Ramp design: part II

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ABSTRACT: In a previous paper [Tappi J. 74(11): 161(1991)], the authors presented a mathematical model that provided a means for the prediction of paper roll velocity and displacement down a given incline. In this second paper, the results of numerous physical tests using rolls of varying hardness on a ramp of known slope are presented in support of the mathematical model. These results are tabulated and graphed to provide reference material for ramp analysis and design.

KEYWORDS: Displacement, dynamics, equations, hardness, inclined design, mathematical models, physical tests, velocity, wound rolls.

Model development

Ramp applications for paper roll handling are extensive. Yet, it was discovered by the authors that no scientific basis had been applied to the selection of ramp slopes until the first paper was presented on the subject *(1)*. Slope selection was based on historical and empirical data, without an understanding of roll dynamics or the ability to predict roll velocity and displacement.

Research uncovered a rolling resistance model developed by Shames *(1)* that assumed rolling resistance was created by the surface deforming and bunching in front of a rigid roll (**Fig. 1A**). This model shows that the deformation of the surface allows the normal reaction force N to rotate through an angle ϕ. This rotation of the normal reaction force results in a component of force that opposes motion. For relatively soft paper rolls rolling down steel or concrete ramps, Shames' model does not seem to conform to what is physically observed (i.e., the paper roll deforming and the ramp surface remaining undeformed). However, Shames' concept was useful to the authors in developing the model illustrated in *Fig. 1B*, wherein it is assumed that the surface remains undeformed while the roll flattens over the region of contact *(2)*. This flattening allows the normal reaction to assume a position offset from the center line of the roll, resulting in an opposition to motion.

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Equations for the velocity and displacement of the paper roll shown in Fig. 1B were developed by considering the forces acting on the roll depicted in **Fig. 2**. As reported in the first paper, the equation for the velocity of the roll down the ramp was found to be:

$$v = dx/dt = K[\sin\theta - (a/\rho)\cos\theta]t + v_0 \quad (1)$$

where v_0 is the initial velocity of the roll down the ramp, a is the distance the reaction force normal to the surface of the ramp is offset from the y axis, ρ is the radius from the center of the paper roll to the ramp, θ is the angle the ramp makes with the horizontal, and

$$K = mg(m + I/\rho^2)$$

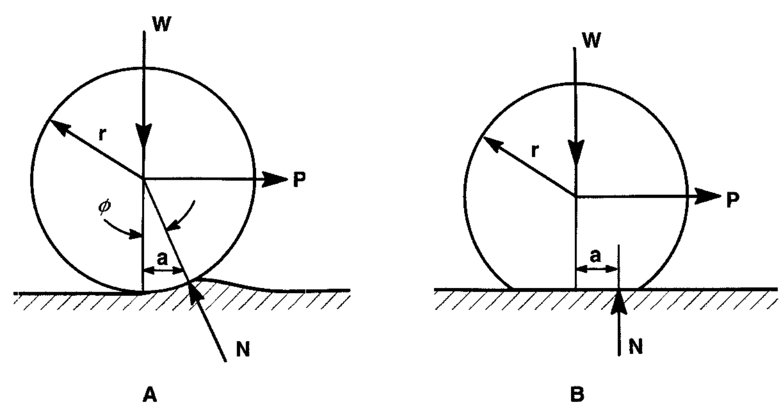
where m is the mass of the roll, g is the gravitational constant, and I is the mass moment of inertia of the roll. Integration of the velocity equation yields the displacement equation:

$$x = K/2[\sin q - (a/r)\cos q]t^2 + v_0 t + x_0 \quad (2)$$

where x_0 is the initial roll displacement.

The term $(a/\rho)\cos\theta$ is seen in both the velocity and displacement equations to be a factor resulting from the opposition to motion. Since θ is a function of the installation of the ramp, a/ρ is the only factor which can be a function of the physical characteristics of the roll. In general, the softer the roll the greater the roll deformation. This greater deformation results in a smaller radius to the ramp and a greater offset of the re-

1. Rolling resistance models. A: Shames *(1)*. B: Moore and Stephens *(2)*.



I. Paper roll attributes

Roll number	*1*	*2*	*3*	*4*	*5*	*6*
Paper type	Fine white	Napkin	Fine white	Newsprint	Coated liner	Tissue
Weight, lb	1358	328	690	68.5	3358	498
Width, in.	36 5/8	23 3/4	19	15	46 1/8	65 1/8
Outside diameter, in.	39 7/8	40 1/16	39 7/8	14 3/8	60 1/8	33 7/16
Deformed diameter, in.	39 7/8	40	39 13/16	14 5/16	60 1/8	33 3/8
Core diameter, in.	3	12	3	3	12	16
Condition	Good	Good	Out of round	Butt	Banded	Wrapped
Average Schmidt hammer	46.2	29	43.3	41.3	46	26.2

action force. Thus, it is seen that there is a correlation between roll hardness and the degree of opposition to rolling.

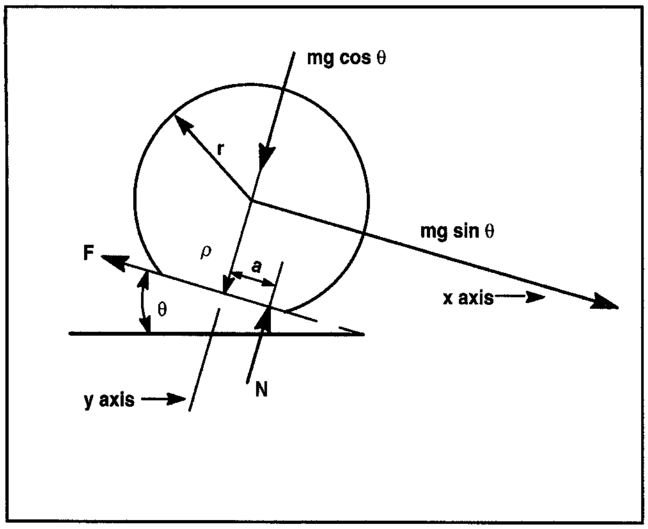
Initial laboratory trials with a few small paper rolls were performed. The test results were sufficiently close to the predicted results (**Fig. 3**). This agreement indicated that the model was able to predict roll behavior. It was acknowledged, however, that measuring techniques used in the laboratory experiment were crude; the number of trials was not statistically valid; and there might be factors associated with rolling a wound roll of paper, such as possible hysteresis losses, that were not yet defined. (Hysteresis loss is defined as the energy converted to heat, as by internal friction, in a material accompanying cyclic variation of the driving variable.)

Arising out of this initial foray into the phenomena associated with the motion of a paper roll on a ramp was the commitment to perform more precise laboratory trials in statistically valid numbers, using full size mill equipment and representative trial rolls. Those trials and the results are described below.

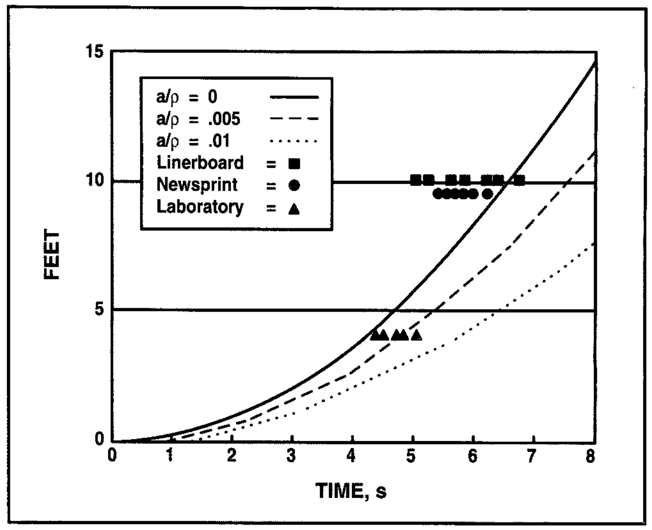
Laboratory setup

The initial step in conducting additional tests was the preparation of a laboratory facility. Through the donation of two roll stops, a set of turning rolls, and connecting ramps from Weyerhaeuser Paper Co. in New Bern, NC, enough equipment was obtained to construct a full-scale ramp facility in a laboratory at the University of Alabama at Birmingham. The ramp was constructed with a roll stop at each end and an average slope of 1/4 in./ft. A rigid end stop was included in the design as a safety precaution. The ramps were

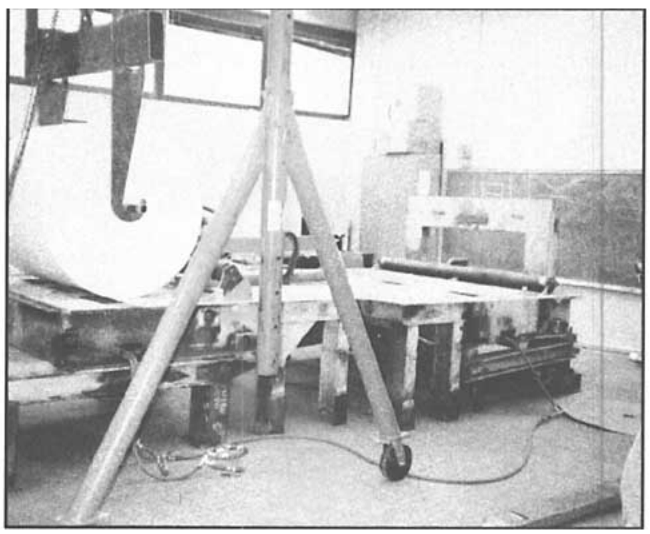
2. Roll free body



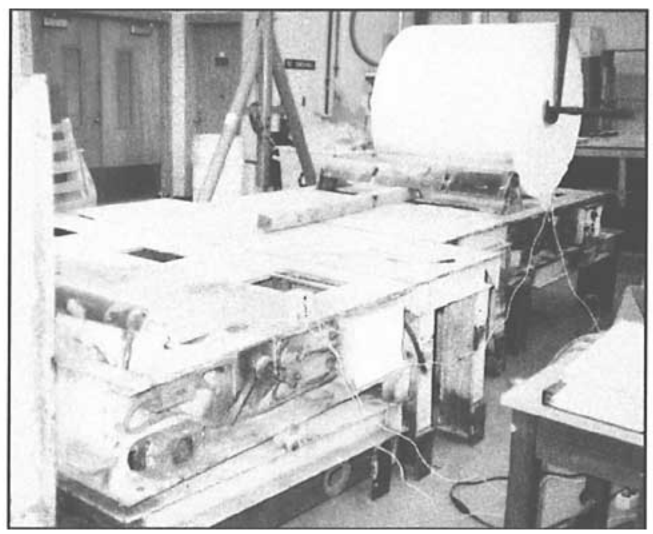
3. Roll displacement



4. Laboratory setup



5. Laboratory setup



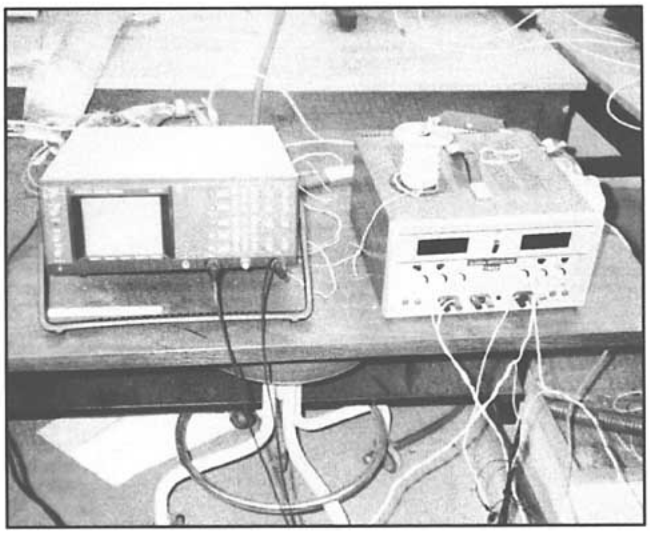
welded together and then secured to the floor. As illustrated in **Fig. 4 and** 5, the length of ramp available for roll testing was approximately 9 ft between roll stops.

It was intended that the paper rolls would be positioned and held by the upper roll stop, then released and stopped by the lower roll stop. The time each paper roll took to travel the known distance down the ramp would be timed by triggering an oscilloscope as the paper roll broke a start beam and then a stop beam. Infrared beam sensors were used so that laboratory lighting would not present a problem. The oscilloscope and sensors are depicted in **Figs. 5 and 6.**

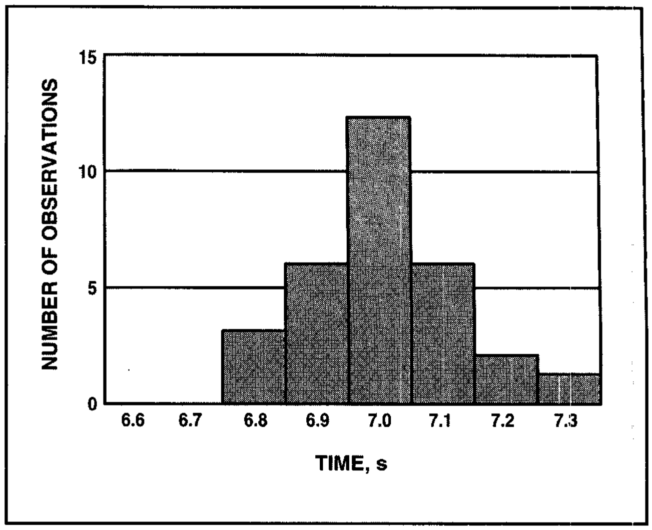
Roll testing

Initial trials indicated that releasing a roll by lowering a roll stop could not provide accurate data. This was due to the fact that the roll stop retarded the initial acceleration of the paper roll down the ramp. While this condition might be acceptable in an industrial setting, it cannot be accounted for by the present theory. It was decided that some quick release mechanism would have to be used to hold and release the paper roll. At the 1/4-in./ft slope, the roll could be positioned by the testing team and then safely held in place by one person. Upon zeroing of the timing system, the roll could be released by simply removing a hand. This method of releasing the rolls proved suitable and provided a true zero initial velocity and a constant roll acceleration. Each paper roll was positioned and released in this manner 30 times. Test times, together with the distance between the start and stop sensors, were recorded for later reduction.

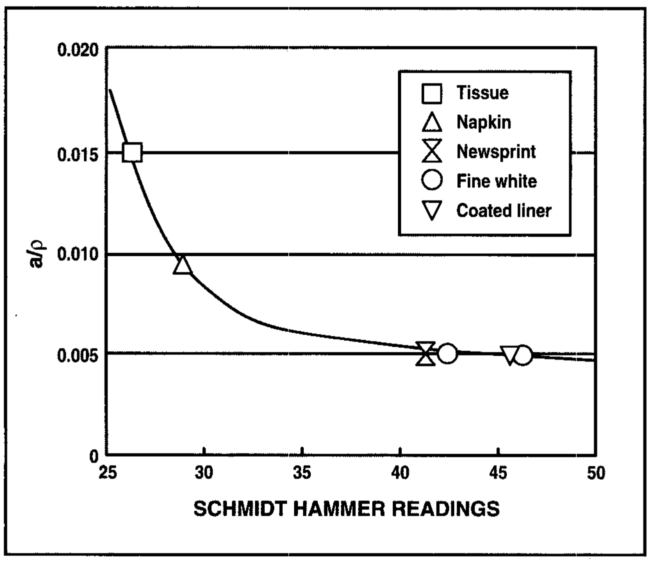
6. Laboratory setup



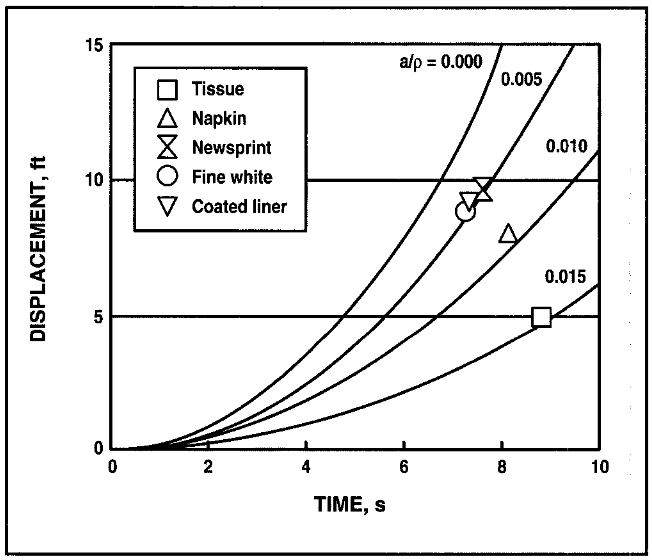
7. Histogram of test times for a hard roll



8. Rolling resistance vs. Schmidt hammer readings



9. Displacement vs. time on 1/4-in./ft steel ramp



Schmidt hammer tests were conducted on each paper roll prior to the timed test. The Schmidt hammer is an impact-based device for measuring roll hardness. The instrument measures the rebound of a small plunger after it strikes the paper roll *(3)*. Schmidt readings were taken at a zero angle or at the point where the x axis would exit the paper roll. Readings were taken close to each end and in the middle of the roll. The average of these values were recorded together with the type of paper, weight, width, nominal outside diameter, deformed diameter, core diameter, and condition of the paper roll (**Table I**).

Data reduction

A mean value of the 30 test times for each paper roll tested was calculated along with standard deviations of test times (**Table II**). A representative histogram of the test times for a hard roll are depicted in **Fig. 7**. Confidence interval testing performed on each set of data indicated that all data fell within a 95% confidence level.

The displacement equation was then solved for the rolling resistance parameter as:

$$a/\rho = [\sin\theta - (2x/Kt^2)]/\cos\theta \quad (3)$$

The average test time together with the known test distance x, the known ramp angle θ, and the calculated value of K were then used to calculate the average value of a/ρ. These values are included in Table II.

II. Average test time, standard deviation, and rolling resistance parameter

Roll number	1	2	3	4	5	6
Test length, in.	101	101	72[a]	111	103	58
Average test time, s	6.97	8.07	5.46	7.38	7.08	8.54
Standard deviation	0.12	0.21	0.14	0.19	0.17	0.30
Calculated rolling resistance parameter	0.0047	0.0091	0.0052	0.0052	0.0050	0.0151

[a]Slope for this run was 9/32 in./ft. All other slopes 1/4 in./ft.

Test results

Figure 8 shows the rolling resistance parameters calculated from the timed tests and the data reduction plotted as a function of roll hardness as indicated by Schmidt hammer readings. Hard paper rolls, indicated by Schmidt hammer readings in excess of 40, had rolling resistance parameters in the range of 0.0047 to 0.0052. Transitional paper rolls, indicated by Schmidt hammer readings of 27 to 40, had rolling resistance parameters in the range of 0.005 to 0.01. Soft paper rolls, indicated by Schmidt hammer readings of less than 27, had rolling resistance parameters greater than 0.01.

It may be seen from the velocity and displacement equation that the limiting value of the rolling resistance parameter for a ramp with a 1/4-in./ft slope is 0.021. In the process of running trials, a roll of coated linerboard was selected for testing. This roll was 37 3/8 in. wide, 60 in. in diameter, and weighed 2668 lb. The roll was steel banded on each edge and had a 12-in. core. The roll was positioned on the ramp and Schmidt hammer readings were taken to establish the roll hardness. As the Schmidt hammer was moved across the width of the roll, it became apparent that there was an extreme variation in roll hardness. One edge of the roll was very hard (Schmidt hammer of 40), but the readings quickly fell as the distance from the hard edge increased. By the middle of the roll and onto the other side of the roll, the Schmidt hammer readings dropped to 20 and 16, respectively. In addition, the radius to the ramp on the hard side of the roll only decreased by 1/16 in., while on the soft side of the roll the radius decreased by more than 1 in. This gave the roll a tapered shape. When the roll was released, it did not move. This indicated that the rolling resistance parameter was greater than 0.021, and the roll was deemed nonusable for test and removed.

The experience with the roll described above suggests that, regardless of the design parameters of a ramp system, there will always be rolls produced that are nonhomogeneous to the point that they must be rejected. Many of these rolls will not roll without intervention on a ramp designed for a homogeneously wound roll. Consequently, it is recognized that proper ramp slope is not a remedy for all paper roll-handling problems. Instead, roll-handling systems should be designed so that reject rolls may be easily removed from the system at the earliest possible point.

Conclusions

The displacement–time plot shown in **Fig.** 9 indicates that the derived equations are capable of accurately predicting roll dynamics. While the definitions of hard, transitional, and soft are arbitrary, the data suggest a direct correlation between paper roll hardness, as measured by Schmidt hammer tests, and rolling resistance parameter. The tests also suggest that rolling resistance is only a function of hardness, not weight or paper roll size. If a nominal value of 0.005 is used as the rolling resistance parameter for all of the hard paper rolls, the largest percent difference between the average test times and the predicted times is 0.92%.

Future research

We plan to continue with the present course of research. As more tests are conducted with the available rolls and additional rolls of varying hardness are obtained and tested, the definitions of hard, transitional, and soft should become more apparent. These test rolls will also be slabbed down and gap tests will be conducted. This new information should provide an additional correlation between rolling resistance and roll quality.

Three other research projects are presently planned and should commence within the year. The first will attempt to address the question of a static rolling resistance coefficient. The ramp facility will have to be rebuilt for this particular project. The rebuild will incorporate an actuator that will allow the slope to be varied. This variable slope ramp will not only provide information on the static rolling resistance coefficient, but will also allow for the testing of softer paper rolls. These new data should complete the information provided in Fig. 8 and provide the designer with information required to design quick drops. The second project will deal with the interaction of a paper roll and a pneumatic roll stop. The intent of this project will be to define the proper roll stop controls and settings needed to bring a paper roll to a stop without damage or rebound. The third project will examine the effect of initial velocity imparted by such actuators as roll kickers, tiltoffs, etc. Additional research, yet unplanned, might also probe the effects of hysteresis on roll dynamics. TJ

Literature cited

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2. Moore, J. R. and Stephens, B. J., *Tappi J.* 74(11): 161(1991).
3. Roisum, D. R., *Tappi J.* 71(10): 91(1988).

This research effort was made possible in part through funding and use of laboratory space by the University of Alabama at Birmingham, through the generous donation of equipment by Weyerhaeuser Paper Co. in New Bern, NC, and through the donation of trial paper rolls by Champion International, Mead Coated Board, Inc., Weyerhaeuser Paper Co., Scott Worldwide, and Westvaco Corp. The authors wish to thank the many individuals within those organizations who contributed their valuable time and support.

Received for review June 30, 1993.

Accepted Nov. 1, 1993.

Presented at the TAPPI 1993 Finishing and Converting Conference.

CORRECTION

Correct address for Mardon

The mailing address listed for Jasper Mardon in the February "On Management" section of *Tappi Journal* and earlier installments of his series on career managment contained a mistake. The correct listing is Jasper Mardon, President, Omni Continental, P.O. Box 91098, West Vancouver, BC, Canada V7V 3N3. The street address for Omni Continental is 2380 Haywood, West Vancouver, BC, Canada V7V 1X7.