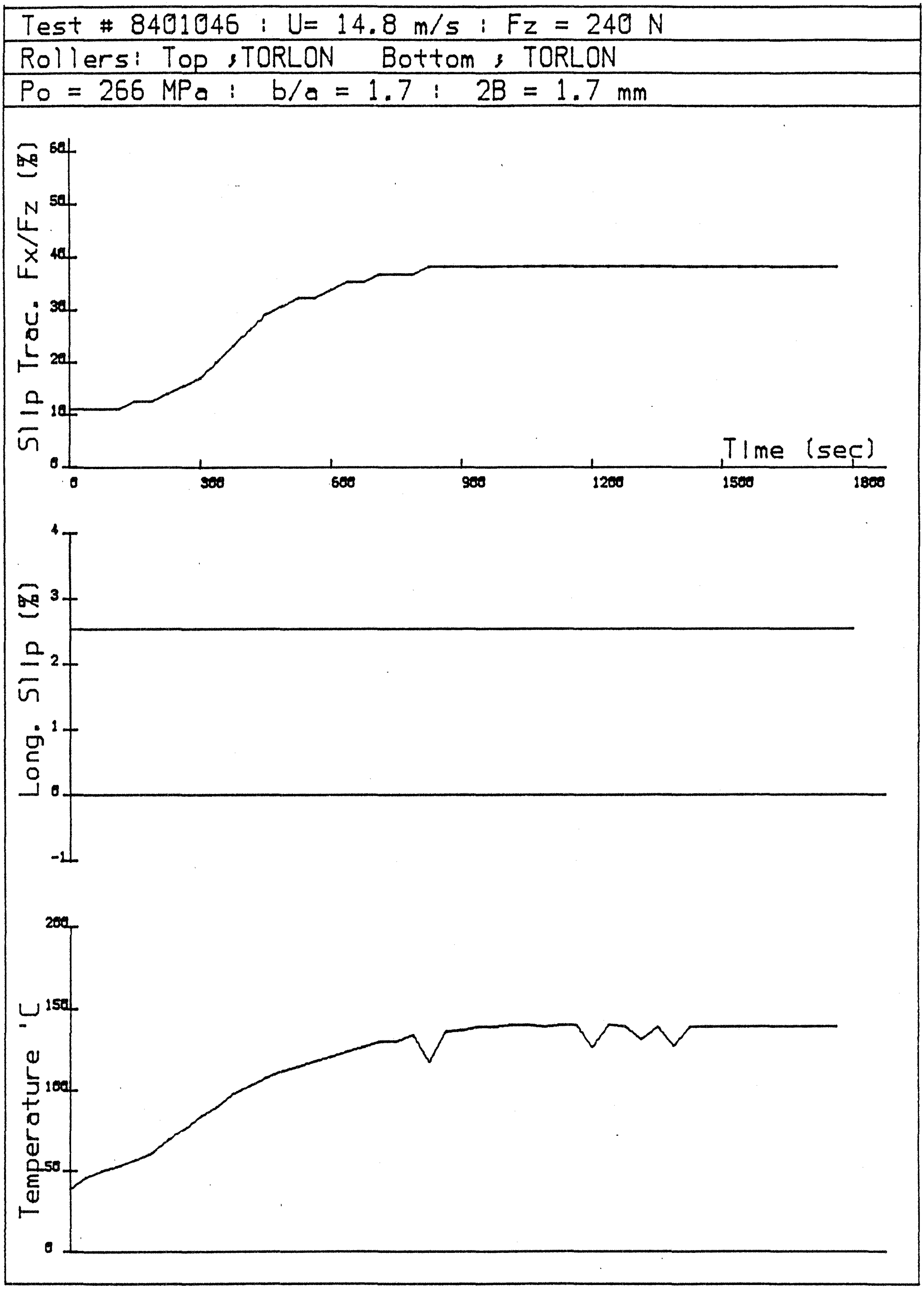


Figure 3-23: Endurance traction test results for the Torlon - Torlon roller combination. Same conditions as in Fig. 3-21 and 3-22 but now under cold start conditions.

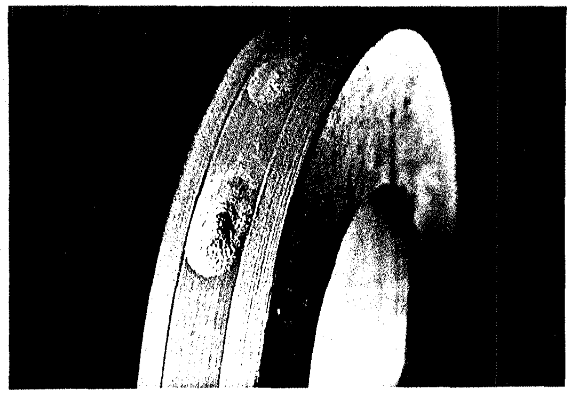


Figure 3-24: Example of thermal blistering on the unfilled Torlon when tested under traction.

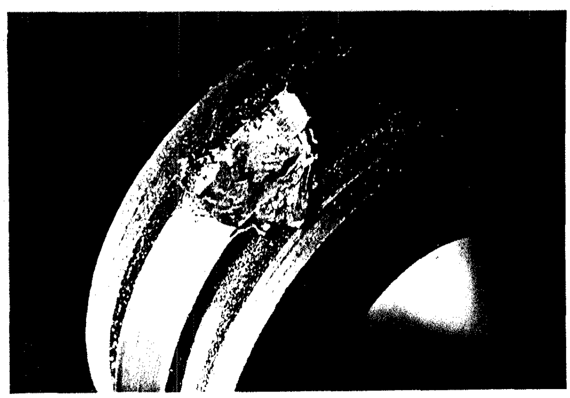


Figure 3-25: Example of a crushing failure on the filled Torlon material under conditions of rolling only

Figure 3-26: Example of crushing failure on the Torlon under slip traction.

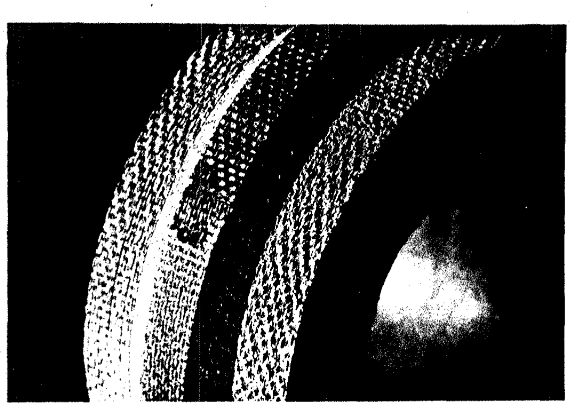


Figure 3-27: Delamination failure on Phenolic test roller.

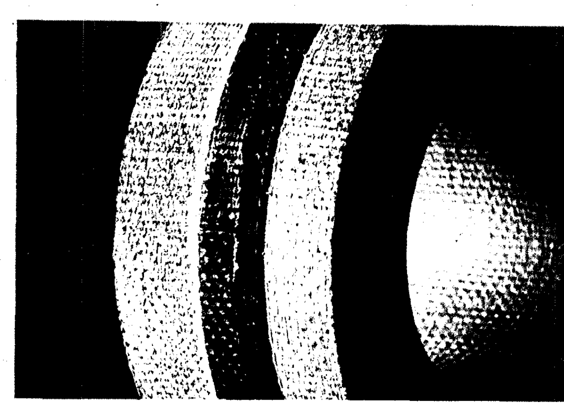


Figure 3-28: Incipient delamination failure on Phenolic. This specimen also showed some burning damage.

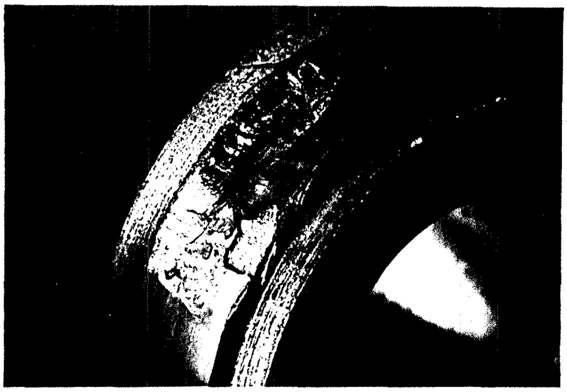


Figure 3-29: Example of a spalling failure on the filled Torlon. This failure occurred under rolling only

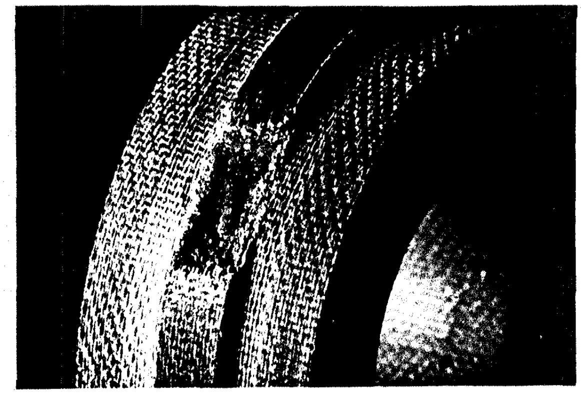


Figure 3-30: Typical spalling failure as observed on Phenolic test rollers under rolling traction only.

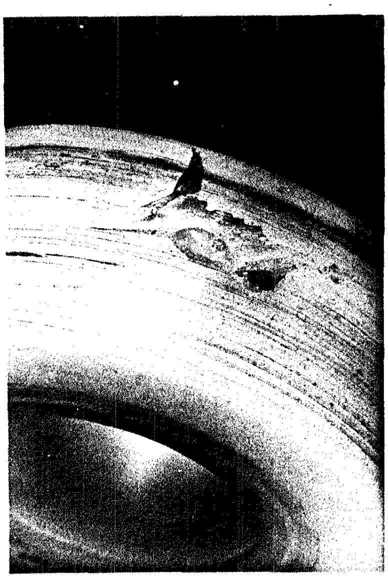


Figure 3-31: Example of sub-surface melting on Acetal. This shows a very early stage where the melted material has just broken through to the surface.

Figure 3-32: Example of a very advanced sub surface failure on Acetal. This one occurred under conditions of rolling only, with another Acetal roller in contact.

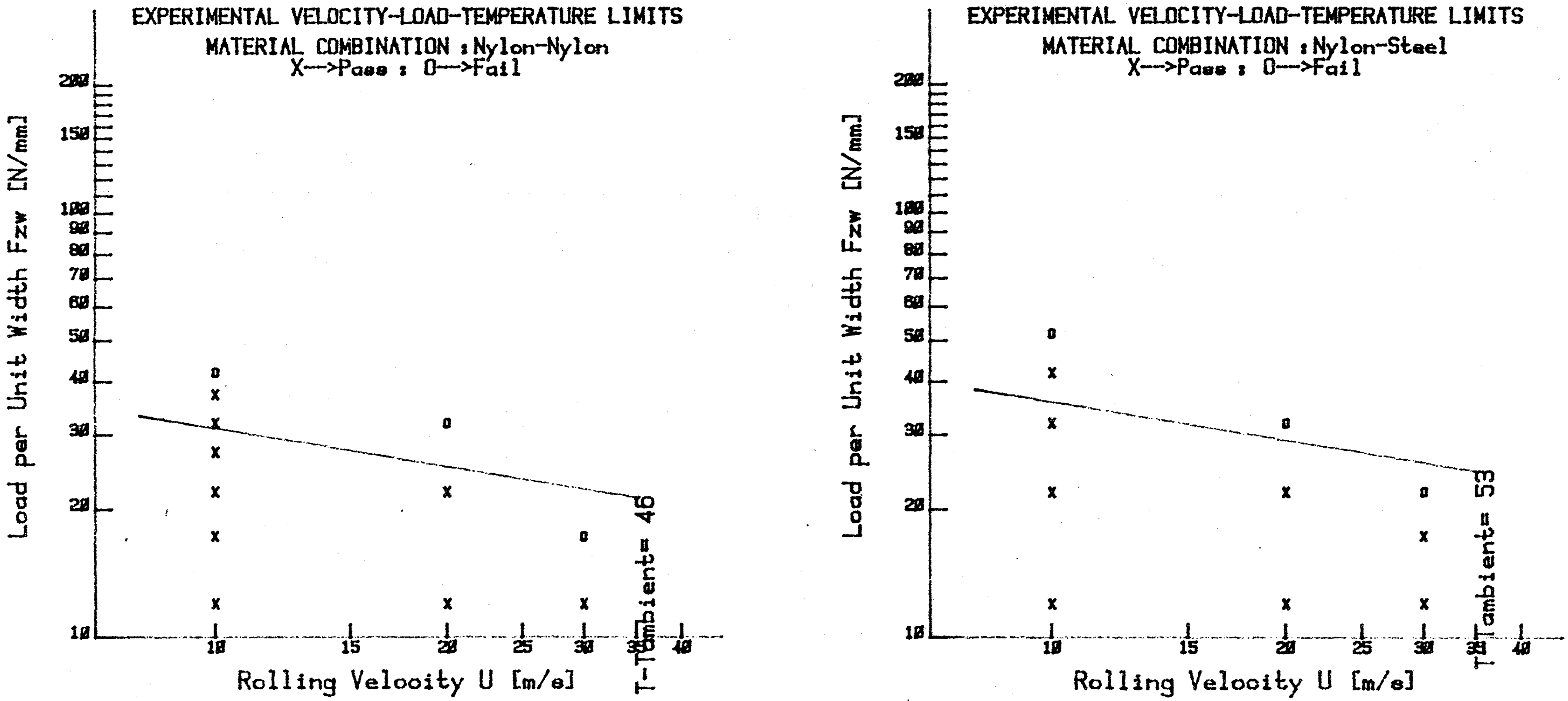


Figure 4-1: Experimental velocity - load -temperature limits for the Nylon - Nylon and Nylon - Steel roller combinations under rolling traction conditions only.

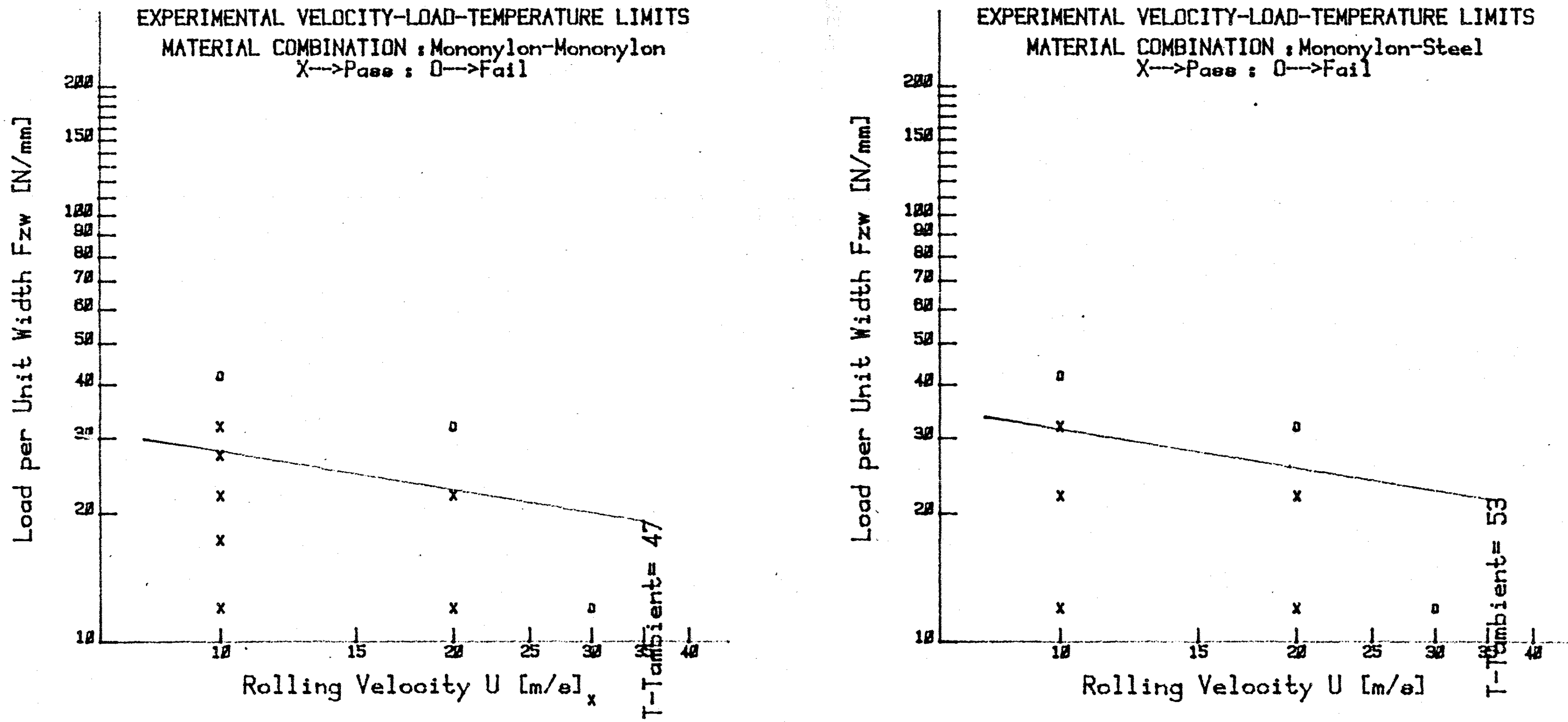


Figure 4-2: Experimental velocity - load -temperature limits for the Mono-Nylon - Mono-Nylon and Mono-Nylon - Steel roller combinations under rolling traction conditions only.

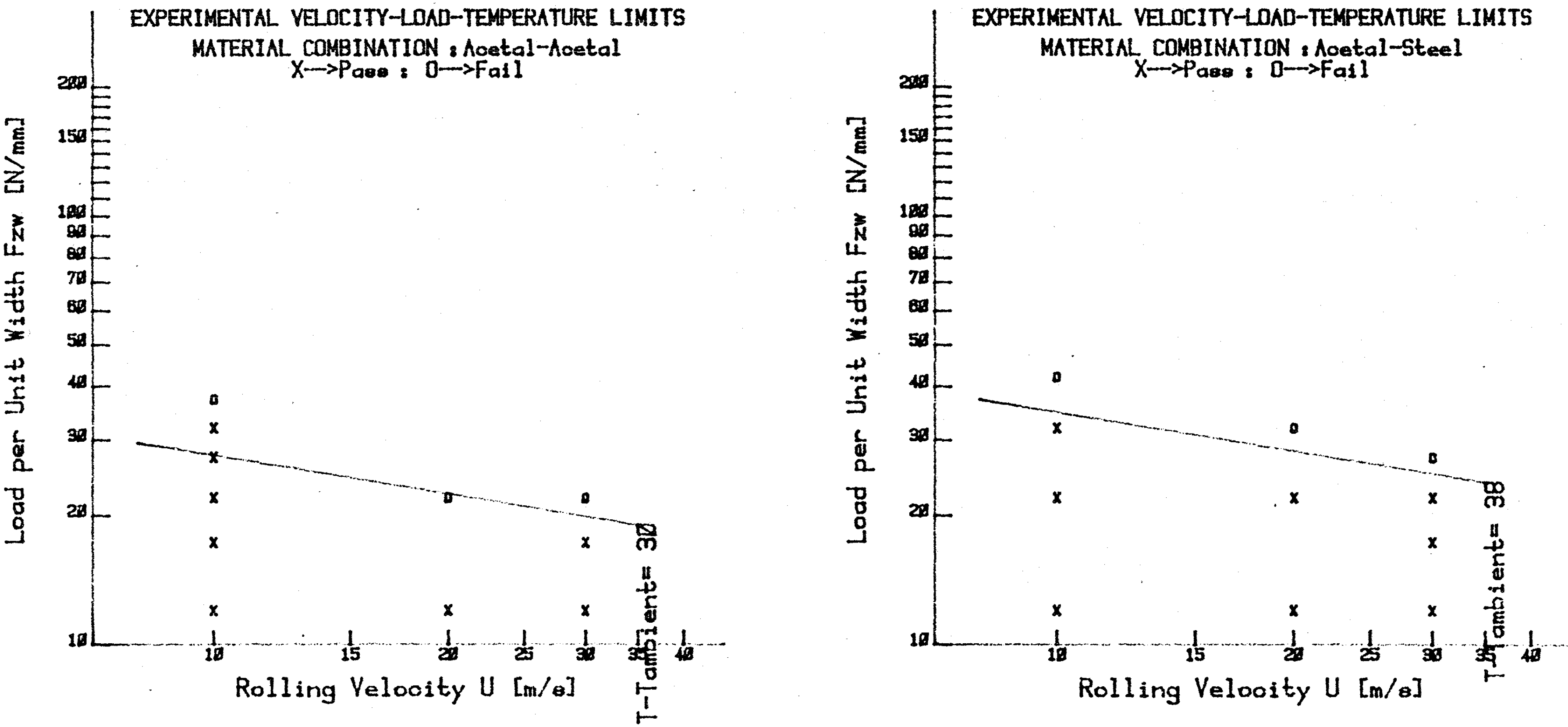


Figure 4-3: Experimental velocity - load -temperature limits for the Acetal - Acetal and Acetal - Steel roller combinations under rolling traction conditions only.

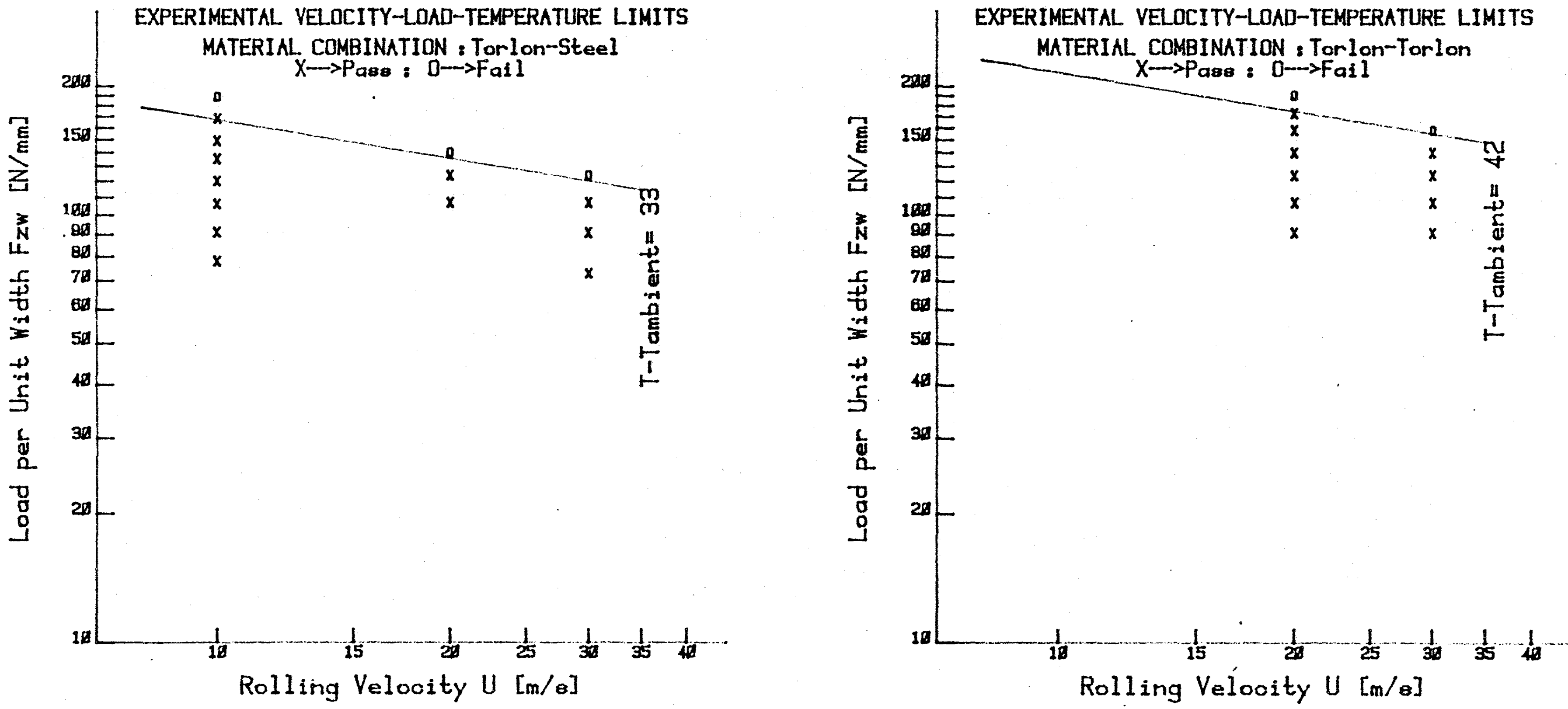
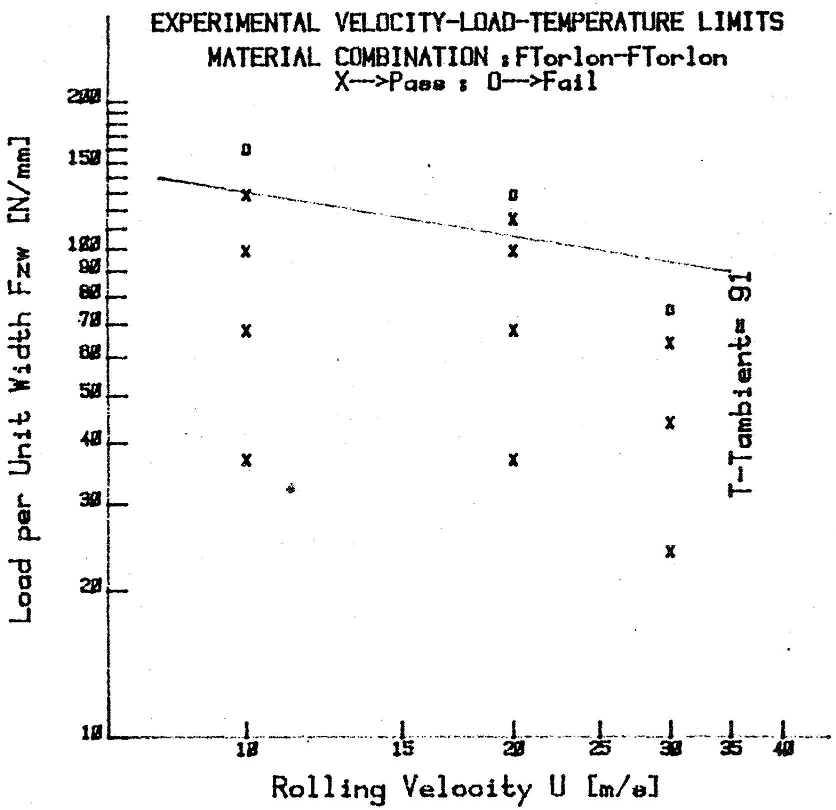


Figure 4-4: Experimental velocity - load -temperature limits for the Torlon - Torlon and Torlon - Steel roller combinations under rolling traction conditions only.



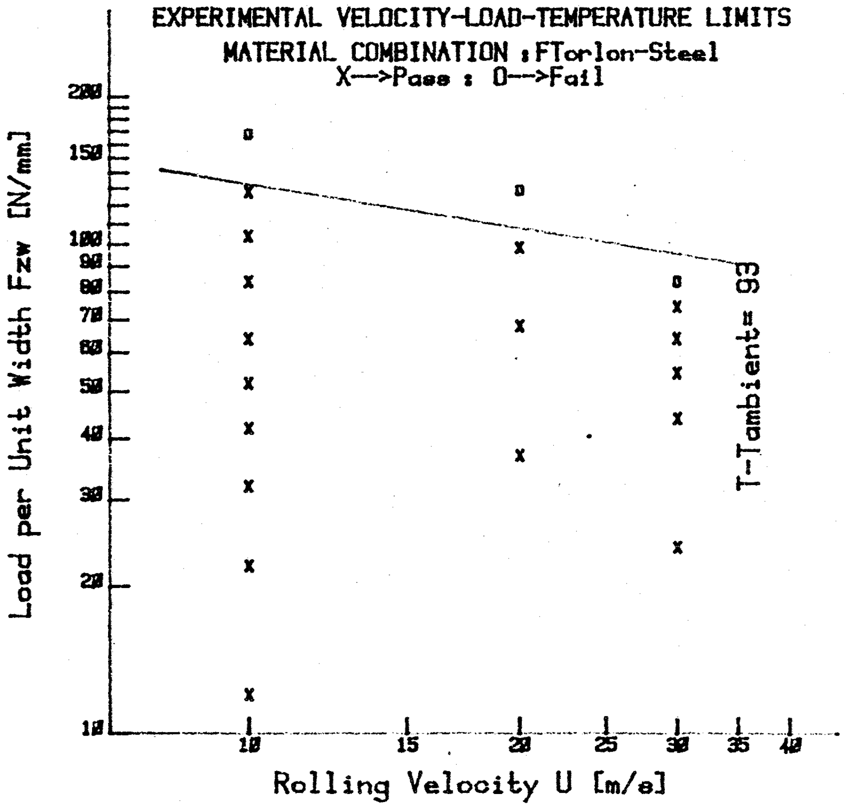


Figure 4-5: Experimental velocity - load -temperature limits for the FTorlon - FTorlon and FTorlon - Steel roller combinations under rolling traction conditions only.

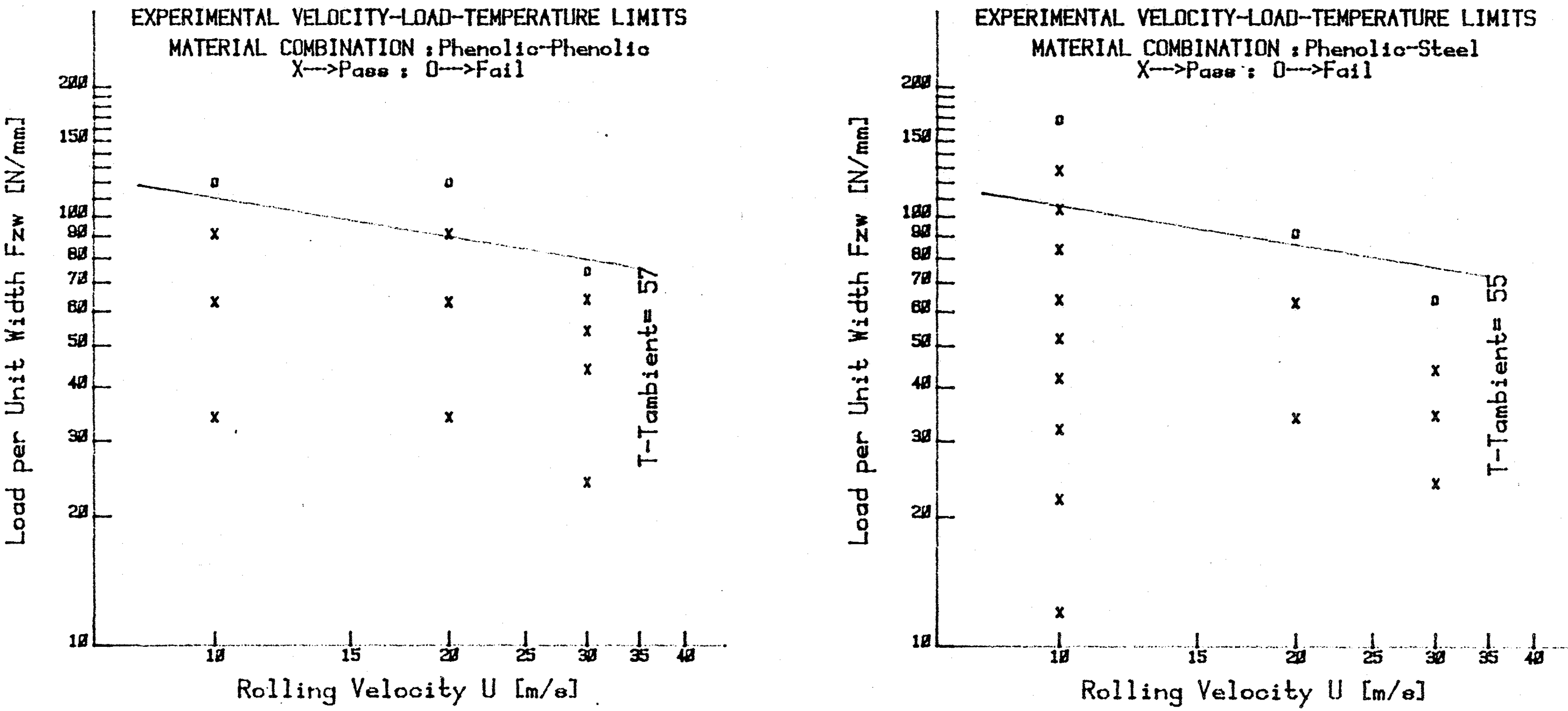
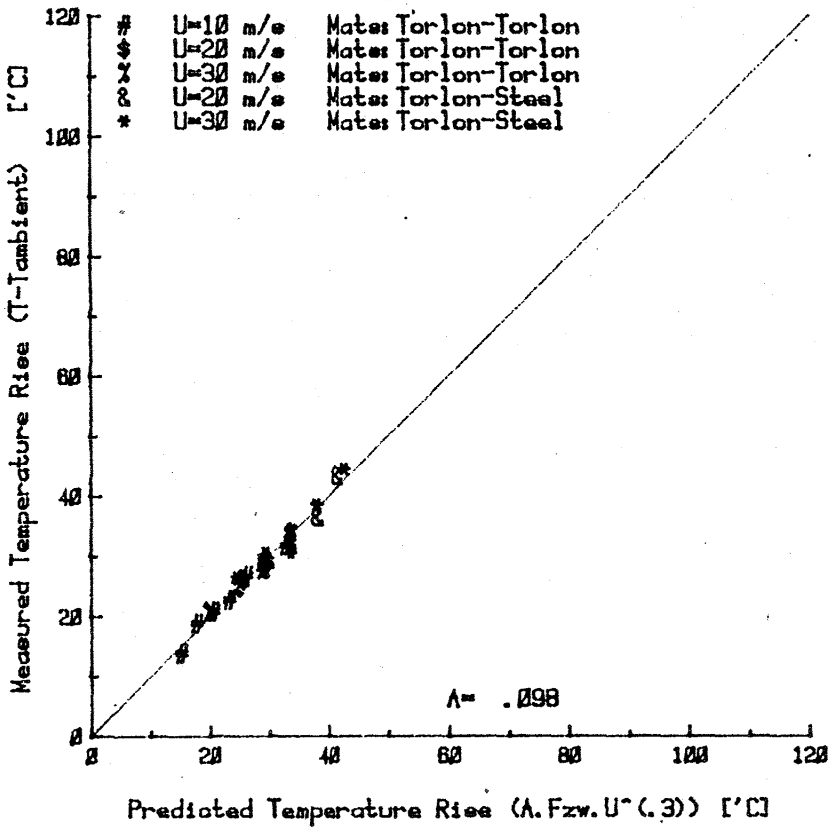
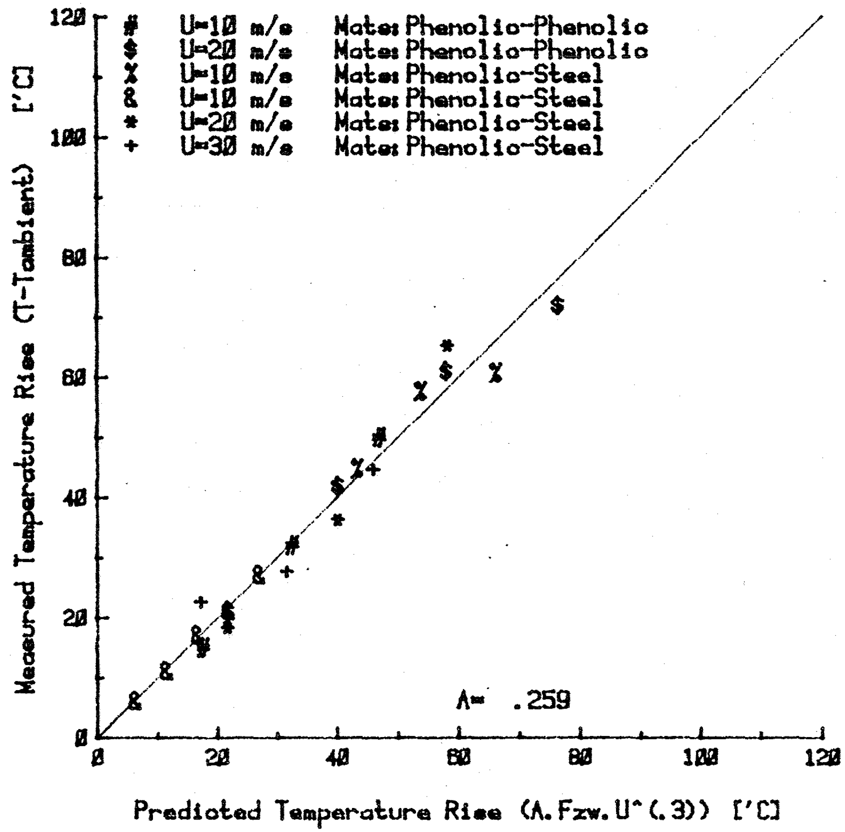
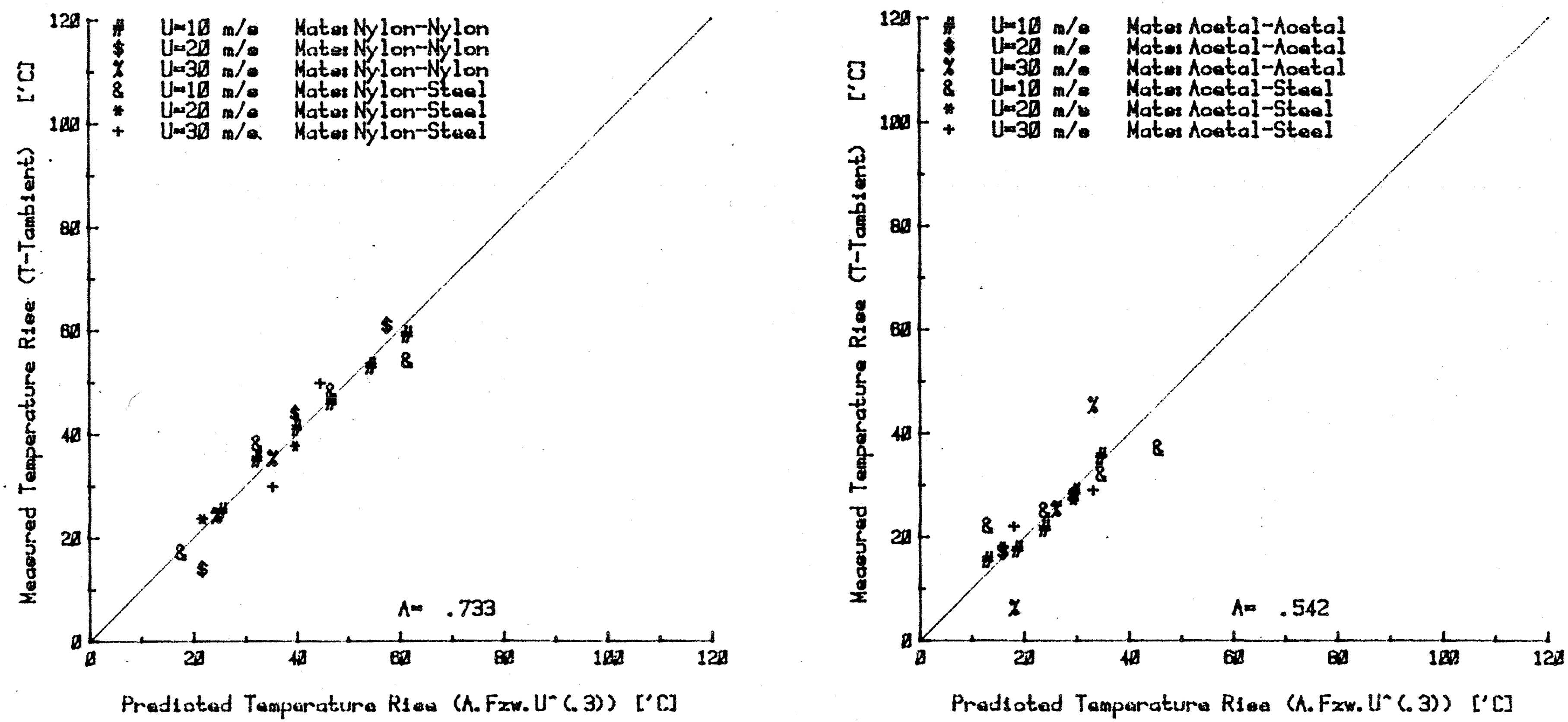


Figure 4-6: Experimental velocity - load -temperature limits for the Phenolic - Phenolic and Phenolic - Steel roller combinations under rolling traction conditions only.

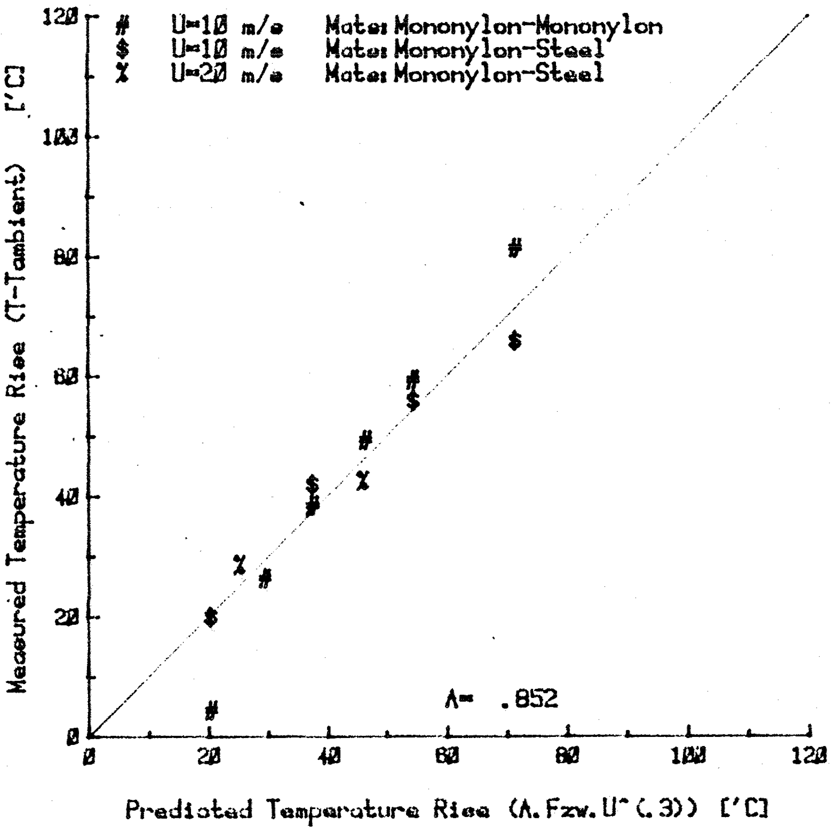


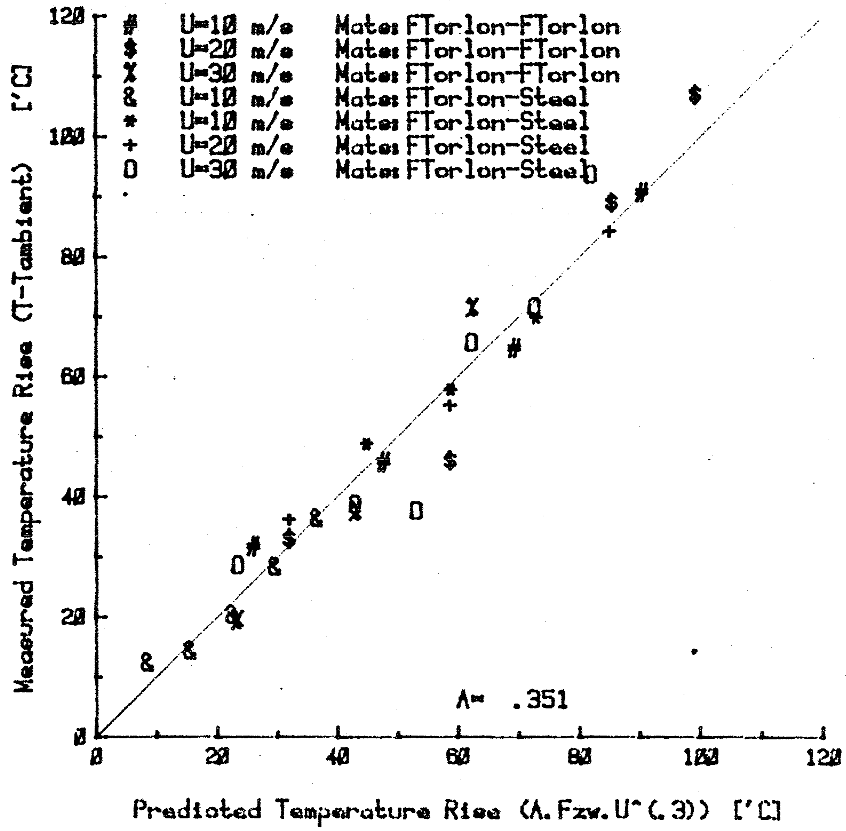


Figures 4-7 and 4-8: Comparison between predicted and experimental roller temperature for Torlon and Phenolic under rolling traction conditions only.



Figures 4-9 and 4-10: Comparison between predicted and experimental roller temperature for Nylon and Acetal under rolling traction conditions only.





Figures 4-11 and 4-12: Comparison between predicted and experimental roller temperature for Mono-Nylon and FTorlon under rolling traction conditions only.

Figures

5-1 and 5-2

Missing in Original Document

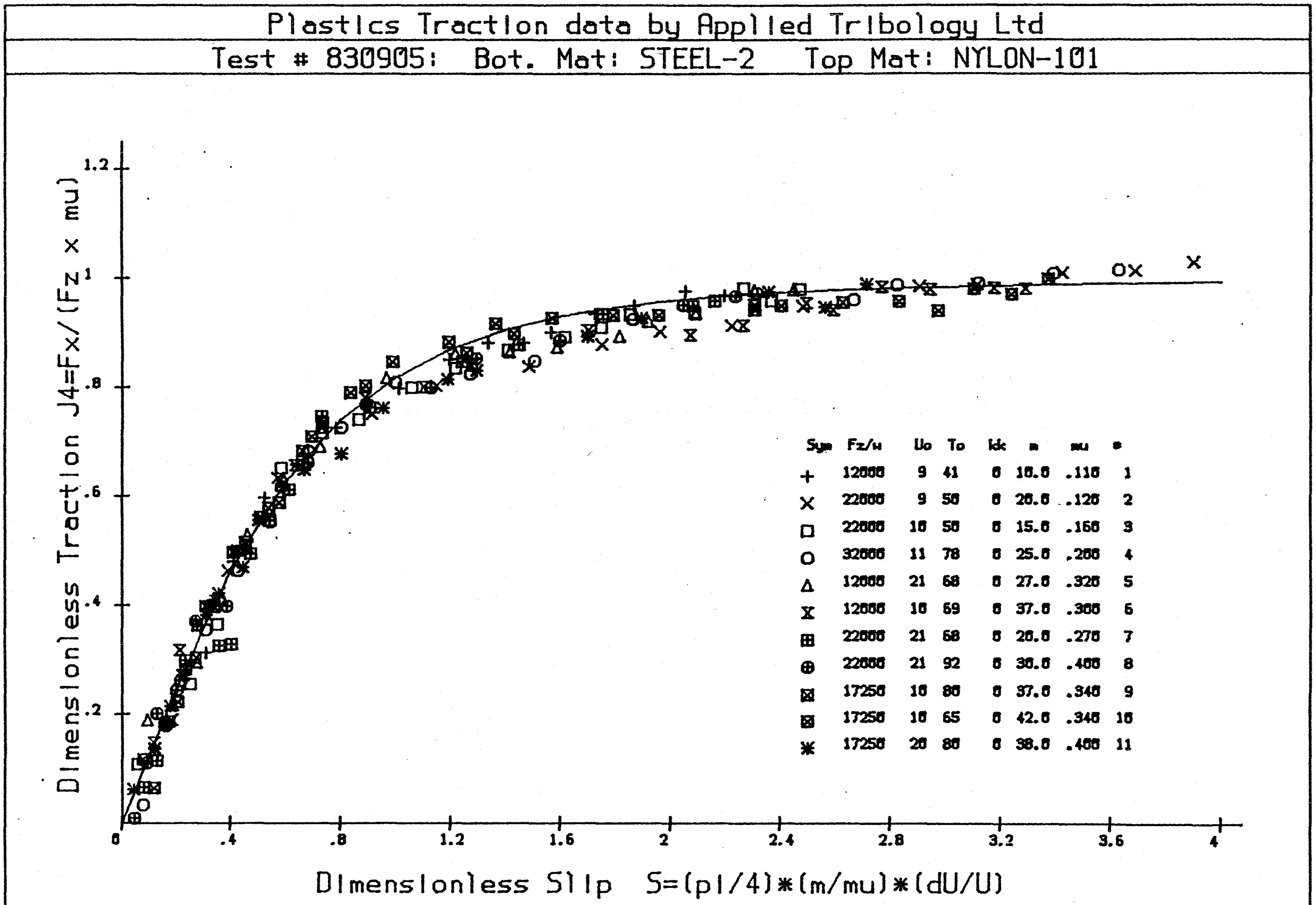


Figure 5-3: Experimental slip traction curves for Nylon - Steel roller combinations reduced to their dimensionless form.

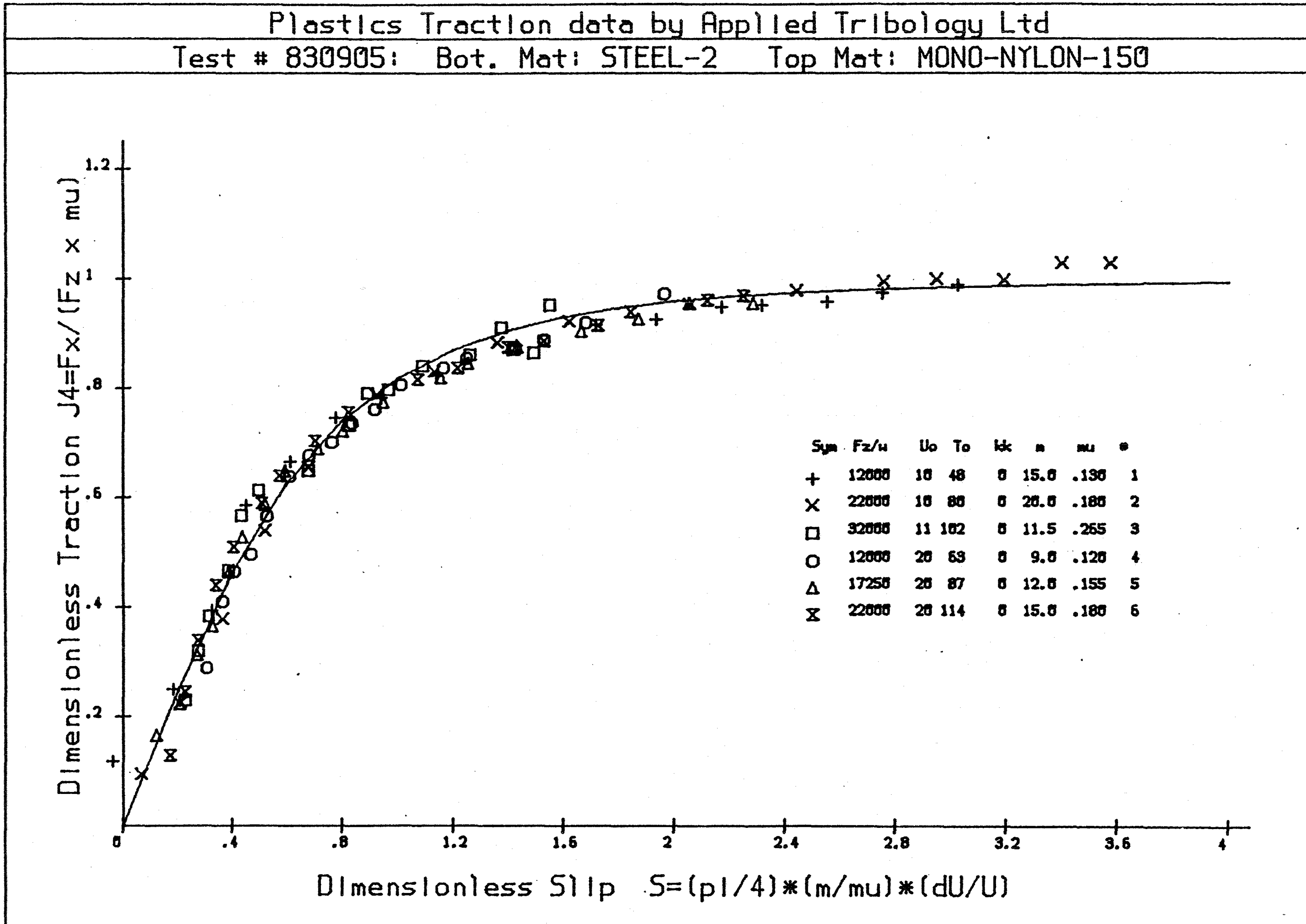


Figure 5-4: Experimental slip traction curves for Mono-Nylon - Steel roller combinations reduced to their dimensionless form.

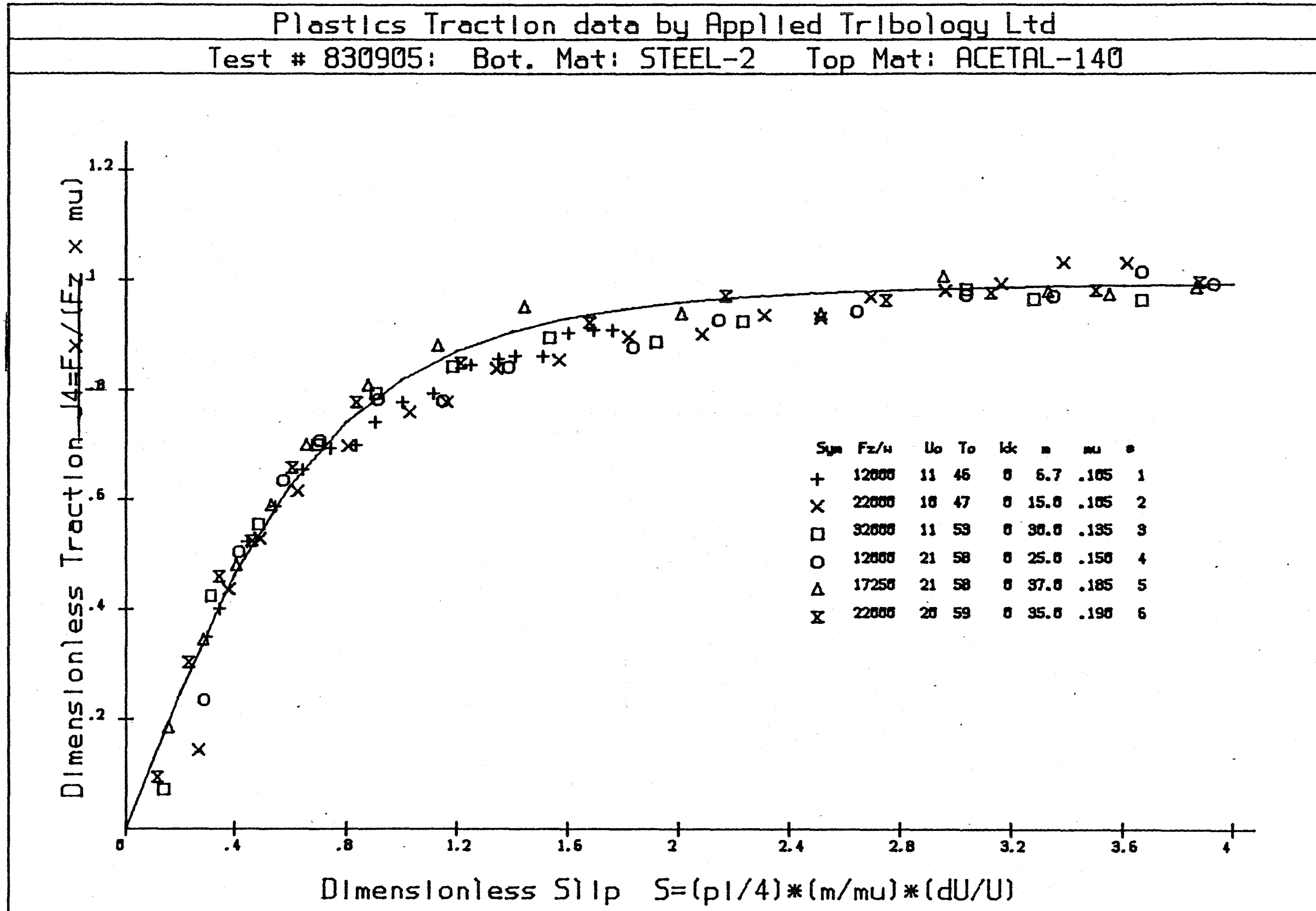


Figure 5-5: Experimental slip traction curves for Acetal - Steel roller combinations reduced to their dimensionless form.

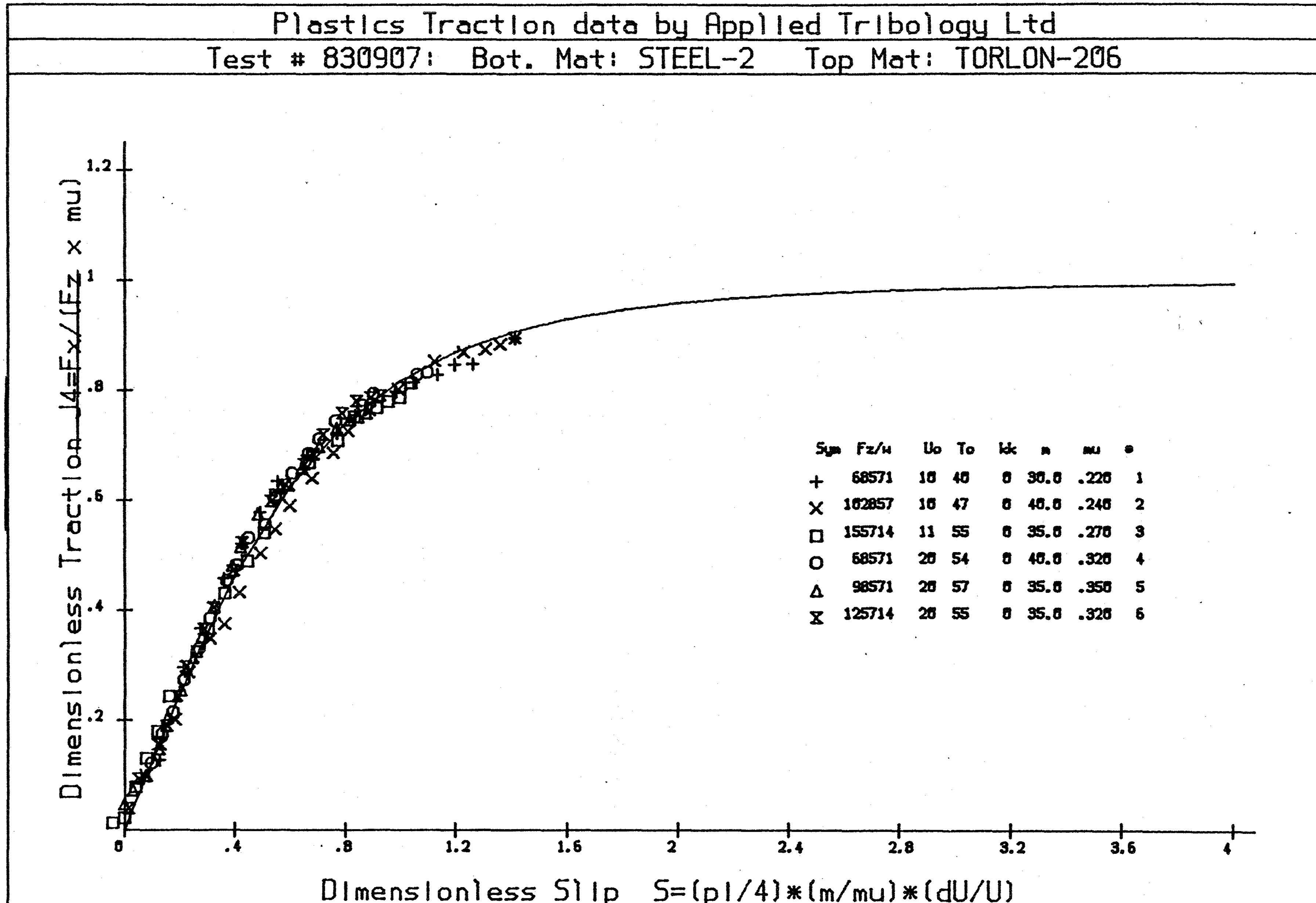


Figure 5-6: Experimental slip traction curves for Torlon - Steel roller combinations reduced to their dimensionless form.

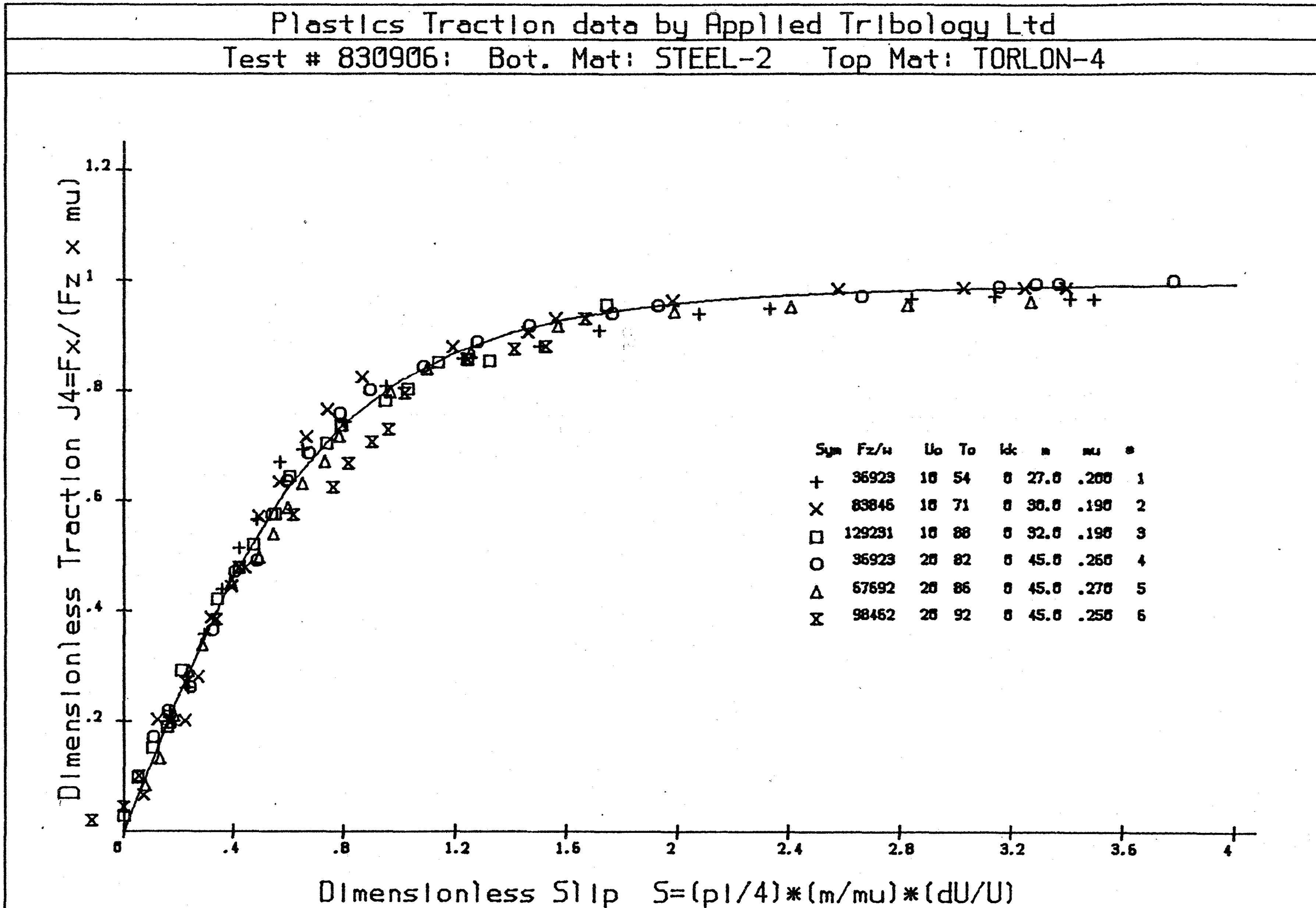


Figure 5-7: Experimental slip traction curves for FTorlon - Steel roller combinations reduced to their dimensionless form.

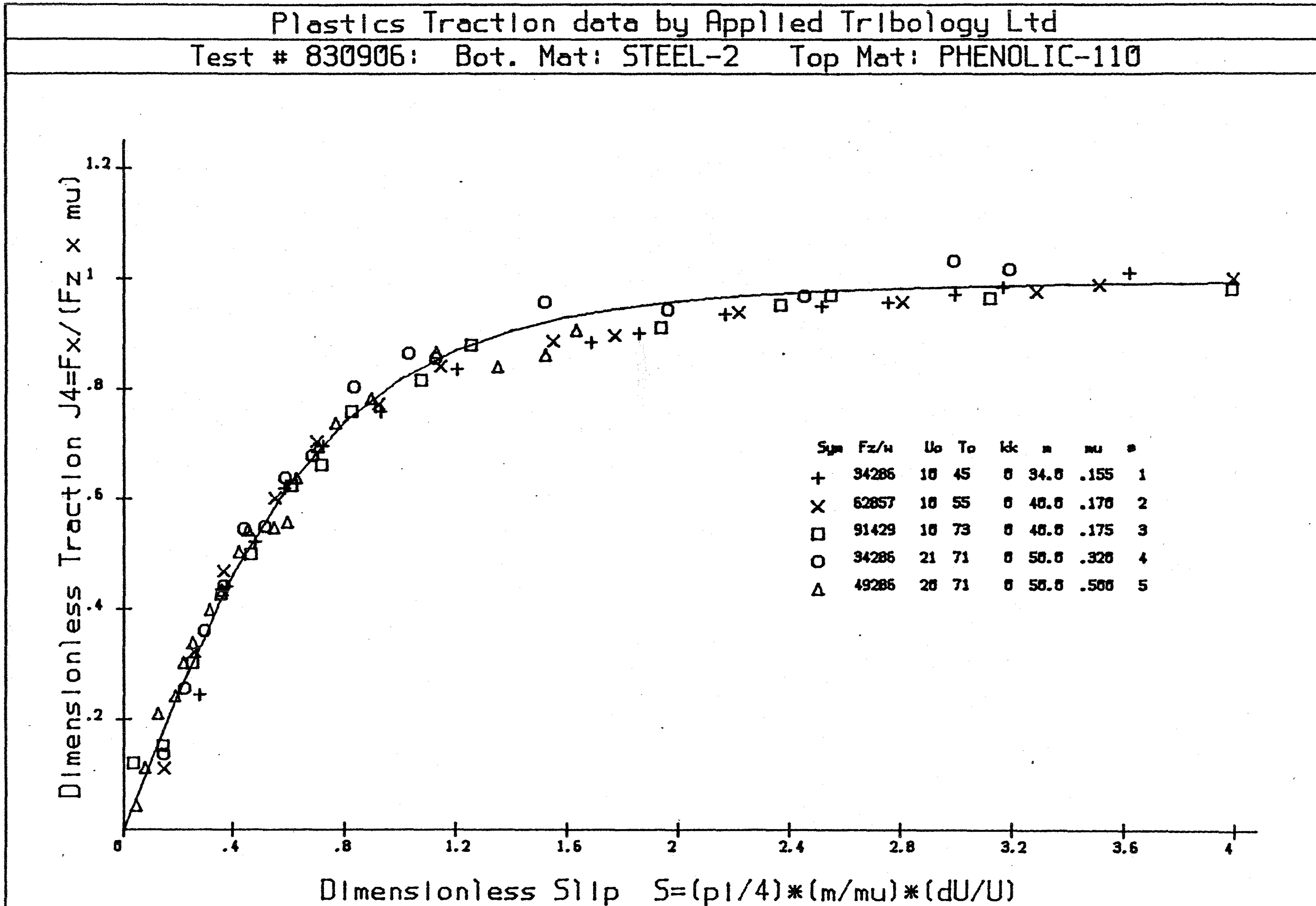
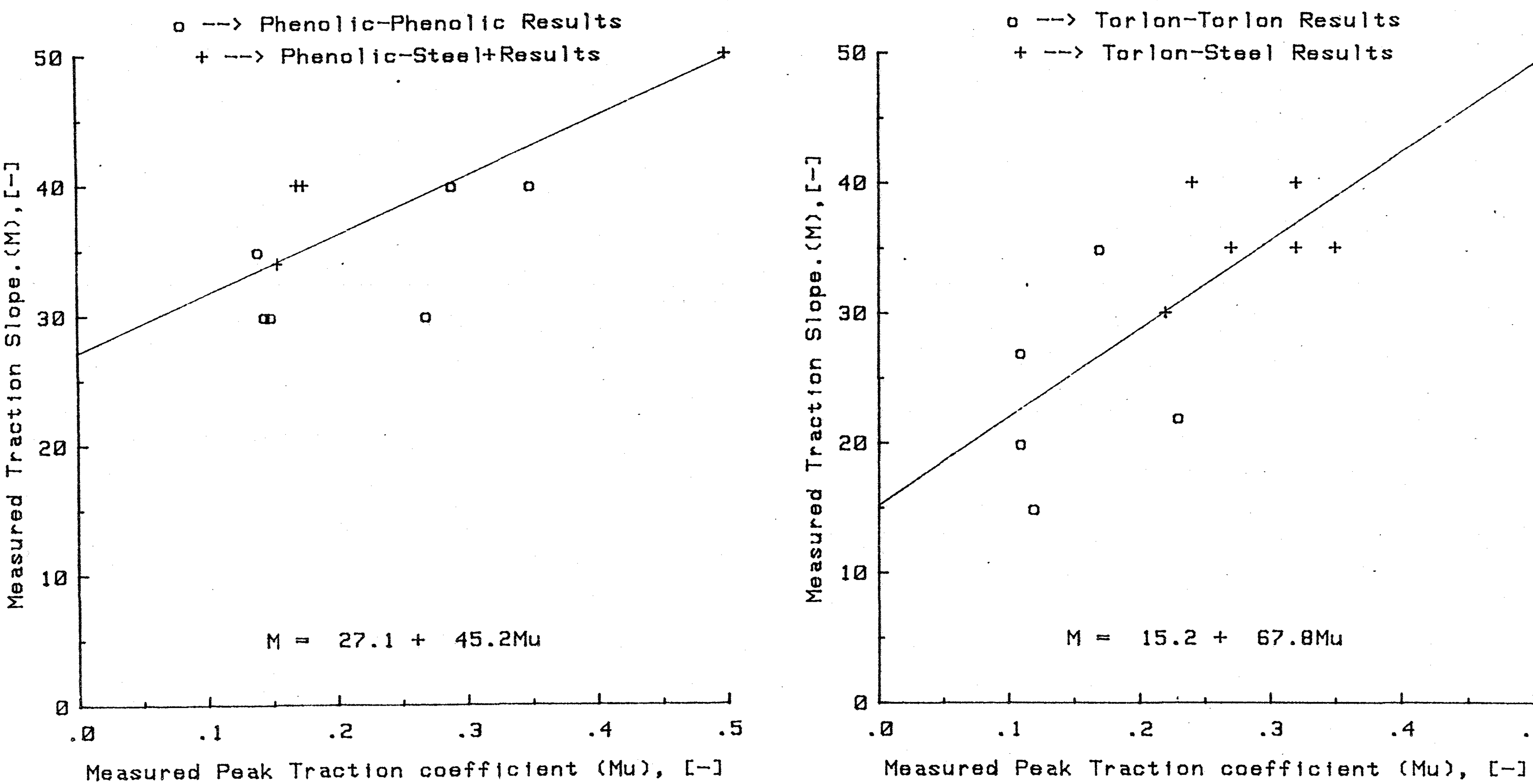
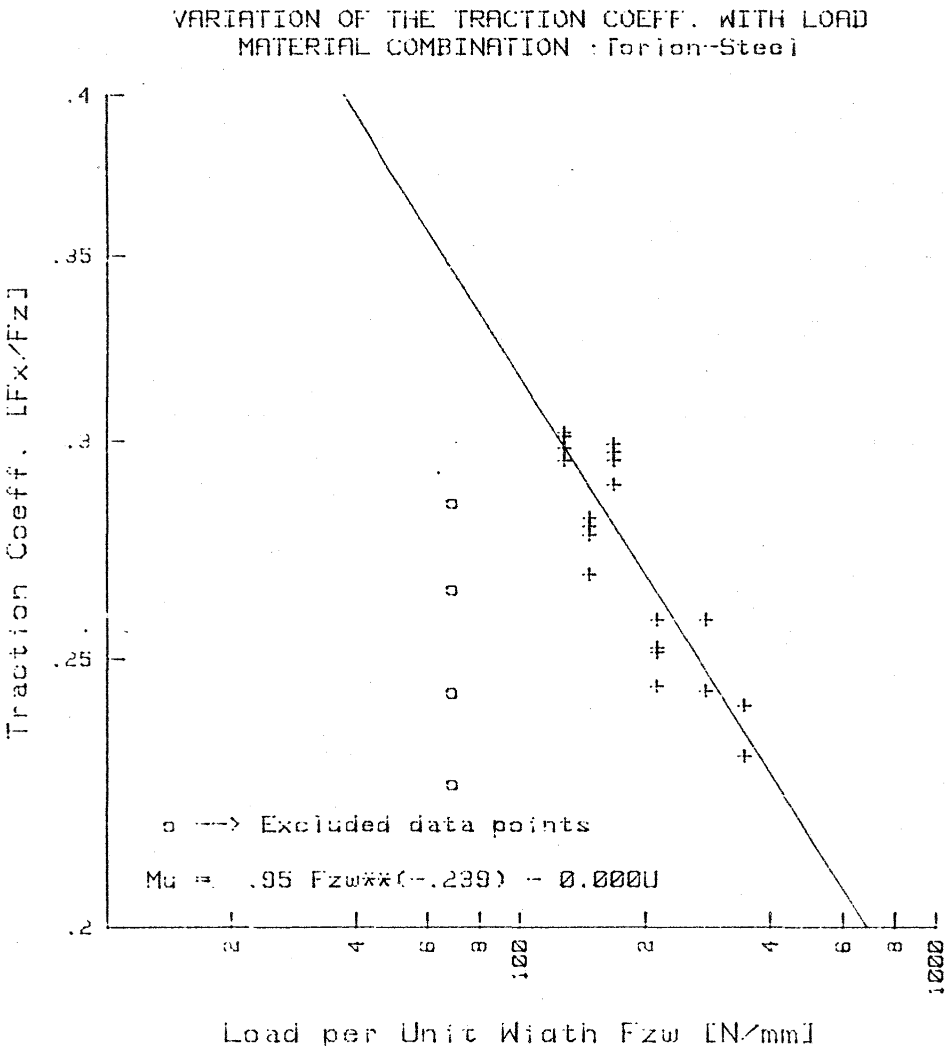
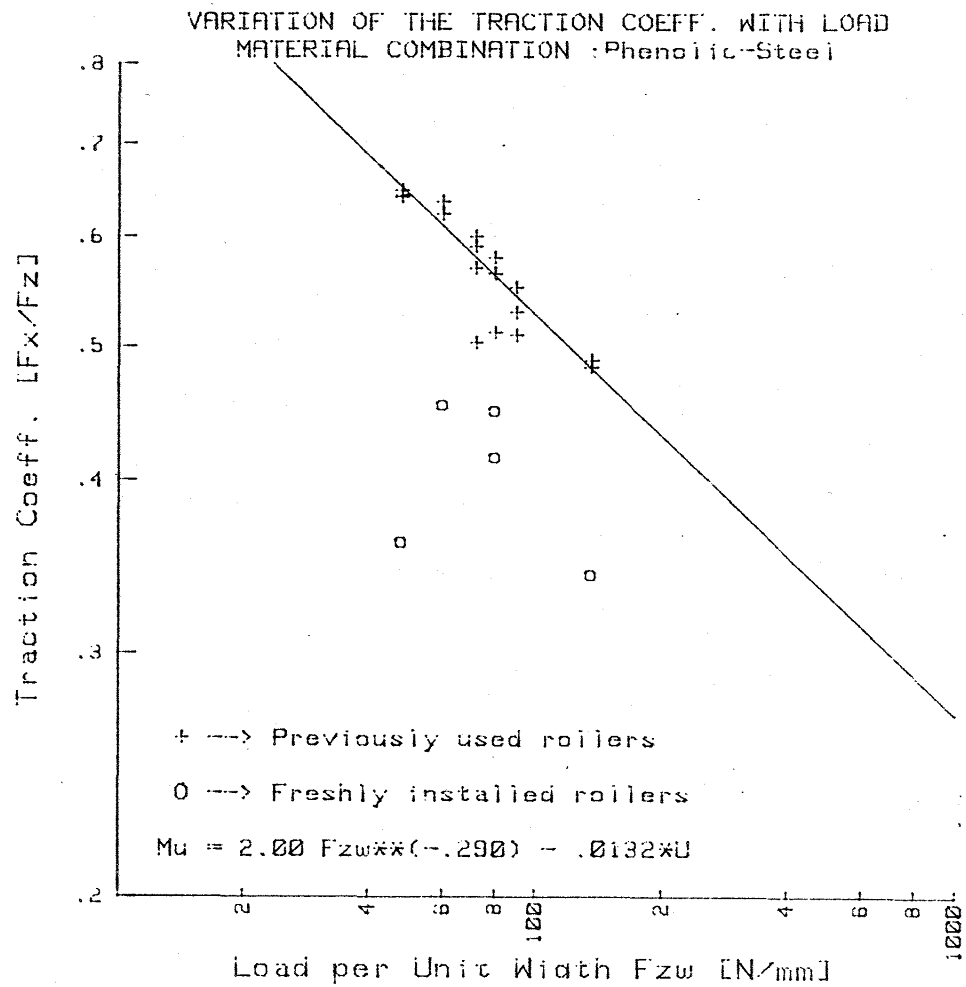


Figure 5-8: Experimental slip traction curves for Phenolic - Steel roller combinations reduced to their dimensionless form.

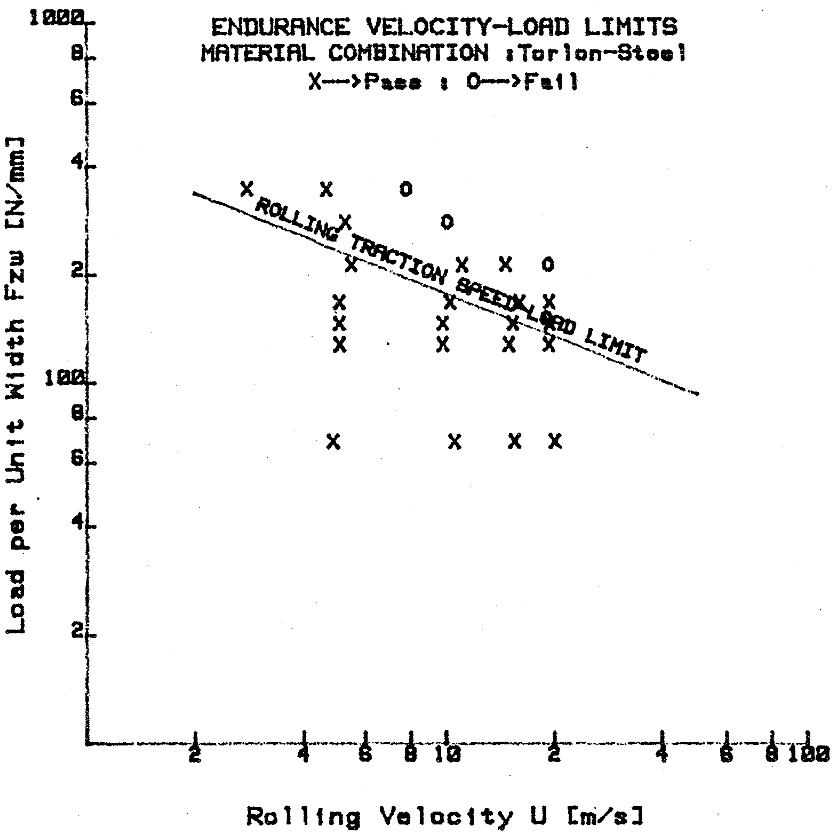


Figures 5-9 and 5-10: Correlation between the measured traction coefficient and the measured traction slope for the Phenolic and Torlon roller combinations tested under slip traction.





Figures 5-11 and 5-12: Variation of the slip traction coefficient, measured during the endurance traction tests, as a function of the contact load F_{zw}. The line through the data corresponds to the correlated function as indicated.



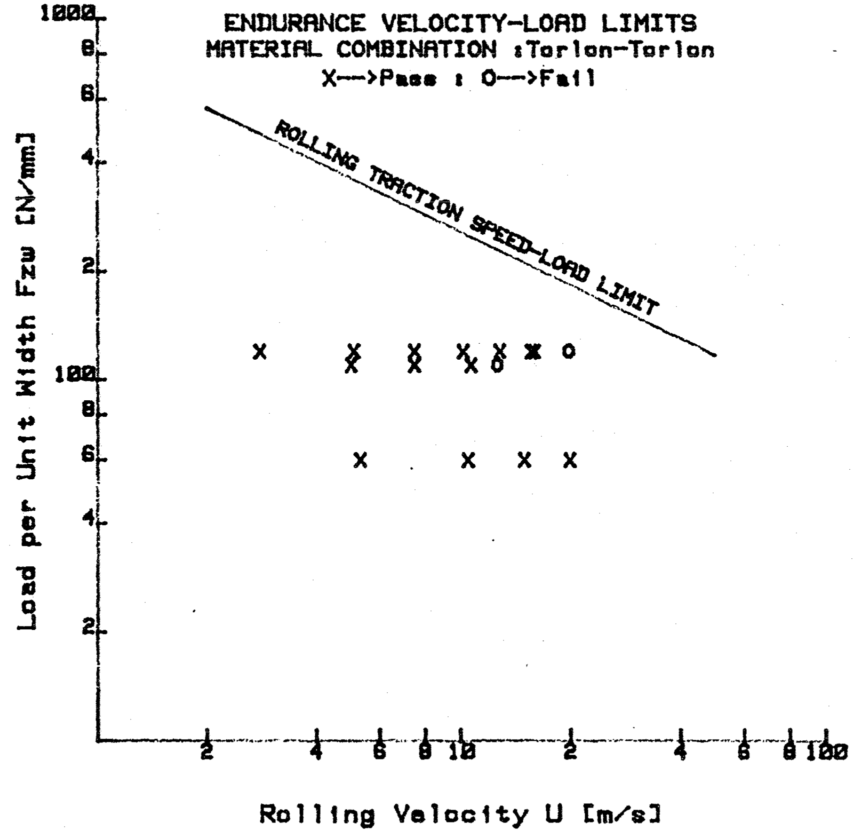
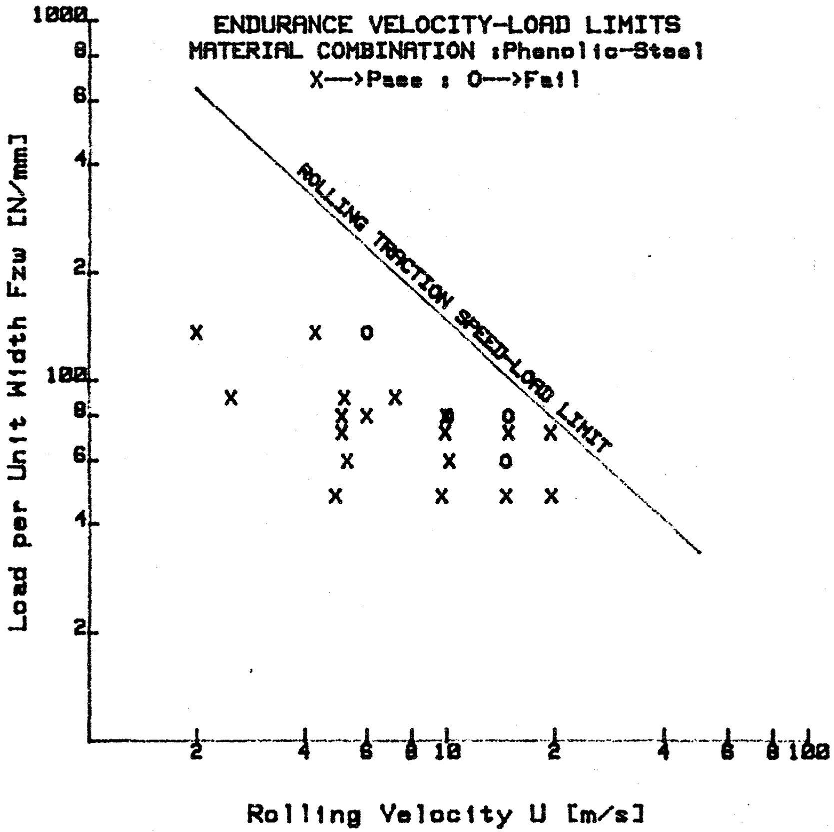


Figure 6-1: Experimental velocity - load limits for the Torlon - Steel and Torlon - Torlon under conditions of slip traction. Also indicated are the velocity - load limits for pure rolling conditions only.



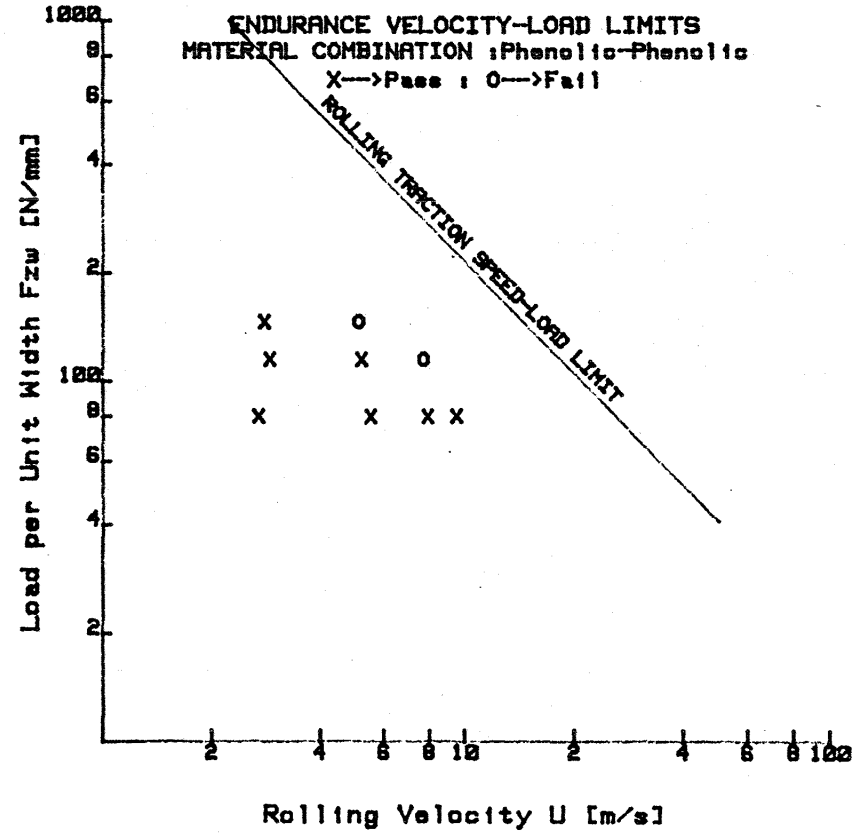
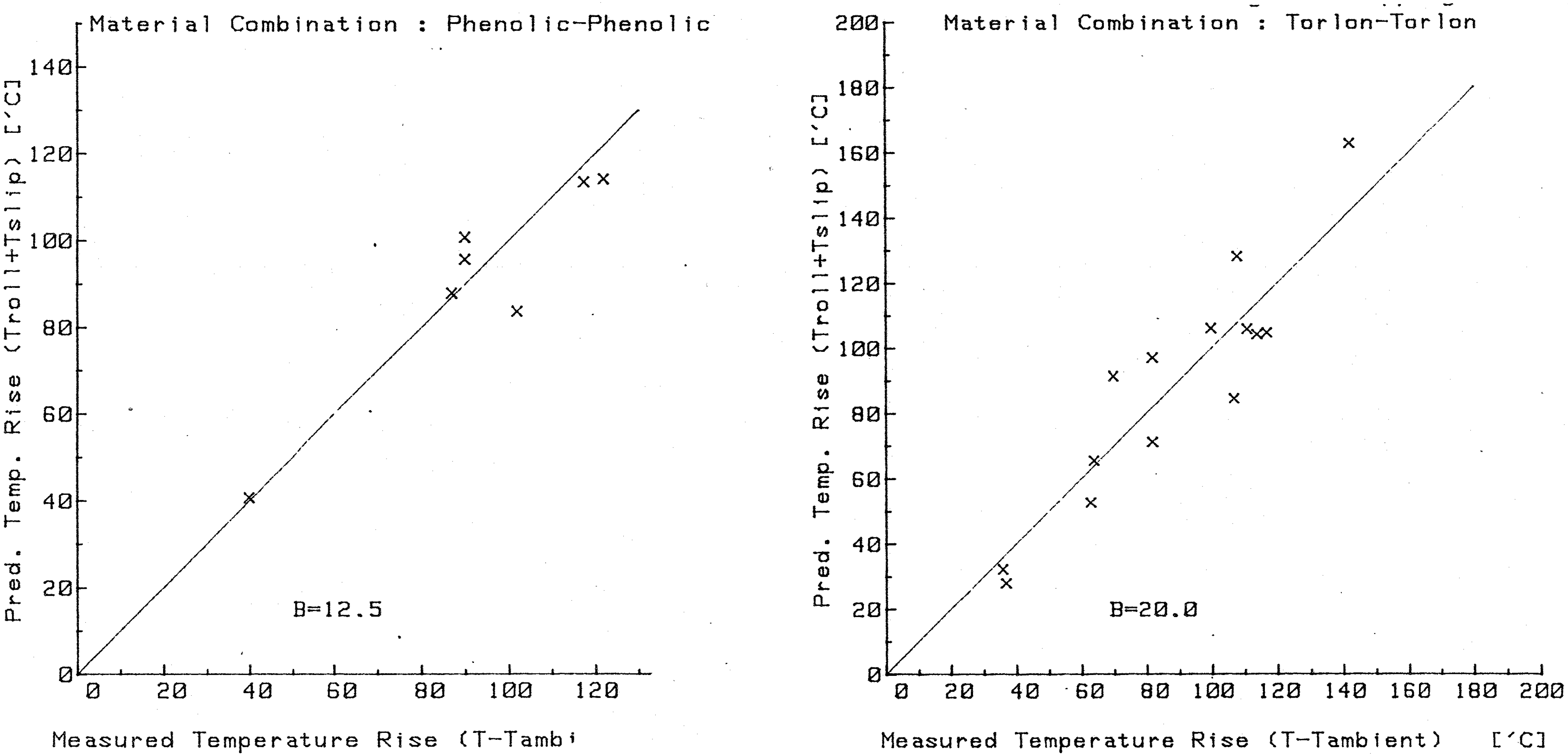
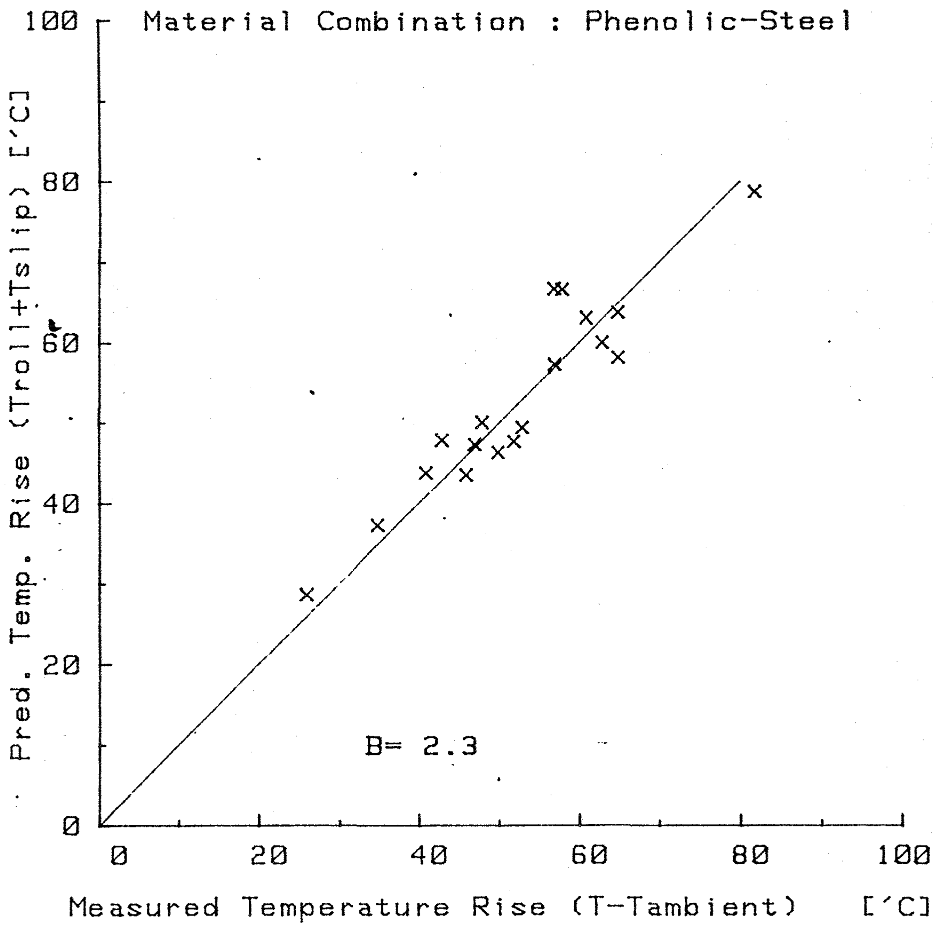
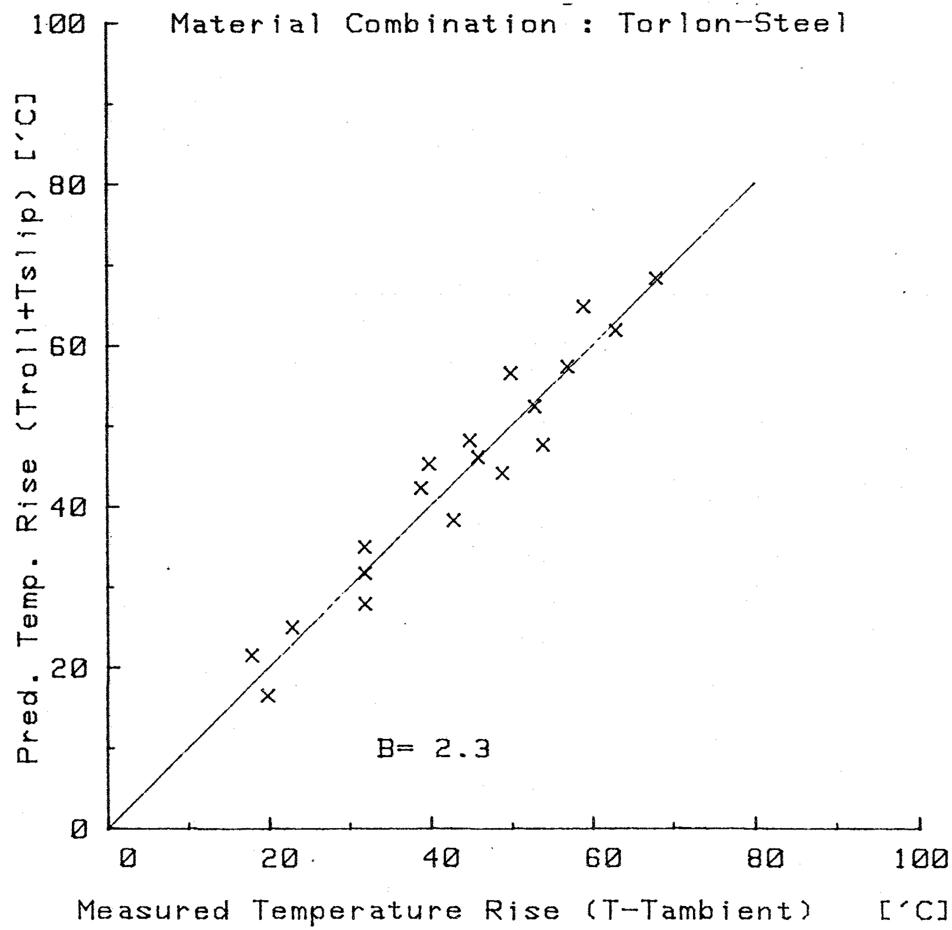


Figure 6-2: Experimental velocity - load limits for the Phenolic - Steel and Phenolic - Phenolic under conditions of slip traction. Also indicated are the velocity - load limits for pure rolling conditions only.



Figures 6-3 and 6-4: Comparison between predicted and experimental roller temperature increases for the Phenolic - Phenolic and Torlon - Torlon roller combinations under conditions of slip traction.





Figures 6-5 and 6-6: Comparison between predicted and experimental roller temperature increases for the Phenolic - Steel and Torlon - Steel roller combinations under conditions of slip traction.

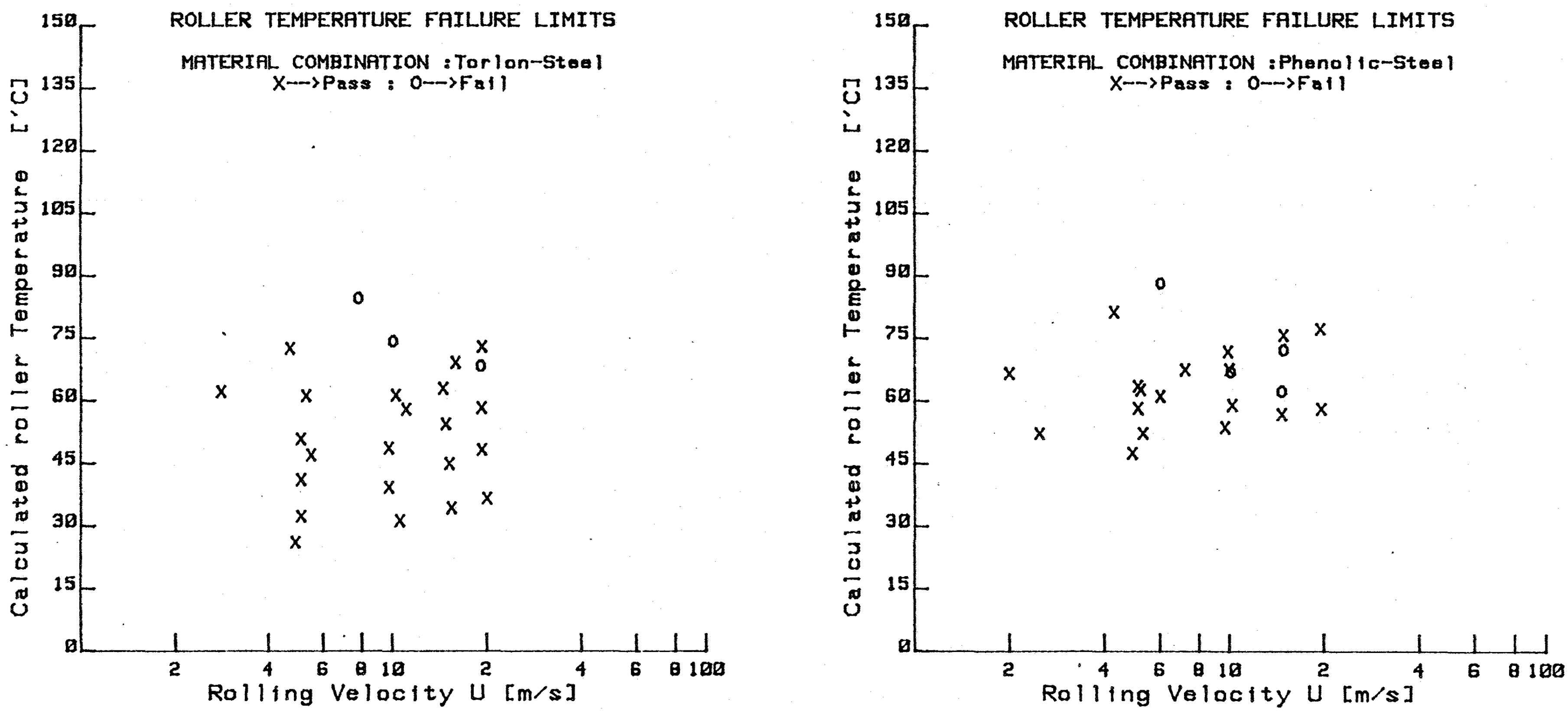


Figure 6-7: Roller temperature failure limits for Torlon -Steel and Phenolic - Steel roller combinations under conditions of slip traction. Both the slip traction and rolling traction power dissipation are used to calculate the roller temperature.

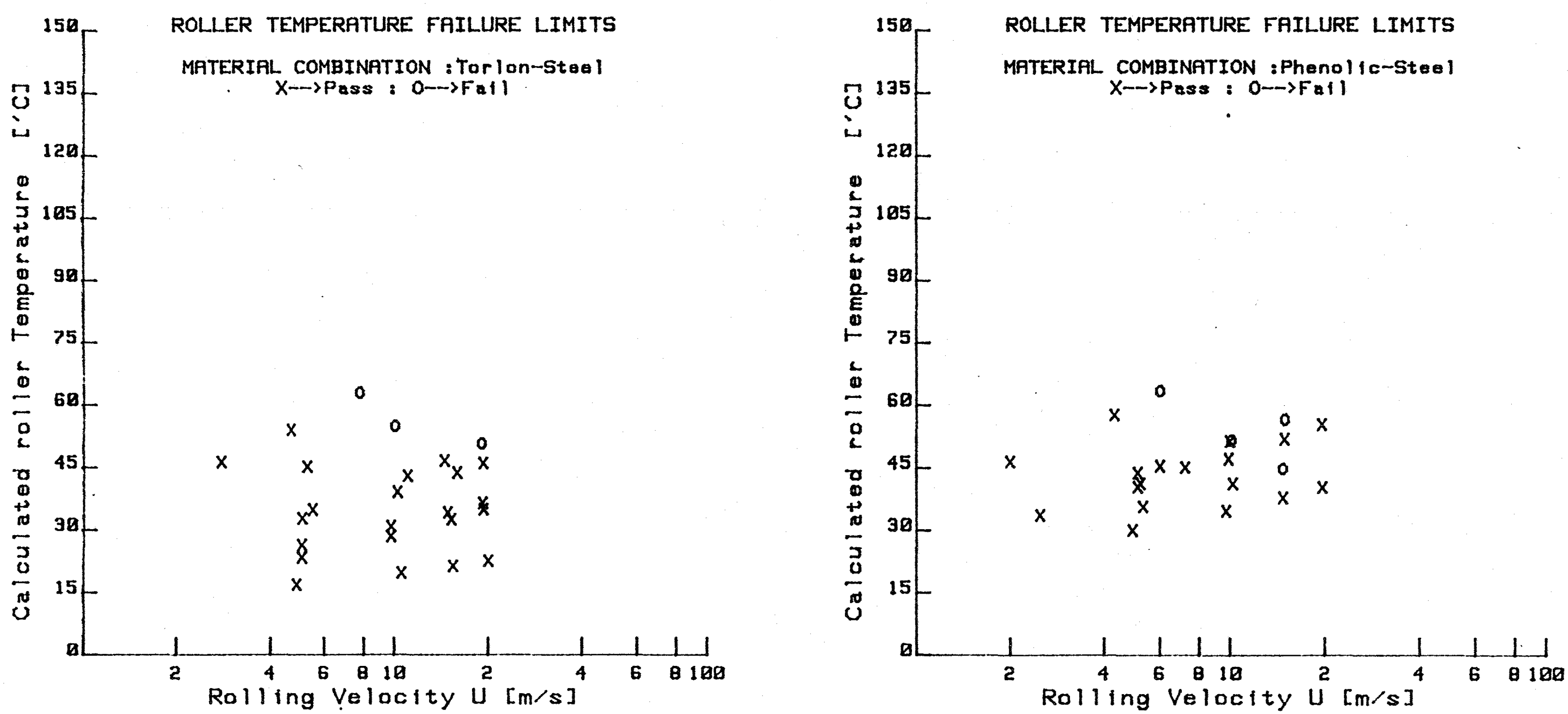


Figure 6-8: Roller temperature failure limits for Torlon -Steel and Phenolic - Steel roller combinations under conditions of slip traction. Only the rolling traction power dissipated is used to calculate the roller temperature.

SUMMARY SHEETS FOR PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Rol. Trac. (%)
8306072	240	1800	PHENOLIC 2	25.03	STEEL 1	24.96	20.0	Lin	12.0	No	10.2	-.0082	47	1.4
8306073	440	1800	PHENOLIC 2	25.03	STEEL 1	24.96	20.0	Lin	22.0	No	10.1	-.1285	52	.8
8306074	640	1800	PHENOLIC 2	25.03	STEEL 1	24.96	20.0	Lin	32.0	No	10.1	-.2246	58	.7
8306075	840	1800	PHENOLIC 2	25.03	STEEL 1	24.96	20.0	Lin	42.0	No	10.1	-.3186	62	.5
8306076	1040	1800	PHENOLIC 2	25.03	STEEL 1	24.96	20.0	Lin	52.0	No	10.1	-.4086	68	.1
8306077	640	1800	PHENOLIC 2	25.02	STEEL 1	24.96	10.0	Lin	64.0	No	10.3	-.4324	57	.5
8306081	840	1800	PHENOLIC 2	25.02	STEEL 1	24.96	10.0	Lin	84.0	No	10.1	-.4790	54	.5
8306082	1040	1800	PHENOLIC 2	25.02	STEEL 1	24.96	10.0	Lin	104.	No	10.3	-.5787	67	.4
8306083	640	1800	PHENOLIC 2	25.02	STEEL 1	24.96	5.0	Lin	128.	No	10.1	-.6120	70	.6
8306084	840	150	PHENOLIC 2	25.02	STEEL 1	24.96	5.0	Lin	168.	Yes	10.1	0.0000	0	0.0
8306134	240	1800	PHENOLIC 1	25.01	STEEL 1	24.96	7.0	Lin	34.3	No	20.1	-.1085	68	.9
8306135	440	1800	PHENOLIC 1	25.01	STEEL 1	24.96	7.0	Lin	62.9	No	20.1	-.2918	86	.5
8306136	640	128	PHENOLIC 1	25.01	STEEL 1	24.96	7.0	Lin	91.4	Yes	20.1	0.0000	0	0.0
8306271	240	1800	PHENOLIC 9	24.98	STEEL 2	24.99	10.0	Lin	24.0	No	30.3	.1000	68	.5
8306272	345	1800	PHENOLIC 9	24.98	STEEL 2	24.99	10.0	Lin	34.5	No	30.3	.0333	72	.4
8306273	440	1800	PHENOLIC 9	24.98	STEEL 2	24.99	10.0	Lin	44.0	No	30.3	-.0333	73	.3
8306274	640	68	PHENOLIC 9	24.98	STEEL 2	24.99	10.0	Lin	64.0	Yes	29.5	0.0000	0	0.0
8306171	240	1800	PHENOLIC 3	25.01	PHENOLIC 5	25.01	7.0	Lin	34.3	No	10.0	.1334	43	1.3
8306172	440	1800	PHENOLIC 3	25.01	PHENOLIC 5	25.01	7.0	Lin	62.9	No	10.2	.1001	60	.8
8306173	640	1800	PHENOLIC 3	25.01	PHENOLIC 5	25.01	7.0	Lin	91.4	No	10.6	.0667	78	.6
8306174	840	263	PHENOLIC 3	25.01	PHENOLIC 5	25.01	7.0	Lin	120.	Yes	10.1	0.0000	0	0.0
8306211	240	1800	PHENOLIC 6	24.98	PHENOLIC 7	24.98	7.0	Lin	34.3	No	20.1	.0333	59	1.0
8306212	440	1800	PHENOLIC 6	24.98	PHENOLIC 7	24.98	7.0	Lin	62.9	No	20.1	.0333	80	.5
8306213	640	1800	PHENOLIC 6	24.98	PHENOLIC 7	24.98	7.0	Lin	91.4	No	20.1	.0333	99	.4
8306214	840	180	PHENOLIC 6	24.98	PHENOLIC 7	24.98	7.0	Lin	120.	Yes	20.1	0.0000	0	0.0
8306301	240	1800	PHENOLIC 8	24.97	PHENOLIC 10	24.96	10.0	Lin	24.0	No	29.8	-.0333	118	.6
8306302	440	1800	PHENOLIC 8	24.97	PHENOLIC 10	24.96	10.0	Lin	44.0	No	29.8	-.0100	91	.4
8306303	545	1800	PHENOLIC 8	24.97	PHENOLIC 10	24.96	10.0	Lin	54.5	No	29.8	0.0000	90	.3
8306304	640	1800	PHENOLIC 8	24.97	PHENOLIC 10	24.96	10.0	Lin	64.0	No	29.8	0.0000	95	.2
8306305	745	270	PHENOLIC 8	24.97	PHENOLIC 10	24.96	10.0	Lin	74.5	Yes	30.0	0.0000	0	0.0

SUMMARY SHEETS FOR PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Rol. Trac. (%)
8306093	240	1800	TORLON 1	25.06	STEEL 1	24.96	20.0	Lin	12.0	No	10.3	.0846	45	1.2
8306094	440	1800	TORLON 1	25.06	STEEL 1	24.96	20.0	Lin	22.0	No	10.1	.0343	47	.7
8306095	640	1800	TORLON 1	25.06	STEEL 1	24.96	20.0	Lin	32.0	No	10.1	.0176	53	.4
8306096	840	1800	TORLON 1	25.06	STEEL 1	24.96	20.0	Lin	42.0	No	10.1	-.0159	61	.3
8306097	1040	1800	TORLON 1	25.06	STEEL 1	24.96	20.0	Lin	52.0	No	10.1	-.0159	69	.3
8306098	640	1800	TORLON 1	25.06	STEEL 1	24.96	10.0	Lin	64.0	No	10.1	-.0159	59	.5
8306099	840	1800	TORLON 1	25.06	STEEL 1	24.96	10.0	Lin	84.0	No	10.1	-.0159	68	.4
83060910	1040	1800	TORLON 1	25.06	STEEL 1	24.96	10.0	Lin	104.	No	10.1	-.0159	80	.4
8306101	640	1800	TORLON 1	25.06	STEEL 1	24.96	5.0	Lin	128.	No	10.1	-.0493	66	.6
8306102	840	428	TORLON 1	25.06	STEEL 1	24.96	5.0	Lin	168.	Yes	10.1	0.0000	0	0.0
8306137	240	1800	TORLON 2	25.03	STEEL 1	24.96	6.5	Lin	36.9	No	20.1	-.0416	67	.8
8306138	440	1800	TORLON 2	25.03	STEEL 1	24.96	6.5	Lin	67.7	No	20.6	-.0984	86	.5
8306139	640	1800	TORLON 2	25.03	STEEL 1	24.96	6.5	Lin	98.5	No	20.1	-.0650	115	.5
8306141	840	53	TORLON 2	25.03	STEEL 1	24.96	6.5	Lin	129.	Yes	17.2	0.0000	0	0.0
8306281	240	1800	TORLON 10	24.99	STEEL 2	24.99	10.0	Lin	24.0	No	29.6	-.0200	63	.5
8306282	440	1800	TORLON 10	24.99	STEEL 2	24.99	10.0	Lin	44.0	No	30.7	-.0433	73	.3
8306283	545	1800	TORLON 10	24.99	STEEL 2	24.99	10.0	Lin	54.5	No	30.8	-.0666	72	.3
8306284	640	1800	TORLON 10	24.99	STEEL 2	24.99	10.0	Lin	64.0	No	30.7	-.0666	100	.3
8306285	745	1800	TORLON 10	24.99	STEEL 2	24.99	10.0	Lin	74.5	No	30.7	-.0533	106	.2
8306286	840	1080	TORLON 10	24.99	STEEL 2	24.99	10.0	Lin	84.0	Yes	30.3	0.0000	0	0.0
8306171	240	1800	TORLON 3	25.08	TORLON 8	24.98	6.5	Lin	36.9	No	10.4	-.2824	53	1.1
8306172	440	1800	TORLON 3	25.08	TORLON 8	24.98	6.5	Lin	67.7	No	10.1	-.2824	67	.7
8306173	640	1800	TORLON 3	25.08	TORLON 8	24.98	6.5	Lin	98.5	No	10.1	-.2824	86	.5
8306204	840	1800	TORLON 3	25.08	TORLON 8	24.98	6.5	Lin	129.	No	10.3	-.2490	112	.5
8306205	1040	15	TORLON 3	25.08	TORLON 8	24.98	6.5	Lin	160.	Yes	10.4	0.0000	0	0.0
8307011	240	1800	TORLON 81	25.04	TORLON 11	24.93	6.5	Lin	36.9	No	20.0	-.1639	65	.5
8307012	440	1800	TORLON 81	25.04	TORLON 11	24.93	6.5	Lin	67.7	No	20.4	-.1672	78	.4
8307013	640	1800	TORLON 81	25.04	TORLON 11	24.93	6.5	Lin	98.5	No	20.1	-.1672	121	.3
8307014	745	1800	TORLON 81	25.04	TORLON 11	24.93	6.5	Lin	115.	No	20.1	-.1672	139	.3
8307015	840	45	TORLON 81	25.04	TORLON 11	24.93	6.5	Lin	129.	Yes	16.8	0.0000	0	0.0
8306301	240	1800	TORLON 12	24.97	TORLON 13	24.97	10.0	Lin	24.0	No	30.3	.0333	70	.5
8306302	440	1800	TORLON 12	24.97	TORLON 13	24.97	10.0	Lin	44.0	No	29.8	.0333	88	.3
8306303	640	1800	TORLON 12	24.97	TORLON 13	24.97	10.0	Lin	64.0	No	29.8	.0433	122	.3
8306304	745	473	TORLON 12	24.97	TORLON 13	24.97	10.0	Lin	74.5	Yes	29.8	0.0000	0	0.0

SUMMARY SHEETS FOR PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Rol. Trac. (%)
8307201	545	1800	TORLON 201	24.90	STEEL 2	24.99	7.0	Lin	77.9	No	10.1	-.3648	34	.26
8307202	640	1800	TORLON 201	24.90	STEEL 2	24.99	7.0	Lin	91.4	No	10.1	-.3648	39	.21
8307213	745	1800	TORLON 201	24.90	STEEL 2	24.99	7.0	Lin	106.	No	10.1	-.3979	38	.28
8307214	840	1800	TORLON 201	24.90	STEEL 2	24.99	7.0	Lin	120.	No	10.1	-.3979	40	.28
8307215	945	1800	TORLON 201	24.90	STEEL 2	24.99	7.0	Lin	135.	No	10.4	-.4310	45	.27
8307216	1040	1800	TORLON 201	24.90	STEEL 2	24.99	7.0	Lin	149.	No	10.1	-.4310	47	.28
8307217	840	1800	TORLON 201	24.90	STEEL 2	24.99	5.0	Lin	168.	No	10.1	-.4640	50	.28
8307218	945	0	TORLON 201	24.90	STEEL 2	24.99	5.0	Lin	189.	Yes	10.2	0.0000	0	0.00
8307222	640	1800	TORLON 202	24.87	STEEL 2	24.99	6.0	Lin	107.	No	20.0	-.4634	43	.25
8307223	745	1800	TORLON 202	24.87	STEEL 2	24.99	6.0	Lin	124.	No	20.1	-.4634	46	.17
8307224	840	1545	TORLON 202	24.87	STEEL 2	24.99	6.0	Lin	140.	Yes	20.1	0.0000	0	0.00
8307231	440	1800	TORLON 203	24.94	STEEL 2	24.99	6.0	Lin	73.3	No	29.7	-.2890	42	.26
8307232	545	1800	TORLON 203	24.94	STEEL 2	24.99	6.0	Lin	90.8	No	29.8	-.3321	44	.24
8307233	640	1800	TORLON 203	24.94	STEEL 2	24.99	6.0	Lin	107.	No	29.8	-.3321	47	.20
8307234	745	923	TORLON 203	24.94	STEEL 2	24.99	6.0	Lin	124.	Yes	29.8	0.0000	0	0.00
8307251	545	1800	TORLON 204	24.90	TORLON 206	24.88	6.0	Lin	90.8	No	20.0	.0668	51	.23
8307252	640	1800	TORLON 204	24.90	TORLON 206	24.88	6.0	Lin	107.	No	20.1	.0668	48	.23
8307253	745	1800	TORLON 204	24.90	TORLON 206	24.88	6.0	Lin	124.	No	20.1	.0668	52	.20
8307254	840	1800	TORLON 204	24.90	TORLON 206	24.88	6.0	Lin	140.	No	20.1	.0668	55	.15
8307255	945	1800	TORLON 204	24.90	TORLON 206	24.88	6.0	Lin	158.	No	20.2	.0668	59	.13
8307256	1040	1800	TORLON 204	24.90	TORLON 206	24.88	6.0	Lin	173.	No	20.5	.0668	66	.12
8307267	1145	780	TORLON 204	24.90	TORLON 206	24.88	6.0	Lin	191.	Yes	20.1	0.0000	0	0.00
8307261	545	1800	TORLON 205	24.96	TORLON 207	24.89	6.0	Lin	90.8	No	29.7	.0334	44	.27
8307262	640	1800	TORLON 205	24.96	TORLON 207	24.89	6.0	Lin	107.	No	29.8	.0334	46	.21
8307263	745	1800	TORLON 205	24.96	TORLON 207	24.89	6.0	Lin	124.	No	29.8	.0334	51	.27
8307264	840	1800	TORLON 205	24.96	TORLON 207	24.89	6.0	Lin	140.	No	29.8	.0334	59	.26
8307265	945	1133	TORLON 205	24.96	TORLON 207	24.89	6.0	Lin	158.	Yes	29.8	0.0000	0	0.00

SUMMARY SHEETS FOR PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Rol. Trac. (%)
8306085	240	1800	NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	12.0	No	10.1	.4457	40	1.1
8306086	440	1800	NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	22.0	No	10.1	.9503	61	.9
8306087	640	1800	NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	32.0	No	10.2	1.1191	71	.7
8306088	840	1800	NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	42.0	No	10.2	1.3220	77	.5
8306089	1040	233	NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	52.0	Yes	10.1	0.0000	0	0.0
8306105	240	1800	NYLON 3	25.02	STEEL 1	24.96	20.0	Lin	12.0	No	19.7	1.1303	69	1.0
8306106	440	1800	NYLON 3	25.02	STEEL 1	24.96	20.0	Lin	22.0	No	20.2	1.3672	83	.7
8306107	640	338	NYLON 3	25.02	STEEL 1	24.96	20.0	Lin	32.0	Yes	20.5	0.0000	0	0.0
8306241	240	1800	NYLON 8	24.99	STEEL 2	24.99	20.0	Lin	12.0	No	30.3	.0787	68	.6
8306242	345	1800	NYLON 8	24.99	STEEL 2	24.99	20.0	Lin	17.3	No	30.3	.0754	73	.4
8306243	440	705	NYLON 8	24.99	STEEL 2	24.99	20.0	Lin	22.0	Yes	30.1	0.0000	0	0.0
8306142	240	1800	NYLON 4	25.02	NYLON 5	25.01	20.0	Lin	12.0	No	10.1	.3268	53	1.2
8306143	345	1800	NYLON 4	25.02	NYLON 5	25.01	20.0	Lin	17.3	No	10.1	.2966	91	1.1
8306144	440	1800	NYLON 4	25.02	NYLON 5	25.01	20.0	Lin	22.0	No	10.1	.2298	101	.9
8306155	545	1800	NYLON 4	25.02	NYLON 5	25.01	20.0	Lin	27.3	No	10.4	.2632	107	.8
8306156	640	1800	NYLON 4	25.02	NYLON 5	25.01	20.0	Lin	32.0	No	10.1	.2298	112	.7
8306157	745	1800	NYLON 4	25.02	NYLON 5	25.01	20.0	Lin	37.3	No	10.3	.2632	119	.6
8306158	840	1793	NYLON 4	25.02	NYLON 5	25.01	20.0	Lin	42.0	Yes	10.1	0.0000	0	0.0
8306201	240	1800	NYLON 6	25.01	NYLON 7	25.01	20.0	Lin	12.0	No	20.1	.3339	112	1.1
8306202	440	1800	NYLON 6	25.01	NYLON 7	25.01	20.0	Lin	22.0	No	20.1	.2938	142	.7
8306203	640	345	NYLON 6	25.01	NYLON 7	25.01	20.0	Lin	32.0	Yes	20.2	0.0000	0	0.0
8306291	240	1800	NYLON 9	24.90	NYLON 10	25.04	20.0	Lin	12.0	No	29.8	.0066	36	.5
8306292	345	495	NYLON 9	24.90	NYLON 10	25.04	20.0	Lin	17.3	Yes	30.3	0.0000	0	0.0

SUMMARY SHEETS FOR PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Rol. Trac. (%)
8306061	240	1800	ACETAL 3	25.06	STEEL 1	25.10	20.0	Lin	12.0	No	9.7	.2015	40	1.2
8306062	440	1800	ACETAL 3	25.06	STEEL 1	25.10	20.0	Lin	22.0	No	10.1	.2417	43	.7
8306063	640	1800	ACETAL 3	25.06	STEEL 1	25.10	20.0	Lin	32.0	No	11.1	.3847	50	.5
8306071	840	1028	ACETAL 3	25.06	STEEL 1	24.96	20.0	Lin	42.0	Yes	10.1	0.0000	0	0.0
8306108	240	1800	ACETAL 4	25.02	STEEL 1	24.96	20.0	Lin	12.0	No	20.1	.7255	55	1.0
8306109	440	1800	ACETAL 4	25.02	STEEL 1	24.96	20.0	Lin	22.0	No	20.1	.9952	64	.6
83061010	640	90	ACETAL 4	25.02	STEEL 1	24.96	20.0	Lin	32.0	Yes	20.1	0.0000	0	0.0
8306241	240	1800	ACETAL 8	24.99	STEEL 2	24.99	20.0	Lin	12.0	No	30.4	.1521	104	.5
8306242	345	1800	ACETAL 8	24.99	STEEL 2	24.99	20.0	Lin	17.3	No	30.1	.1855	108	.3
8306243	440	1800	ACETAL 8	24.99	STEEL 2	24.99	20.0	Lin	22.0	No	30.8	.2858	111	.3
8306244	545	188	ACETAL 8	24.99	STEEL 2	24.99	20.0	Lin	27.3	Yes	30.3	0.0000	0	0.0
8306151	240	1800	ACETAL 1	25.02	ACETAL 5	25.01	20.0	Lin	12.0	No	10.1	.2298	67	1.2
8306152	345	1800	ACETAL 1	25.02	ACETAL 5	25.01	20.0	Lin	17.3	No	10.2	.1963	69	.8
8306153	440	1800	ACETAL 1	25.02	ACETAL 5	25.01	20.0	Lin	22.0	No	10.1	.1629	73	.7
8306154	545	1800	ACETAL 1	25.02	ACETAL 5	25.01	20.0	Lin	27.3	No	10.2	.1629	80	.6
8306165	640	1800	ACETAL 1	25.02	ACETAL 5	25.01	20.0	Lin	32.0	No	10.1	.1629	87	.6
8306166	745	525	ACETAL 1	25.02	ACETAL 5	25.01	20.0	Lin	37.3	Yes	10.3	0.0000	0	0.0
8306201	240	1800	ACETAL 6	25.02	ACETAL 7	25.01	20.0	Lin	12.0	No	20.1	.3000	95	1.1
8306202	440	390	ACETAL 6	25.02	ACETAL 7	25.01	20.0	Lin	22.0	Yes	19.8	0.0000	0	0.0
8306291	240	1800	ACETAL 9	25.03	ACETAL 10	25.07	20.0	Lin	12.0	No	30.3	.0666	42	.5
8306292	345	1800	ACETAL 9	25.03	ACETAL 10	25.07	20.0	Lin	17.3	No	30.2	.0599	61	.4
8306293	440	878	ACETAL 9	25.03	ACETAL 10	25.07	20.0	Lin	22.0	Yes	30.3	0.0000	0	0.0

SUMMARY SHEETS FOR PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Rol. Trac. (%)
83060810	240	1800	MONO-NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	12.0	No	10.1	.7482	48	1.3
83060811	440	1800	MONO-NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	22.0	No	10.1	1.3220	70	.9
8306091	640	1800	MONO-NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	32.0	No	10.6	1.4914	74	.8
8306092	840	743	MONO-NYLON 2	25.01	STEEL 1	24.96	20.0	Lin	42.0	Yes	10.1	0.0000	0	0.0
83061011	240	1800	MONO-NYLON 3	25.01	STEEL 1	24.96	20.0	Lin	12.0	No	20.1	1.3898	77	1.2
8306132	440	1800	MONO-NYLON 3	25.01	STEEL 1	24.96	20.0	Lin	22.0	No	20.0	1.6340	91	.8
8306133	640	165	MONO-NYLON 3	25.01	STEEL 1	24.96	20.0	Lin	32.0	Yes	20.2	0.0000	0	0.0
8306261	240	225	ONO-NYLON 10	24.98	STEEL 2	24.94	20.0	Lin	12.0	Yes	30.1	0.0000	0	0.0
8306161	240	1800	MONO-NYLON 4	25.02	ONO-NYLON 5	24.96	20.0	Lin	12.0	No	10.1	.3291	94	1.4
8306162	345	1800	MONO-NYLON 4	25.02	ONO-NYLON 5	24.96	20.0	Lin	17.3	No	10.6	.1884	116	1.1
8306163	440	1800	MONO-NYLON 4	25.02	ONO-NYLON 5	24.96	20.0	Lin	22.0	No	10.2	.1549	128	.9
8306164	545	1800	MONO-NYLON 4	25.02	ONO-NYLON 5	24.96	20.0	Lin	27.3	No	10.2	.1583	139	.8
8306165	640	1800	MONO-NYLON 4	25.02	ONO-NYLON 5	24.96	20.0	Lin	32.0	No	10.2	.1549	149	.7
8306166	840	840	MONO-NYLON 4	25.02	ONO-NYLON 5	24.96	20.0	Lin	42.0	Yes	10.1	0.0000	0	0.0
8306201	240	1800	MONO-NYLON 6	24.98	ONO-NYLON 7	24.98	20.0	Lin	12.0	No	20.1	.1334	167	1.2
8306212	440	1800	MONO-NYLON 6	24.98	ONO-NYLON 7	24.98	20.0	Lin	22.0	No	20.1	.1368	159	.8
8306213	640	45	MONO-NYLON 6	24.98	ONO-NYLON 7	24.98	20.0	Lin	32.0	Yes	19.2	0.0000	0	0.0
8306291	145	1800	MONO-NYLON 9	25.03	ONO-NYLON 8	25.03	20.0	Lin	7.3	No	30.3	.0333	97	.7
8306292	240	150	MONO-NYLON 9	25.03	ONO-NYLON 8	25.03	20.0	Lin	12.0	Yes	29.8	0.0000	0	0.0

SUMMARY SHEETS FOR THE SLIP TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Speed (m/s)	Temp ('C)	Calculated Slope (--)	Calculated Mu (%)	Fitted Slope (--)	Fitted Mu (%)
8309061	240	PHENOLIC 110	25.02	STEEL 2	24.99	7.0	Lin	34.3	10.3	45	25	17.3	34	15.5
8309062	440	PHENOLIC 110	25.02	STEEL 2	24.99	7.0	Lin	62.9	10.5	55	34	19.0	40	17.0
8309063	640	PHENOLIC 110	25.02	STEEL 2	24.99	7.0	Lin	91.4	10.3	73	33	18.9	40	17.5
8309064	240	PHENOLIC 110	25.02	STEEL 2	24.99	7.0	Lin	34.3	20.7	71	42	35.2	50	32.0
8309065	345	PHENOLIC 110	25.02	STEEL 2	24.99	7.0	Lin	49.3	20.2	71	45	46.9	50	50.0
8309071	240	PHENOLIC 111	25.03	PHENOLIC 112	25.01	7.0	Lin	34.3	10.0	58	21	16.6	30	15.0
8309072	440	PHENOLIC 111	25.03	PHENOLIC 112	25.01	7.0	Lin	62.9	10.0	72	24	15.4	30	14.5
8309073	640	PHENOLIC 111	25.03	PHENOLIC 112	25.01	7.0	Lin	91.4	10.0	95	25	15.0	35	14.0
8309074	240	PHENOLIC 111	25.03	PHENOLIC 112	25.01	7.0	Lin	34.3	20.1	108	34	28.8	40	29.0
8309075	440	PHENOLIC 111	25.03	PHENOLIC 112	25.01	7.0	Lin	62.9	20.0	129	33	32.6	40	35.0
8309076	640	PHENOLIC 111	25.03	PHENOLIC 112	25.01	7.0	Lin	91.4	20.0	141	25	21.2	30	27.0

SUMMARY SHEETS FOR THE SLIP TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Speed (m/s)	Temp ('C)	Calculated Slope (--)	Calculated Mu (%)	Fitted Slope (--)	Fitted Mu (%)
8309061	240	FTORLON 4	25.12	STEEL 2	24.99	6.5	Lin	36.9	10.5	54	25	21.4	27	20.0
8309062	545	FTORLON 4	25.12	STEEL 2	24.99	6.5	Lin	83.8	10.5	71	25	20.5	30	19.0
8309063	840	FTORLON 4	25.12	STEEL 2	24.99	6.5	Lin	129.	10.2	88	26	17.8	32	19.0
8309064	240	FTORLON 4	25.12	STEEL 2	24.99	6.5	Lin	36.9	20.0	82	34	28.4	45	26.0
8309065	440	FTORLON 4	25.12	STEEL 2	24.99	6.5	Lin	67.7	19.9	86	33	27.8	45	27.0
8309066	640	FTORLON 4	25.12	STEEL 2	24.99	6.5	Lin	98.5	20.1	92	35	23.2	45	25.0
8309091	240	FTORLON 4	25.13	FTORLON 13	24.98	6.5	Lin	36.9	10.0	49	20	19.5	25	18.0
8309092	545	FTORLON 4	25.13	FTORLON 13	24.98	6.5	Lin	83.8	10.0	81	18	17.1	23	16.0
8309093	840	FTORLON 4	25.13	FTORLON 13	24.98	6.5	Lin	129.	10.2	131	15	16.0	20	15.0
8309094	240	FTORLON 4	25.13	FTORLON 13	24.98	6.5	Lin	36.9	19.9	95	22	28.2	28	27.0
8309095	440	FTORLON 4	25.13	FTORLON 13	24.98	6.5	Lin	67.7	20.3	106	21	25.5	30	24.0
8309096	640	FTORLON 4	25.13	FTORLON 13	24.98	6.5	Lin	98.5	19.8	123	19	20.4	0	100.
8309071	240	TORLON 206	24.59	STEEL 2	24.99	3.5	Lin	68.6	10.1	40	26	20.6	30	22.0
8309072	360	TORLON 206	24.59	STEEL 2	24.99	3.5	Lin	103.	10.2	47	30	23.2	40	24.0
8309073	545	TORLON 206	24.59	STEEL 2	24.99	3.5	Lin	156.	10.5	55	31	22.9	35	27.0
8309074	240	TORLON 206	24.59	STEEL 2	24.99	3.5	Lin	68.6	19.8	54	37	28.4	40	32.0
8309075	345	TORLON 206	24.59	STEEL 2	24.99	3.5	Lin	98.6	20.0	57	31	28.1	35	35.0
8309076	440	TORLON 206	24.59	STEEL 2	24.99	3.5	Lin	126.	19.9	55	32	27.0	35	32.0
8309081	240	TORLON 206	24.57	TORLON 205	24.66	3.5	Lin	68.6	9.8	39	27	11.8	27	11.0
8309082	360	TORLON 206	24.57	TORLON 205	24.66	3.5	Lin	103.	10.2	42	12	11.7	15	12.0
8309083	545	TORLON 206	24.57	TORLON 205	24.66	3.5	Lin	156.	9.9	53	15	11.7	20	11.0
8309084	240	TORLON 206	24.57	TORLON 205	24.66	3.5	Lin	68.6	19.7	50	25	17.7	35	17.0
8309085	345	TORLON 206	24.57	TORLON 205	24.66	3.5	Lin	98.6	19.8	68	18	23.4	22	23.0

SUMMARY SHEETS FOR THE SLIP TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS

											Calculated		Fitted	
Test #	Load	Top roller	R1	Bottom roller	R2	W	K	Fw	Speed	Temp	Slope	Mu	Slope	Mu
YYMMDD #	(N)	Material #	(mm)	Material #	(mm)	(mm)	(-)	(N/mm)	(m/s)	('C)	(--)	(%)	(--)	(%)
8309051	240	ACETAL 140	25.07	STEEL 2	24.99	20.0	Lin	12.0	10.5	46	7	10.5	7	10.5
8309052	440	ACETAL 140	25.07	STEEL 2	24.99	20.0	Lin	22.0	10.3	47	11	11.8	15	10.5
8309053	640	ACETAL 140	25.07	STEEL 2	24.99	20.0	Lin	32.0	10.7	53	23	15.2	30	13.5
8309054	240	ACETAL 140	25.07	STEEL 2	24.99	20.0	Lin	12.0	20.7	58	20	16.8	25	15.0
8309055	345	ACETAL 140	25.07	STEEL 2	24.99	20.0	Lin	17.3	20.6	58	29	20.0	37	18.5
8309056	440	ACETAL 140	25.07	STEEL 2	24.99	20.0	Lin	22.0	20.2	59	29	21.1	35	19.0
8309071	240	ACETAL 141	25.03	ACETAL 142	25.04	20.0	Lin	12.0	10.0	53	11	11.6	13	11.0
8309072	440	ACETAL 141	25.03	ACETAL 142	25.04	20.0	Lin	22.0	10.0	59	15	12.0	18	11.0
8309073	640	ACETAL 141	25.03	ACETAL 142	25.04	20.0	Lin	32.0	10.2	65	12	11.7	17	11.0
8309074	145	ACETAL 141	25.03	ACETAL 142	25.04	20.0	Lin	7.3	19.7	74	21	16.0	15	16.0
8309075	240	ACETAL 141	25.03	ACETAL 142	25.04	20.0	Lin	12.0	20.1	77	15	16.8	20	16.0
8309076	345	ACETAL 141	25.03	ACETAL 142	25.04	20.0	Lin	17.3	19.9	80	17	17.9	20	17.0

SUMMARY SHEETS FOR THE SLIP TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Speed (m/s)	Temp ('C)	Calculated Slope (--)	Calculated Mu (%)	Fitted Slope (--)	Fitted Mu (%)
8309051	240	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	12.0	8.9	41	9	11.8	10	11.0
8309052	440	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	22.0	9.1	50	16	13.7	20	12.0
8309053	440	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	22.0	10.3	50	12	16.9	15	16.0
8309054	640	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	32.0	10.5	78	18	22.5	25	20.0
8309055	240	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	12.0	20.5	68	23	34.5	27	32.0
8309056	240	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	12.0	10.2	69	31	32.3	37	30.0
8309057	440	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	22.0	20.9	68	15	28.2	20	27.0
8309058	440	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	22.0	20.7	92	25	41.1	30	40.0
8309059	345	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	17.3	10.3	80	30	35.6	37	34.0
83090510	345	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	17.3	10.4	65	34	36.7	42	34.0
83090511	345	NYLON 101	25.02	STEEL 2	24.99	20.0	Lin	17.3	20.3	80	32	42.1	38	40.0
8309071	345	NYLON 131	25.13	NYLON 132	24.99	20.0	Lin	17.3	9.8	41	11	9.7	13	9.0
8309072	545	NYLON 131	25.13	NYLON 132	24.99	20.0	Lin	27.3	9.8	53	12	9.3	15	8.5
8309073	745	NYLON 131	25.13	NYLON 132	24.99	20.0	Lin	37.3	10.3	89	9	9.0	12	8.5
8309074	240	NYLON 131	25.13	NYLON 132	24.99	20.0	Lin	12.0	20.0	80	8	10.9	9	10.5
8309075	440	NYLON 131	25.13	NYLON 132	24.99	20.0	Lin	22.0	19.9	99	8	10.6	9	10.5
8309076	640	NYLON 131	25.13	NYLON 132	24.99	20.0	Lin	32.0	19.7	116	11	10.2	12	9.5

SUMMARY SHEETS FOR THE SLIP TRACTION MEASUREMENTS ON LOW MODULUS MATERIALS

Test # YYMMDD #	Load (N)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	W (mm)	K (-)	Fw (N/mm)	Speed (m/s)	Temp ('C)	Calculated Slope (--)	Calculated Mu (%)	Fitted Slope (--)	Fitted Mu (%)
8309051	240	NO-NYLON 150	25.01	STEEL 2	24.99	20.0	Lin	12.0	10.2	48	14	14.1	15	13.0
8309052	440	NO-NYLON 150	25.01	STEEL 2	24.99	20.0	Lin	22.0	10.5	80	15	20.3	20	18.0
8309053	640	NO-NYLON 150	25.01	STEEL 2	24.99	20.0	Lin	32.0	10.6	102	12	26.5	12	26.5
8309064	240	NO-NYLON 151	25.00	STEEL 2	24.99	20.0	Lin	12.0	19.8	63	7	12.4	9	12.0
8309065	345	NO-NYLON 151	25.00	STEEL 2	24.99	20.0	Lin	17.3	20.0	87	11	16.1	12	15.5
8309066	440	NO-NYLON 151	25.00	STEEL 2	24.99	20.0	Lin	22.0	19.9	114	13	19.1	15	18.0
8309071	240	NO-NYLON 152	25.01	NO-NYLON 153	25.01	20.0	Lin	12.0	10.1	58	9	9.7	10	9.0
8309072	440	NO-NYLON 152	25.01	NO-NYLON 153	25.01	20.0	Lin	22.0	10.0	83	9	9.7	10	9.0
8309073	640	NO-NYLON 152	25.01	NO-NYLON 153	25.01	20.0	Lin	32.0	10.3	130	8	10.7	10	10.5
8309074	240	NO-NYLON 152	25.01	NO-NYLON 153	25.01	20.0	Lin	12.0	19.6	129	7	13.0	7	13.0
8309075	345	NO-NYLON 152	25.01	NO-NYLON 153	25.01	20.0	Lin	17.3	19.8	142	9	12.7	11	12.5
8309076	440	NO-NYLON 152	25.01	NO-NYLON 153	25.01	20.0	Lin	22.0	19.9	150	10	12.4	12	12.0

SUMMARY SHEETS FOR ENDURANCE PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS UNDER TRACTION

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	2B (mm)	K (-)	Po MPa	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Slip Trac. (%)
8312221	240	600	PHENOLIC 113	25.03	STEEL 3	24.95	5.0	Inf	149.	No	4.9	3.3579	36	30.2
8312222	240	600	PHENOLIC 113	25.03	STEEL 3	24.95	5.0	Inf	149.	No	9.7	3.3579	56	52.8
8312223	240	600	PHENOLIC 113	25.03	STEEL 3	24.95	5.0	Inf	149.	No	14.7	3.3579	60	45.5
8312224	240	600	PHENOLIC 113	25.03	STEEL 3	24.95	5.0	Inf	149.	No	19.6	3.3579	62	39.2
8312225	360	600	PHENOLIC 113	25.03	STEEL 3	24.95	5.0	Inf	183.	No	5.1	3.3579	58	44.2
8312226	360	600	PHENOLIC 113	25.03	STEEL 3	24.95	5.0	Inf	183.	No	9.9	3.3579	71	47.7
8312227	360	600	PHENOLIC 113	25.03	STEEL 3	24.95	5.0	Inf	183.	No	14.9	3.3579	68	40.1
8312228	360	600	PHENOLIC 113	25.03	STEEL 3	24.95	5.0	Inf	183.	No	19.5	3.3579	67	31.9
8312229	240	600	PHENOLIC 113	25.00	STEEL 3	24.94	3.0	Inf	193.	No	5.1	3.2583	51	35.5
83122210	240	563	PHENOLIC 113	25.00	STEEL 3	24.94	3.0	Inf	193.	Yes	10.1	3.2583	0	-5.1
83122211	240	600	PHENOLIC 114	25.04	STEEL 3	24.94	3.0	Inf	193.	No	6.0	3.4376	57	37.7
83122212	240	600	PHENOLIC 114	25.04	STEEL 3	24.94	3.0	Inf	193.	No	10.0	3.4376	75	45.5
83122213	240	108	PHENOLIC 114	25.04	STEEL 3	24.94	3.0	Inf	193.	Yes	14.9	3.4376	0	-5.6
83122313	240	600	PHENOLIC 115	25.03	STEEL 3	24.94	4.0	Inf	167.	No	5.3	3.3859	45	39.1
83122314	240	600	PHENOLIC 115	25.03	STEEL 3	24.94	4.0	Inf	167.	No	10.2	3.3859	63	49.6
83122315	240	565	PHENOLIC 115	25.03	STEEL 3	24.94	4.0	Inf	167.	Yes	14.7	3.3859	0	-5.6
83122316	360	600	PHENOLIC 116	25.02	STEEL 3	24.94	4.0	Inf	205.	No	2.5	3.3381	46	48.3
83122317	360	600	PHENOLIC 116	25.02	STEEL 3	24.94	4.0	Inf	205.	No	5.2	3.3381	66	49.0
83122318	360	600	PHENOLIC 116	25.02	STEEL 3	24.94	4.0	Inf	205.	No	7.2	3.3381	68	44.1
83122319	545	600	PHENOLIC 117	24.90	STEEL 3	24.94	4.0	Inf	252.	No	2.0	2.8777	60	32.1
83122320	545	600	PHENOLIC 117	24.90	STEEL 3	24.94	4.0	Inf	252.	No	4.3	2.8777	85	43.8
83122321	545	323	PHENOLIC 117	24.90	STEEL 3	24.94	4.0	Inf	252.	Yes	6.0	2.8777	0	-2.1
8401021	240	600	PHENOLIC 131	25.98	STEEL 4	25.98	1.4	1.6	375.	No	5.3	3.0303	54	41.4
8401022	240	600	PHENOLIC 131	25.98	STEEL 4	25.98	1.4	1.6	375.	No	9.8	3.0303	68	50.3
8401023	240	600	PHENOLIC 131	25.98	STEEL 4	25.98	1.4	1.6	375.	No	14.7	3.0303	68	44.2
8401024	240	138	PHENOLIC 131	25.98	STEEL 4	25.98	1.4	1.6	375.	Yes	18.0	3.0303	0	-5.9
8401025	440	600	PHENOLIC 132	25.97	STEEL 4	25.98	1.7	1.6	459.	No	2.7	2.9995	63	44.0
8401026	440	600	PHENOLIC 132	25.97	STEEL 4	25.98	1.7	1.6	459.	No	5.0	2.9995	90	45.4

SUMMARY SHEETS FOR ENDURANCE PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS UNDER TRACTION

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	2B (mm)	K (-)	Po MPa	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Slip Trac. (%)
8401027	440	600	PHENOLIC 132	25.97	STEEL 4	25.98	1.7	1.6	459.	No	7.4	2.9995	92	42.2
8401028	345	600	PHENOLIC 133	25.98	STEEL 4	25.98	1.6	1.6	423.	No	2.8	3.0111	51	43.0
8401029	345	600	PHENOLIC 133	25.98	STEEL 4	25.98	1.6	1.6	423.	No	5.4	3.0111	66	50.6
84010210	345	600	PHENOLIC 133	25.98	STEEL 4	25.98	1.6	1.6	423.	No	10.2	3.0111	72	46.7
84010211	345	600	PHENOLIC 133	25.98	STEEL 4	25.98	1.6	1.6	423.	No	12.5	3.0111	79	40.1
84010212	345	600	PHENOLIC 133	25.98	STEEL 4	25.98	1.6	1.6	423.	No	13.4	3.0111	83	30.4
8401051	240	600	PHENOLIC 121	24.91	HENOLIC 151	24.98	1.8	1.7	250.	No	5.3	2.7493	76	32.0
8401052	240	600	PHENOLIC 121	24.91	HENOLIC 151	24.98	1.8	1.7	250.	No	7.9	2.7493	89	36.0
8401053	240	600	PHENOLIC 121	24.91	HENOLIC 151	24.98	1.8	1.7	250.	No	10.6	2.7493	90	36.5
8401054	240	600	PHENOLIC 121	24.91	HENOLIC 151	24.98	1.8	1.7	250.	No	12.4	2.7493	90	34.9
8401055	240	600	PHENOLIC 121	24.91	HENOLIC 151	24.98	1.8	1.7	250.	No	15.1	2.7493	84	33.7
8401056	240	600	PHENOLIC 121	24.91	HENOLIC 151	24.98	1.8	1.7	250.	No	17.4	2.7493	79	31.4
8401057	240	5	PHENOLIC 121	24.91	HENOLIC 151	24.98	1.8	1.7	250.	Yes	9.0	2.7493	0	-5.0
8401058	440	600	PHENOLIC 122	24.97	HENOLIC 152	24.99	2.2	1.7	306.	No	2.6	2.9422	120	31.9
8401059	440	600	PHENOLIC 122	24.97	HENOLIC 152	24.99	2.2	1.7	306.	No	5.7	2.9422	124	33.8
84010510	440	110	PHENOLIC 122	24.97	HENOLIC 152	24.99	2.2	1.7	306.	Yes	7.5	2.9422	0	-2.6
84010511	640	240	PHENOLIC 123	24.92	HENOLIC 156	24.98	2.4	1.7	347.	Yes	2.1	2.7694	0	-1.6
8401061	240	600	PHENOLIC 110	25.03	HENOLIC 153	24.97	3.0	Inf	143.	No	2.7	3.2660	48	10.1
8401062	240	600	PHENOLIC 110	25.03	HENOLIC 153	24.97	3.0	Inf	143.	No	5.5	3.2660	95	33.0
8401063	240	600	PHENOLIC 110	25.03	HENOLIC 153	24.97	3.0	Inf	143.	No	7.9	3.2660	100	31.7
8401064	240	600	PHENOLIC 110	25.03	HENOLIC 153	24.97	3.0	Inf	143.	No	9.5	3.2660	100	31.5
8401065	440	600	PHENOLIC 141	24.96	HENOLIC 154	24.98	3.0	Inf	193.	No	2.8	2.9542	135	28.5
8401066	440	145	PHENOLIC 141	24.96	HENOLIC 154	24.98	3.0	Inf	193.	Yes	5.1	2.9542	0	-2.5
8401067	345	600	PHENOLIC 143	24.98	HENOLIC 155	24.97	3.0	Inf	171.	No	2.9	3.0663	116	23.8
8401068	345	600	PHENOLIC 143	24.98	HENOLIC 155	24.97	3.0	Inf	171.	No	5.2	3.0663	132	30.1
8401069	345	145	PHENOLIC 143	24.98	HENOLIC 155	24.97	3.0	Inf	171.	Yes	7.7	3.0663	0	-3.4
8312191	345	1800	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	188.	No	4.9	2.0789	26	22.7

SUMMARY SHEETS FOR ENDURANCE PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS UNDER TRACTION

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	2B (mm)	K (-)	Po MPa	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Slip Trac. (%)
8312202	345	888	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	188.	No	10.6	2.0789	24	24.5
8312203	345	888	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	188.	No	15.5	2.0789	29	26.7
8312204	345	888	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	188.	No	20.1	2.0789	38	28.7
8312205	640	600	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	256.	No	5.1	2.0544	38	30.3
8312206	640	600	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	256.	No	9.8	2.0544	45	29.7
8312207	640	600	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	256.	No	14.9	2.0544	51	30.0
8312208	640	600	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	256.	No	19.3	2.0544	59	30.4
8312209	840	600	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	293.	No	5.1	2.0544	46	29.1
83122010	840	600	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	293.	No	10.3	2.0544	56	29.9
83122011	840	600	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	293.	No	16.0	2.0544	65	30.1
83122012	840	600	TORLON 220	24.70	STEEL 3	24.94	5.0	Inf	293.	No	19.4	2.0544	74	29.7
83122113	440	600	TORLON 220	24.65	STEEL 3	24.94	3.0	Inf	274.	No	5.1	1.8701	32	28.1
83122114	440	600	TORLON 220	24.65	STEEL 3	24.94	3.0	Inf	274.	No	9.8	1.8701	43	27.0
83122115	440	600	TORLON 220	24.65	STEEL 3	24.94	3.0	Inf	274.	No	15.3	1.8701	49	27.9
83122116	440	600	TORLON 220	24.65	STEEL 3	24.94	3.0	Inf	274.	No	19.4	1.8701	54	28.3
83122117	640	600	TORLON 220	24.65	STEEL 3	24.94	3.0	Inf	330.	No	5.5	1.8701	46	25.8
83122118	640	600	TORLON 220	24.65	STEEL 3	24.94	3.0	Inf	330.	No	11.1	1.8701	57	26.0
83122119	640	600	TORLON 220	24.65	STEEL 3	24.94	3.0	Inf	330.	No	14.6	1.8701	63	25.3
83122120	640	320	TORLON 220	24.65	STEEL 3	24.94	3.0	Inf	330.	Yes	19.2	1.8701	0	-2.3
83122121	840	600	TORLON 221	24.71	STEEL 3	24.96	3.0	Inf	378.	No	5.3	2.0265	56	24.5
83122122	840	438	TORLON 221	24.71	STEEL 3	24.95	3.0	Inf	378.	Yes	10.1	2.0508	0	-1.5
83122223	1040	600	TORLON 222	24.71	STEEL 3	24.94	3.0	Inf	421.	No	2.8	2.0792	53	23.2
83122224	1040	600	TORLON 222	24.71	STEEL 3	24.94	3.0	Inf	421.	No	4.7	2.0792	87	24.2
83122225	1040	85	TORLON 222	24.71	STEEL 3	24.94	3.0	Inf	421.	Yes	7.8	2.0792	0	-1.1

SUMMARY SHEETS FOR ENDURANCE PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS UNDER TRACTION

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	2B (mm)	K (-)	Po MPa	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Slip Trac. (%)
8401031	240	600	TORLON 251	25.99	STEEL 4	25.98	1.3	1.6	397.	No	5.1	3.0611	34	28.3
8401032	240	600	TORLON 251	25.99	STEEL 4	25.98	1.3	1.6	397.	No	10.4	3.0611	46	32.7
8401033	240	600	TORLON 251	25.99	STEEL 4	25.98	1.3	1.6	397.	No	14.9	3.0611	51	33.0
8401034	240	600	TORLON 251	25.99	STEEL 4	25.98	1.3	1.6	397.	No	19.9	3.0611	53	30.1
8401035	440	600	TORLON 251	26.00	STEEL 4	25.98	1.6	1.6	486.	No	5.1	3.1111	49	32.3
8401036	440	600	TORLON 251	26.00	STEEL 4	25.98	1.6	1.6	486.	No	10.6	3.1111	59	34.1
8401037	440	600	TORLON 251	26.00	STEEL 4	25.98	1.6	1.6	486.	No	15.2	3.1111	64	31.5
8401038	440	600	TORLON 251	26.00	STEEL 4	25.98	1.6	1.6	486.	No	19.9	3.1111	71	30.5
8401039	640	600	TORLON 251	26.00	STEEL 4	25.98	1.9	1.6	551.	No	4.8	3.1111	57	31.0
84010310	640	600	TORLON 251	26.00	STEEL 4	25.98	1.9	1.6	551.	No	10.3	3.1111	65	31.4
84010311	640	600	TORLON 251	26.00	STEEL 4	25.98	1.9	1.6	551.	No	15.0	3.1111	79	30.3
84010312	640	600	TORLON 252	26.00	STEEL 4	25.99	1.9	1.6	551.	No	5.2	3.0649	60	28.0
84010313	640	600	TORLON 252	26.00	STEEL 4	25.99	1.9	1.6	551.	No	10.1	3.0649	67	29.4
8401041	240	600	TORLON 232	25.00	TORLON 233	24.96	1.7	1.7	266.	No	5.4	3.2023	36	3.2
8401042	240	600	TORLON 232	25.00	TORLON 233	24.96	1.7	1.7	266.	No	9.9	3.2023	37	4.1
8401043	240	600	TORLON 232	25.00	TORLON 233	24.96	1.7	1.7	266.	No	9.8	3.2023	45	5.6
8401044	240	600	TORLON 232	25.00	TORLON 233	24.96	1.7	1.7	266.	No	15.1	3.2023	86	14.0
8401045	240	1800	TORLON 232	25.01	TORLON 233	24.97	1.7	1.7	266.	No	14.7	3.1782	87	33.0
8401046	240	1800	TORLON 232	25.01	TORLON 233	24.97	1.7	1.7	266.	No	14.9	3.1782	134	32.8
8401047	440	600	TORLON 235	24.99	TORLON 234	24.98	2.1	1.7	326.	No	2.0	3.0823	41	4.0
8401048	440	600	TORLON 235	24.99	TORLON 234	24.98	2.1	1.7	326.	No	4.0	3.0823	66	7.1
8401049	440	600	TORLON 235	24.99	TORLON 234	24.98	2.1	1.7	326.	No	6.0	3.0823	100	12.9
84010410	440	120	TORLON 235	24.99	TORLON 234	24.98	2.1	1.7	326.	Yes	8.1	3.0823	0	-2.7
84010411	640	600	TORLON 231	24.99	TORLON 236	24.97	2.4	1.7	369.	No	2.0	3.1263	53	4.6
84010412	640	600	TORLON 231	24.99	TORLON 236	24.97	2.4	1.7	369.	No	4.6	3.1263	66	5.7
84010413	640	600	TORLON 231	24.99	TORLON 236	24.97	2.4	1.7	369.	No	6.3	3.1263	92	8.0

SUMMARY SHEETS FOR ENDURANCE PRESSURE-SPEED-TEMPERATURE LIMITS OF LOW MODULUS MATERIALS UNDER TRACTION

Test # YYMMDD #	Load (N)	Time (sec)	Top roller Material #	R1 (mm)	Bottom roller Material #	R2 (mm)	2B (mm)	K (-)	Po MPa	Fail (--)	Speed (m/s)	Slip (%)	Temp ('C)	Slip Trac. (%)
8401091	240	600	TORLON 245	25.02	TORLON 247	24.97	4.0	Inf	130.	No	5.3	3.2142	51	7.5
8401092	240	600	TORLON 245	25.02	TORLON 247	24.97	4.0	Inf	130.	No	10.5	3.2142	63	13.3
8401093	240	600	TORLON 245	25.02	TORLON 247	24.97	4.0	Inf	130.	No	14.9	3.2142	114	26.5
8401094	240	600	TORLON 245	25.02	TORLON 247	24.97	4.0	Inf	130.	No	19.9	3.2142	102	31.3
8401095	440	600	TORLON 245	25.02	TORLON 247	24.97	4.0	Inf	176.	No	5.0	3.2142	145	31.9
8401096	440	600	TORLON 245	25.02	TORLON 247	24.97	4.0	Inf	176.	No	7.5	3.2142	68	9.0
8401097	440	600	TORLON 245	25.02	TORLON 247	24.97	4.0	Inf	176.	No	10.7	3.2142	86	14.9
8401098	440	90	TORLON 245	25.02	TORLON 247	24.97	4.0	Inf	176.	Yes	12.6	3.2142	0	-2.9
8401099	240	600	TORLON 242	25.03	TORLON 241	24.98	2.0	Inf	183.	No	2.8	3.2021	43	8.1
84010910	240	600	TORLON 242	25.03	TORLON 241	24.98	2.0	Inf	183.	No	5.1	3.2021	90	21.0
84010911	240	600	TORLON 242	25.03	TORLON 241	24.98	2.0	Inf	183.	No	7.5	3.2021	116	22.6
84010912	240	600	TORLON 242	25.03	TORLON 241	24.98	2.0	Inf	183.	No	10.2	3.2021	126	26.5
84010913	240	600	TORLON 242	25.03	TORLON 241	24.98	2.0	Inf	183.	No	12.8	3.2021	122	24.6
84010914	240	600	TORLON 242	25.03	TORLON 241	24.98	2.0	Inf	183.	No	15.6	3.2021	111	22.8
84010915	240	600	TORLON 242	25.03	TORLON 241	24.98	2.0	Inf	183.	No	16.0	3.2021	93	20.0
84010916	240	578	TORLON 242	25.03	TORLON 241	24.98	2.0	Inf	183.	Yes	19.8	3.2021	0	-6.1

SUMMARY OF THE WEAR DATA FOR LOW MODULUS MATERIAL ROLLERS

Roller # 1, Mat:Torlon Speciman#:20
Roller # 2, Mat:Steel Speciman#: 3

Test Date :831219	Test Number : 1	Diameter Change: -.0122 mm
Test Date :831220	Test Number : 2	Diameter Change: -.0122 mm
Test Date :831220	Test Number : 3	Diameter Change: -.0081 mm
Test Date :831220	Test Number : 4	Diameter Change: .0041 mm
Test Date :831220	Test Number : 5	Diameter Change: -.0244 mm
Test Date :831220	Test Number : 6	Diameter Change: .0041 mm
Test Date :831219	Test Number : 8	Diameter Change: -.0203 mm
Test Date :831220	Test Number : 7	Diameter Change: .0081 mm
Test Date :831220	Test Number : 8	Diameter Change: -.0203 mm
Test Date :831220	Test Number : 9	Diameter Change: .0203 mm
Test Date :831220	Test Number :10	Diameter Change: -.0081 mm
Test Date :831220	Test Number :11	Diameter Change: -.0284 mm
Test Date :831220	Test Number :12	Diameter Change: -.0041 mm
Test Date :831221	Test Number :13	Diameter Change: .0122 mm
Test Date :831221	Test Number :14	Diameter Change: -.0041 mm
Test Date :831221	Test Number :15	Diameter Change: 0.0000 mm
Test Date :831221	Test Number :16	Diameter Change: -.0122 mm
Test Date :831221	Test Number :17	Diameter Change: .0366 mm
Test Date :831221	Test Number :18	Diameter Change: -.0081 mm
Test Date :831221	Test Number :19	Diameter Change: -.0041 mm

Roller # 1, Mat:Torlon Speciman#:21
Roller # 2, Mat:Steel Speciman#: 3

Test Date :831221	Test Number :21	Diameter Change: .1260 mm

Roller # 1, Mat:Torlon Speciman#:22
Roller # 2, Mat:Steel Speciman#: 3

Test Date :831222	Test Number :23	Diameter Change: -.0122 mm
Test Date :831222	Test Number :24	Diameter Change: -.0122 mm

Roller # 1, Mat:Phenolic Speciman#:13
Roller # 2, Mat:Steel Speciman#: 3

Test Date :831222	Test Number : 1	Diameter Change: -.0203 mm
Test Date :831222	Test Number : 2	Diameter Change: -.0203 mm
Test Date :831222	Test Number : 3	Diameter Change: .0041 mm
Test Date :831222	Test Number : 4	Diameter Change: 0.0000 mm
Test Date :831222	Test Number : 5	Diameter Change: .0366 mm
Test Date :831222	Test Number : 6	Diameter Change: -.0244 mm
Test Date :831222	Test Number : 7	Diameter Change: -.0406 mm
Test Date :831222	Test Number : 8	Diameter Change: .0447 mm
Test Date :831222	Test Number : 9	Diameter Change: -.0081 mm

SUMMARY OF THE WEAR DATA FOR LOW MODULUS MATERIAL ROLLERS

```
     Roller # 1,  Mat:Phenolic      Speciman#:14
     Roller # 2,  Mat:Steel         Speciman#: 3

Test Date :831222   Test Number :11  Diameter Change: -.0569 mm
Test Date :831222   Test Number :12  Diameter Change:  .0813 mm


     Roller # 1,  Mat:Phenolic      Speciman#:15
     Roller # 2,  Mat:Steel         Speciman#: 3

Test Date :831222   Test Number :13  Diameter Change: -.0284 mm
Test Date :831222   Test Number :14  Diameter Change:  .0325 mm


     Roller # 1,  Mat:Phenolic      Speciman#:16
     Roller # 2,  Mat:Steel         Speciman#: 3

Test Date :831222   Test Number :16  Diameter Change: -.0203 mm
Test Date :831222   Test Number :17  Diameter Change:  .0244 mm
Test Date :831222   Test Number :18  Diameter Change: 0.0000 mm


     Roller # 1,  Mat:Phenolic      Speciman#:17
     Roller # 2,  Mat:Steel         Speciman#: 3

Test Date :831222   Test Number :19  Diameter Change:  .0691 mm
Test Date :831222   Test Number :20  Diameter Change:  .0041 mm


     Roller # 1,  Mat:Phenolic      Speciman#:31
     Roller # 2,  Mat:Steel         Speciman#: 4

Test Date :840102   Test Number : 1  Diameter Change: -.0366 mm
Test Date :840102   Test Number : 2  Diameter Change:  .0488 mm
Test Date :840102   Test Number : 3  Diameter Change:  .0447 mm


     Roller # 1,  Mat:Phenolic      Speciman#:32
     Roller # 2,  Mat:Steel         Speciman#: 4

Test Date :840102   Test Number : 5  Diameter Change: -.0284 mm
Test Date :840102   Test Number : 6  Diameter Change:  .0244 mm
```

SUMMARY OF THE WEAR DATA FOR LOW MODULUS MATERIAL ROLLERS

Roller # 1, Mat:Phenolic Speciman#:33
Roller # 2, Mat:Steel Speciman#: 4

Test Date :840102	Test Number : 8	Diameter Change: .0081 mm
Test Date :840102	Test Number : 9	Diameter Change: -.0447 mm
Test Date :840102	Test Number :10	Diameter Change: 0.0000 mm
Test Date :840102	Test Number :11	Diameter Change: .0163 mm
Test Date :840102	Test Number :12	Diameter Change: .0203 mm

Roller # 1, Mat:Torlon Speciman#:51
Roller # 2, Mat:Steel Speciman#: 4

Test Date :840103	Test Number : 1	Diameter Change: -.0325 mm
Test Date :840103	Test Number : 2	Diameter Change: 0.0000 mm
Test Date :840103	Test Number : 3	Diameter Change: -.0163 mm
Test Date :840103	Test Number : 4	Diameter Change: -.0325 mm
Test Date :840103	Test Number : 5	Diameter Change: -.0041 mm
Test Date :840103	Test Number : 6	Diameter Change: -.0041 mm
Test Date :840103	Test Number : 7	Diameter Change: -.0244 mm
Test Date :840103	Test Number : 8	Diameter Change: .0163 mm
Test Date :840103	Test Number : 9	Diameter Change: .0203 mm
Test Date :840103	Test Number :10	Diameter Change: .0041 mm

Roller # 1, Mat:Torlon Speciman#:52
Roller # 2, Mat:Steel Speciman#: 4

Test Date :840103	Test Number :12	Diameter Change: -.0122 mm

Roller # 1, Mat:Torlon Speciman#:32
Roller # 2, Mat:Torlon Speciman#:33

Test Date :840104	Test Number : 1	Diameter Change: -.0732 mm
Test Date :840104	Test Number : 2	Diameter Change: -.0406 mm
Test Date :840104	Test Number : 3	Diameter Change: -.0203 mm
Test Date :840104	Test Number : 4	Diameter Change: -.0406 mm
Test Date :840104	Test Number : 5	Diameter Change: .0122 mm
Test Date :840104	Test Number : 6	Diameter Change: .0081 mm

Roller # 1, Mat:Torlon Speciman#:35
Roller # 2, Mat:Torlon Speciman#:34

Test Date :840104	Test Number : 7	Diameter Change: -.0650 mm
Test Date :840104	Test Number : 8	Diameter Change: -.0203 mm
Test Date :840104	Test Number : 9	Diameter Change: -.0163 mm

SUMMARY OF THE WEAR DATA FOR LOW MODULUS MATERIAL ROLLERS

Roller # 1, Mat:Torlon Speciman#:31
Roller # 2, Mat:Torlon Speciman#:36

Test Date :840104	Test Number :11	Diameter Change: .1626 mm
Test Date :840104	Test Number :12	Diameter Change: -.0081 mm
Test Date :840104	Test Number :13	Diameter Change: -.0081 mm

Roller # 1, Mat:Phenolic Speciman#:21
Roller # 2, Mat:Phenolic Speciman#:51

Test Date :840105	Test Number : 1	Diameter Change: -.0325 mm
Test Date :840105	Test Number : 2	Diameter Change: -.0041 mm
Test Date :840105	Test Number : 3	Diameter Change: .0772 mm
Test Date :840105	Test Number : 4	Diameter Change: -.0203 mm
Test Date :840105	Test Number : 5	Diameter Change: -.0244 mm
Test Date :840105	Test Number : 6	Diameter Change: .0325 mm

Roller # 1, Mat:Phenolic Speciman#:22
Roller # 2, Mat:Phenolic Speciman#:52

Test Date :840105	Test Number : 8	Diameter Change: .0569 mm
Test Date :840105	Test Number : 9	Diameter Change: 0.0000 mm

Roller # 1, Mat:Phenolic Speciman#:10
Roller # 2, Mat:Phenolic Speciman#:53

Test Date :840106	Test Number : 1	Diameter Change: -.0610 mm
Test Date :840106	Test Number : 2	Diameter Change: .0163 mm
Test Date :840106	Test Number : 3	Diameter Change: .0935 mm

Roller # 1, Mat:Phenolic Speciman#:41
Roller # 2, Mat:Phenolic Speciman#:54

Test Date :840106	Test Number : 5	Diameter Change: .0488 mm

Roller # 1, Mat:Phenolic Speciman#:43
Roller # 2, Mat:Phenolic Speciman#:55

Test Date :840106	Test Number : 7	Diameter Change: .0163 mm
Test Date :840106	Test Number : 8	Diameter Change: .0325 mm

SUMMARY OF THE WEAR DATA FOR LOW MODULUS MATERIAL ROLLERS

Roller # 1, Mat:Torlon Speciman#:45
Roller # 2, Mat:Torlon Speciman#:47

Test Date :840109	Test Number : 1	Diameter Change: -.1219 mm
Test Date :840109	Test Number : 2	Diameter Change: .0041 mm
Test Date :840109	Test Number : 3	Diameter Change: -.0163 mm
Test Date :840109	Test Number : 4	Diameter Change: -.0041 mm
Test Date :840109	Test Number : 5	Diameter Change: .0122 mm
Test Date :840109	Test Number : 6	Diameter Change: -.0041 mm
Test Date :840109	Test Number : 7	Diameter Change: .0041 mm

Roller # 1, Mat:Torlon Speciman#:42
Roller # 2, Mat:Torlon Speciman#:41

Test Date :840106	Test Number : 9	Diameter Change: -.0447 mm
Test Date :840109	Test Number :10	Diameter Change: -.1382 mm
Test Date :840109	Test Number :11	Diameter Change: .0203 mm
Test Date :840109	Test Number :12	Diameter Change: .1260 mm
Test Date :840109	Test Number :13	Diameter Change: -.0528 mm
Test Date :840109	Test Number :14	Diameter Change: .0935 mm
Test Date :840109	Test Number :15	Diameter Change: -.0853 mm

Roller # 1, Mat:Torlon Speciman#:46
Roller # 2, Mat:Torlon Speciman#:48

Test Date :840110	Test Number : 1	Diameter Change: -.0366 mm

SUMMARY OF THE FAILURES OF LOW MODULUS MATERIAL ROLLERS

Roller #1		Roller #2		Failed Roller		Failure Mode
Torlon	4	Steel	3	Torlon	4	Thermal Blistering
Torlon	21	Steel	3	Torlon	21	Crushing
Torlon	22	Steel	3	Torlon	22	Crushing
Torlon	1	Steel	2	Torlon	1	Crushing
Torlon	20	Steel	3	Torlon	20	Crushing
Torlon	2	Steel	2	Torlon	2	Crushing
Torlon	51	Steel	4	Torlon	51	Plastic Flow
Torlon	52	Steel	4	Torlon	52	Plastic Flow
Torlon	32	Torlon	33	Both		Glazing
Torlon	5	Torlon	6	Torlon	6	Crushing
Torlon	7	Torlon	3	Both		Crushing
Torlon	46	Torlon	48	Torlon	46	Blistered/Crushed
Torlon	42	Torlon	41	Torlon	41	Blistered/Glazed
Torlon	45	Torlon	47	Torlon	47	Thermal Blistering
Torlon	35	Torlon	34	Torlon	34	Thermal Blistering
Torlon	31	Torlon	36	Torlon	36	Thermal Blistering
Phenolic	6	Phenolic	7	Phenolic	7	Spalled
Phenolic	54	Phenolic	41	Phenolic	54	Spalled/Burned
Phenolic	53	Phenolic	10	Both		Noisy/Burned
Phenolic	11	Phenolic	12	Phenolic	11	Incep. Delamination
Phenolic	5	Phenolic	3	Phenolic	5	Incep. Del/Burned
Phenolic	22	Phenolic	52	Both		Glazed/Burned
Phenolic	55	Phenolic	43	Phenolic	43	Delaminated/Burned
Phenolic	10	Phenolic	8	Phenolic	10	Incep. Del/Burned
Phenolic	51	Phenolic	21	Both		Glazed/Burned
Phenolic	14	Steel	3	Phenolic	14	Incep. Del/Burned
Phenolic	31	Steel	4	Phenolic	31	Incep. Delamination
Phenolic	17	Steel	3	Phenolic	17	Delaminated
Phenolic	16	Steel	3	Phenolic	16	Delaminated
Phenolic	32	Steel	4	Phenolic	32	Delaminated
Phenolic	33	Steel	4	Phenolic	33	Delaminated
Phenolic	9	Steel	2	Phenolic	9	Incep. Delamination
Phenolic	15	Steel	3	Phenolic	15	Noisy
Phenolic	2	Steel	2	Phenolic	2	Spalled
Phenolic	13	Steel	3	Phenolic	13	Spalled
Phenolic	1	Steel	2	Phenolic	1	Incep. Delamination

SUMMARY OF THE FAILURES OF LOW MODULUS MATERIAL ROLLERS

Roller #1		Roller #2		Failed Roller		Failure Mode
Acetal	3	Steel	2	Acetal	3	Subsurface Melting
Acetal	4	Steel	2	Acetal	4	Subsurface Melting
Acetal	8	Steel	2	Acetal	8	Subsurface Melting
Acetal	2	Steel	2	Acetal	2	Subsurface Melting
Acetal	9	Acetal	10	Both		Subsurface Melting
Acetal	1	Acetal	5	Acetal	1	Subsurface Melting
Acetal	6	Acetal	7	Acetal	6	Subsurface Melting
Nylon	2	Steel	2	Nylon	2	Subsurface Melting
Nylon	1	Steel	2	Nylon	1	Subsurface Melting
Nylon	3	Steel	2	Nylon	3	Subsurface Melting
Nylon	8	Steel	2	Nylon	8	Subsurface Melting
Nylon	9	Nylon	10	Nylon	9	Subsurface Melting
Mononylon	2	Steel	2	Mononylon	2	Subsurface Melting
Mononylon	3	Steel	2	Mononylon	3	Subsurface Melting
Mononylon	10	Steel	2	Mononylon	1	Subsurface Melting
Mononylon	6	Mononylon	7	Mononylon	6	Subsurface Melting
Mononylon	8	Mononylon	9	Neither		Noisy
Mononylon	5	Mononylon	4	Mononylon	5	Subsurface Melting
FTorlon	81	FTorlon	11	FTorlon	81	Gauged/Crushed
FTorlon	12	FTorlon	13	FTorlon	12	Spalled
FTorlon	5	FTorlon	6	FTorlon	5	Gauged
FTorlon	1	Steel	2	FTorlon	1	Spalled
FTorlon	10	Steel	2	FTorlon	10	Spalled
FTorlon	2	Steel	2	FTorlon	2	Spalled/Crushed
FTorlon	3	Steel	2	FTorlon	3	Crushing

End of Document