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Stress-Strain Testing of Rubbers at High Rates of Elongation

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INTRODUCTION

It is well known that the properties of rubbery materials depend upon the speed or rate at which they are tested or used. A considerable body of work has shown that the dynamic properties of rubber change with the time scale of the test and, in particular, at very short times or at very fast rates, the properties approach those of plastics, i.e., high modulus and low elongation. These dynamic properties are measured by oscillation methods, usually at small strains.

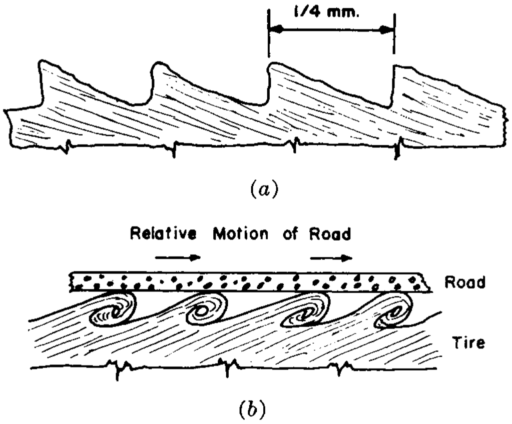
In contrast to this class of information, where the material is rarely strained to failure, one can also strain rubbers unidirectionally to failure at strain rates that correspond to the high frequencies of dynamic measurements. In linear extension experiments, as the rate of stretching increases tensile strength rises, elongation drops, apparent modulus increases, and relaxation losses may go up or down depending upon the particular rubber and the time scale of the phenomenon that is being investigated. Extrapolating the change in tensile strength with rate of testing suggests that tensile strength as we know it should change drastically when measured at very high rates of speed. That is, since the viscoelastic properties of rubber are time dependent, and also dependent upon the speed at which they are tested, the tensile properties of rubbers measured at room conditions with the ordinary Scott or Instron machines probably do not have the same values as at the speeds and frequencies that might be encountered in such situations as tire wear. Hence, we should like to measure the properties of rubbers at very high rates of speed, presumably comparable to those encountered in tire tread wear, in order to find out how much properties do change as the speed of test is increased.

In order to measure stress-strain properties at rates of elongation comparable to those we believe exist in tire tread usage, we had to develop a small high speed tensile machine. The purpose of this paper is to describe that machine and some results obtained with it.

BACKGROUND

The most familiar tests on rubber properties are those run on the Scott machine or its more modern equivalent, the Instron tensile machine. These tests are run at jaw speeds nominally 20 in./min. to give elongation rates computed as 33% per second for a 1-in. dumbbell sample. However, the actual elongation of the necked portion of the dumbbell samples conventionally used is considerably less than this figure (about 20% per second), since the tabs at the ends stretch considerably. The Instron is capable of a slightly higher range, with speeds up to 100% per second. These stretch rates are too low for some purposes, hence in recent years there has been a great deal of interest in trying to measure properties of rubbers at much higher rates of elongation.[1-4] Since it is fairly difficult to drive the screw and crosshead table arrangement at fairly high rates of speed at *constant* velocity, attempts have been made to obtain high, constant speeds from stored energy in flywheels or inertia machines. In this type of machine the energy required to break the sample is only a small portion of the energy that is stored in the machine. Under these conditions the sample can be stretched at roughly constant speed throughout the duration of the test. Machines of this kind using flywheels,[2] or flywheels driving tapes[3] to provide linear extension over a long range of travel, are described in the literature and work well at rates of elongation up to about 20 m./sec. The size and shape of the sample will determine the elongation rate in per cent/second. In most of the various kinds of apparatus that are under development currently some variety of strain-gage beam or weigh bar is used to record the load transmitted by the sample. This beam or load cell usually has a very low response time, so that resolution to less than 1 msec. can be attained. Those types of apparatus which still use dumbbell samples do not try to correct for the difference between jaw movement and sample extension, but simply state it as such. Several experimenters[3,4] have tried to eliminate problems of jaw grip by going to Schopper rings or a specimen closely related to them.

The problem of high speed testing makes it necessary to define what is meant by "high speed." At first, we shall assume that high speed is tire speed. Consider some of the quantities that are known from tire performance. A typical 7.50 by 14 tire has a circumference of 91 in. This tire, on a car driven at 60 m.p.h., has an angular speed about 12 revolutions/second. However, the footprint of the tire, which is the portion in actual contact with the road, is only about $6^1/_2$ in. long, or represents 7% of the total circumference. The load and unloading of the portion of the tread in contact with the road then takes place in approximately 6 msec. The unloading and loading steps are not symmetrically equal and opposite to one another. The time for unloading of a tread portion in contact with the road is only about one-third of the contact time or about 2 msec. Some years ago it was pointed out that if a rubber is extended to break in this unloading cycle and if the extension is about the same as the elongation measured at ordinary test conditions (namely about 500%) then the rate of extension in that time interval is about 250,000% per second. This figure then, a quarter million per cent/second, is a reasonable estimate of the elongation rates that are needed for tire tread testing. This estimate of the rate of extension does not give any idea of the size of the sample that might be tested to destruction or stretched to break at this speed. This figure looks so high that it would be well to test it or check it in other ways.



(a)

(b)

Fig. 1. (*a*) Cross section of wear pattern at tread surface. Idealized radial section. (*b*) Hypothetical wear process against smooth surfaces (Vickers and Robinson[7]).

Some estimate of the actual size of the specimen and of actual elongation can be made from other kinds of tests on tire performance. Scratch plate data[5] indicate that the actual scrubbing of tread rubber on the road is of course quite complicated, with a path length of about 0.01 in. That is, within the footprint area itself, and during the movement of the tread on the road first in compression and later in unloading, individual portions of the tread may move about 0.01 in. relative to asperites of the road. The concept that tire wear or tread abrasion takes place through a mechanism in which tendrils of rubber are pulled off the tire has been presented by Schallamach[6] and refined by a good many others to give both a picture of how the abrading process may take place and an estimate of the size of the tendrils of rubber that might be involved in this operation. These concepts are presented schematically in Figure 1. In Figure 1*a*, the wear patterns that have been observed on tires are schematically reproduced in section. The spacing between crests is about $^1/_4$ mm. (0.01 in.) scaled from photographs.[7] While the wear pattern has a frequency or repetition interval that varies with the severity of the wear, the value of 0.01 in. is typical for tires driven on ordinary roads at moderate speeds. Also, Figure 1*b* shows the scheme wherein the tendrils or ridges of rubber can be elongated by friction, being rolled up between the tire surface and the road. While such a rolling process results in an extremely nonuniform tensile elongation for the material, one may compute an average rate with the recognition that individual portions may actually be stretched at a much higher rate. Ridges with a spacing of $^1/_{100}$ of an inch have heights that are approximately the same. Hence one can say that the rubber tendril 0.01 in. long is stretched 0.01 in., as indicated by the scratch movement in the 2-msec. interval of unloading to give a nominal stretch rate approximately 50,000% per second. Even if the overall stretch rate is this figure, individual portions near the base of the tendril may be stretched as much as four or five times this rate, in good agreement with the estimate presented above.

This means that our laboratory attempts to run tensile tests comparable to suspected abrasion severity in a tire must be run at rates the order of

50,000% per second or higher. Considering the convenience of measurements on samples that have a nominal length of 1 in. this defines rates of extension about 500 in./sec. (2500 ft./min., or $12^1/_2$ m./sec.) as a rough figure. While speeds in this range can be obtained from tapes driven by flywheels, the associated centrifugal and tensile forces in the machines themselves become formidable, so that this development took another path.

Velocities of this order of magnitude can be obtained easily by dropping weights from convenient heights. The original experiment was then proposed simply as follows. Is it practical to make tensile measurements at high rates of elongation by using a falling weight to provide the speed and energy necessary to break a rubber specimen? As will be shown several pages later, the answer is "yes."

The velocity of a falling weight is given by the formula:

$$V = \sqrt{2\,gh}$$

This reduces to the formula:

$$V = 8.05\sqrt{h}$$

where h is expressed in feet and V in feet/second. The value of the striking velocity as a function of the height in feet for several representative and convenient heights or velocities is listed in Table I.

TABLE I
Velocity and Fall Values

Drop height, ft.	Impact velocity, in./sec.
1	96.5
10[a]	305
35[b]	572
107	1000

[a] Ceiling height in laboratory modules.
[b] Height of a convenient chimney exhaust.

In the discussion that follows, an attempt has been made to use the terms *(1)* "high speed" referring to speeds over 200 in./sec., *(2)* "intermediate speeds" roughly 1 to 200 in./sec., and *(3)* "low speeds" being below $^1/_2$ in./sec. As will be evident later, the high speed range is comparable to the speed of sound in rubber, a factor which introduces new complications.

APPARATUS AND TECHNIQUE

Preliminary Experiments

The first set of experiments was run using an experimental setup shown in Figures 2 and 3. A dumbbell sample was cemented into steel jaws using Eastman 910 cement and hung from a strain-gage beam on a tower. A lug on the bottom jaw caught the falling weight and provided means for extending the sample. The load on the sample was transmitted to the beam, bending it sufficiently to give a signal. The output of the strain-gage beam was amplified, displayed on an oscilloscope, and photographed in a double exposure technique on the same frame showing the extension of the sample. A Fastex camera was used to obtain adequate speeds for reasonable time resolution, following previously published reports.[8-10] Since the falling weight must possess enough kinetic energy that the tensile energy supplied to the sample does not slow it down appreciably, most of the kinetic energy of the falling weight will be dissipated in some form of braking mechanism at the bottom. Rather than trying to build a rather sturdy brake, or apparatus sufficiently rugged to withstand impact

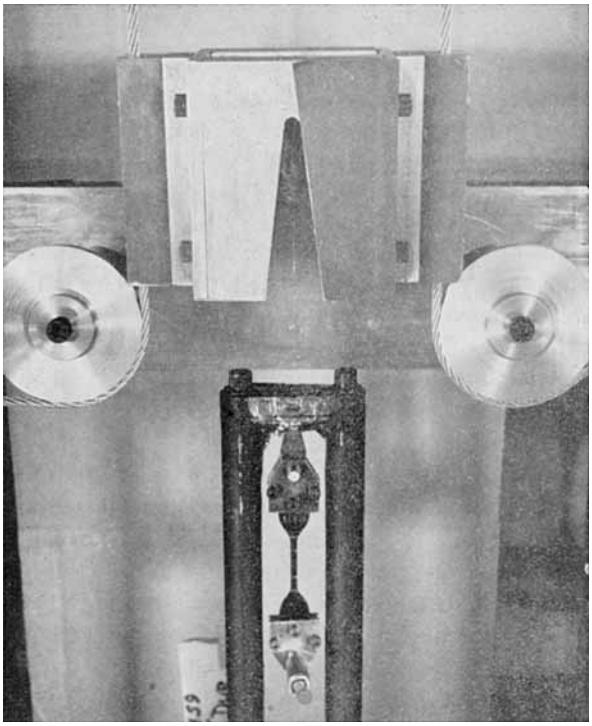


Fig. 2. View of dumbbell sample hung on the tower. The falling weight is shown almost at the end of its track slightly before it passes over the sample to engage the lug protruding from the lower jaw.

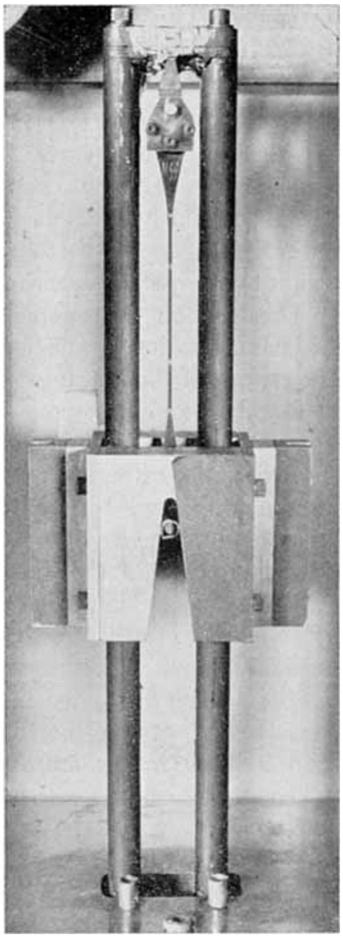
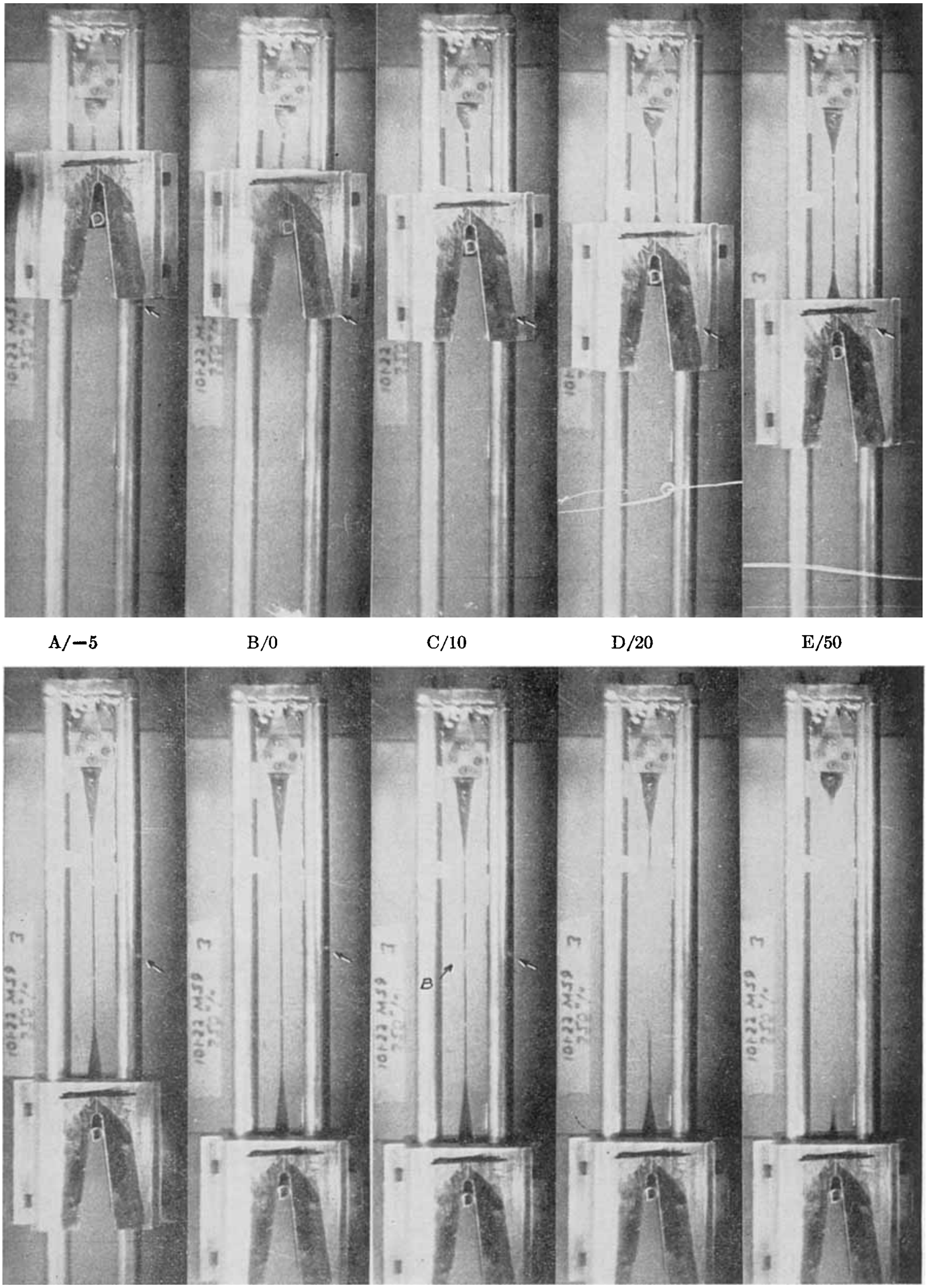


Fig. 3. Stretched sample. Crushable lead cylinders are in place on the inertia plate. One crushed cylinder is also shown. Bench marks on the sample are obvious.

loads up to 300 ft.-lb. energy, a system of expendable energy mechanisms was devised. The falling weight passes the sample, then crushes a set of lead cylinders. The cylinders rest on a steel slab, an inertia plate, in turn cushioned by a "dead" rubber. Another inertia plate and rubber sub-base provide additional damping arrangements.

A drop tower 35 ft. high was installed in an unused chimney originally planned for hood ventilation purposes at the time the building was built. Stations at an effective 9-ft. height and at the full 35 ft. were installed to hold the weight and to drop it in a reproducible manner. A small electromagnet with brass locating lugs on its face provided a convenient grip and release mechanism for the weight. The weight itself is plane symmetric and has tapered slots on both sides designed to engage the striker bar and pull the sample in a balanced manner. Clearances between the weight and the sample tower were about $^1/_{32}$ in. Hence careful alignment was necessary in order to make sure that the weight cleared the tower, both initially and during sample extension, to avoid errors and masking vibrations from a possible strike. One-inch bench marks were drawn in the neck of the dumbbell using a "silver" pencil in order to be able to follow the elongation of the rubber on the photographic record.

Operation of the test was conducted as follows. The sample was installed in its frame. The lead bumpers were put in place. The weight was hoisted to the holding station by cables, crank, and elbow grease. The magnet was turned on. The hoist carriage was lowered and moved out of the way. All equipment was checked and the weight released. The release of the weight also started the timing control on the Fastex camera, and a photographic record was taken as soon as the lights came on. The falling weight engaged the striker bar at the bottom of the sample, stretched it at that velocity. The load transmitted to the strain-gage beam was displayed on the scope. The two records, scope face and sample, were photographed simultaneously on the same frame. The nominal speed of the Fastex was calibrated from its own internal mechanism. In most of this series of tests, the speed was close to 4000 frames/sec. Several individual frames have been enlarged and are presented as Figures 4*A*–*J* attached. The oscilloscope spot is indicated by the added arrow. Figure 4*A* shows a picture of the system five frames prior to contact of the falling weights and the striker bar. The next photograph, *B*/0, shows frame Zero, the moment of striking. It will be noted that this frame shows some vibration and what looks like a double exposure, meaning that the striker bar and lower jaw of the sample moved appreciably in the interval of the exposure itself, slightly less than 0.0001 sec. This enlargement is from one frame of a motion picture record. There is no possibility of a double exposure, despite the appearance thereof. Subsequent enlargements show the position of the weight, elongation of the sample, and the movement of the oscilloscope record spot at various stages during the elongation (frame Nos. 10, 20, 50, 100, and 122). Particular attention should be given to the three frames just prior to break (*G*/122), at break (*H*/123), and immediately thereafter (*I*/124). These show a contraction of the sample, very rapid compared to its relatively slow elongation. The broken pieces of the stretched sample had completely retracted to the



A/−5 B/0 C/10 D/20 E/50

F/100 G/122 H/123 I/124 J/125

Fig. 4. Enlargements from the Fastex film record. Arrows point to the oscilloscope spot. Incipient break in frame H is labeled "B."

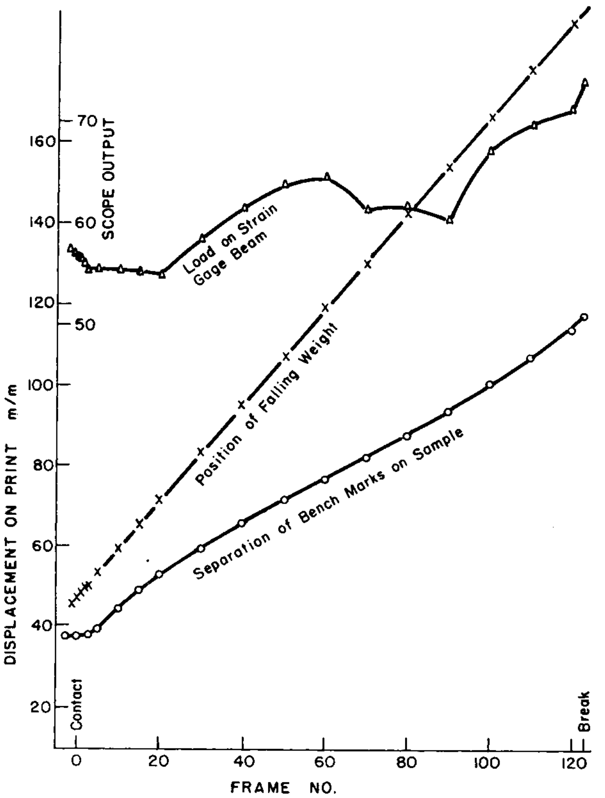


Fig. 5. Photographic measurements.

grip positions within the frame at this exposure speed (*J*/125). That is, retraction was complete in less than 0.001 sec. compared to 30 msec. for stretching. This extremely rapid retraction has been described before[8-10] and poses a goal for elongation experiments.

Measurements were made on enlargements of the individual frames to determine the position of the weight, the space between the bench marks, and the movement of the oscillograph spot during the progress of the test. These data are plotted against frame number in Figure 5. It will be noted that the weight moved at constant speed throughout most of the test, even as expected. The position of the bench marks, or their separation, did not follow the weight, also as expected from the well-known behavior of dumbbell specimens. While there is some uncertainty of bench-mark spacing in the first several frames, no appreciable movement of the bench marks seems to have occurred. It is also to be noted that the bench marks did not move apart uniformly at some constant fraction of the weight or lower jaw movement. Rather they seemed to have moved at different rates during extension, i.e., the slope of the curve changes continuously. The movement of the oscilloscope spot, while measurable in the original frame, is so confusing that unfortunately no significance can be attached to this record. It seems as though this record has been affected by a possible vibration of the tower and of the strain-gage beam, in which the amplitude of the vibration was very large compared to the actual load record from the sample itself. In more common terms, the noise was greater than the signal.

This experiment, while not completely satisfactory, taught us a good many lessons with regard to running tests of this kind. First, it was obvious that drop tests or drop techniques represented a practical way to get high rates of extension. Second, very careful alignment of the weight and drop system were necessary in order to secure usable results. Near misses of the falling weight were fatal to the equipment and nearly so to the operators. Third, the weigh bar system was adequately rugged and fast enough to record the load curve, but the oscilloscope amplifiers were not satisfactory. Fourth, frame-by-frame measurements on the photographic record or on enlargements were so tedious that measurements of this type had to be considered impractical for anything except a few pilot operations. These considerations provided enough incentive to revamp the apparatus and continue the experiments in the manner indicated in the next section.

Current Procedures

The revised setup, shown in Figure 6, retained the successful principles shown in the first line of experiments, namely, a symmetric dropped weight stretching the sample, with a strain-gage weigh bar and photorecording. However, the system was revised to provide a much greater convenience and reliability of operation. Ring samples were made and used, eliminating some of the problems connected with the irregular elongation of dumbbell samples. These ring samples were used in either two-legged or four-legged configurations, as illustrated in Figure 7, in which the movement of the lower bar becomes the elongation (rate) of the sample itself. The rings were molded individually in a radial-injection mold. A dual beam oscilloscope, Tektronix type 502, having a sensitivity up to 200 μv./cm. scale division was obtained. The strain-gage beam was thinned down to make it more sensitive, since some of the safety factor originally designed into the system was not needed. Starin gages were cemented to the active portions of the beam in pairs giving a 240-ohm pushpull bridge directly on the beam itself. The strain-

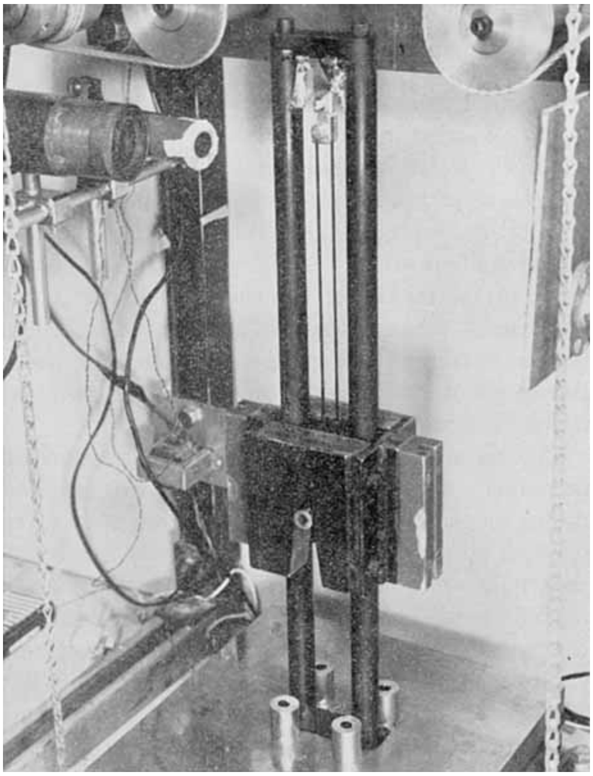
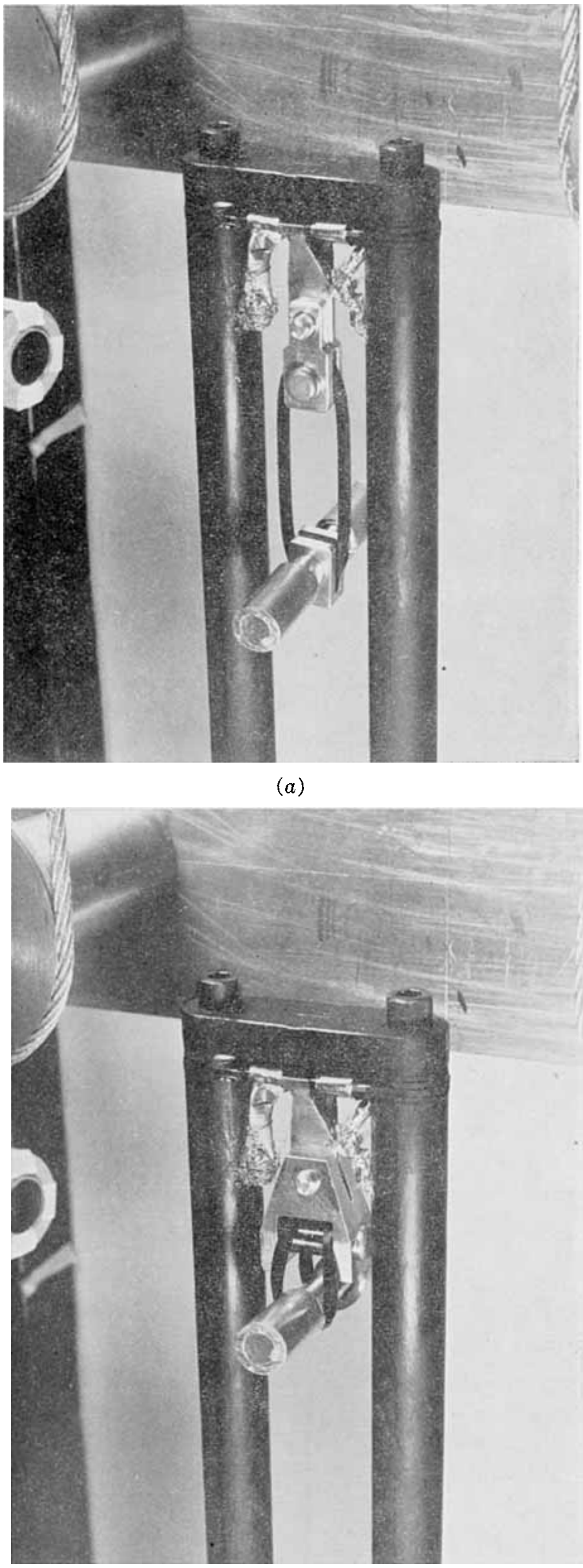


Fig. 6. Revised tower for high speed stress-strain testing. The photoelectric triggering arrangement is visible in the upper left, behind the plane of the tower.

gage bridge was powered by a 12-v. battery and had a load sensitivity determined by dead weight calibration, close to 0.091 mv. output/pound load. This voltage output was high enough to be presented directly on the scope without the need for external preamplifiers. Connecting wires were protected within tower support legs, which had been drilled for this purpose.

Since (*1*) the weight moves with almost constant velocity during the time of the test, (*2*) the weight carries the striker bar in contact with it, and (*3*) the movement of the striker bar is elongation of the sample, the sample is stretched at constant velocity. Hence, the simple time sweep of the scope could be used to display the information on its screen. The sweep is calibrated to give elongation. Thus a load curve could be displayed on the scope. Load in the vertical sense calibrates to stress, against time or extension in the horizontal axis. However, some method was needed to turn on the scope at the appropriate time, just as the sample started to stretch. Accordingly, a photoelectric circuit was designed to provide a starting impulse, triggered by the passage of the weight itself. A small lamp seen in the upper left of Figure 6 was focused at a point in space just above the lower



(*a*)

(*b*)

Fig. 7. Arrangement of ring samples in (*a*) two-legged and (*b*) four-legged configurations. Effective length: (*a*) 2.74 in. and (*b*) 1.35 in. Lead sleeves on the striker bar cushion the impact of the falling weight on the bar.

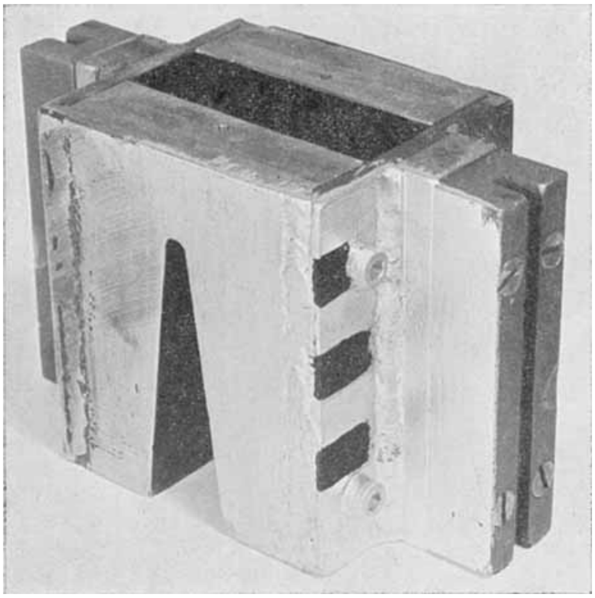


Fig. 8. Back side of drop weight showing reflective area and signal bars.

edge of the sample. In normal operation nothing was present at that spot, hence the light passed on through and was lost on the general background of the room. When, however, a reflecting screen was put at that position, light was reflected onto a photocell focused also at that particular point, and visible in Figure 6 just behind the lamp housing. The back side of the weight was painted with aluminum paint to provide the highly reflective surface needed, as shown in Figure 8. Only the first passage of the weight into this focal spot was needed to start this signal. The weight itself was painted with black bars interrupting the reflective paint to provide a distinctive pattern which could be used to provide other information.

Direct static measurement showed that the sample should be stretched, beginning when the light hit the center of the first black bar in the two-legged configuration. Similarly, stretching should begin in the middle of the third black bar in the four-legged arrangement. Thus the signal could be used to trigger the scope, start the record, check the speed of the weight, and define the point at which elongation of the sample began.

The signal on the scope was photographed for permanent record using either of two cameras. A long focus camera having a reduction of two and one-half to one was originally the only one available. Records obtained using this were so small that it was difficult to see detail unless enlargements were made. Later, a Hewlett-Packard camera was obtained having a reduction of only 1.0 to 0.9. This gave fairly large photographs, easy to read, which could be used for permanent records. The photography is usually done on Polaroid film, type 47. Occasionally records are obtained on negatives in order to get multiple prints for later distribution. A typical record of the photosignal used to trigger the scope, showing the modulation by the individual black bars, is presented as Figure 9.

Even though the contact point of the sample could be obtained by direct measurement in static

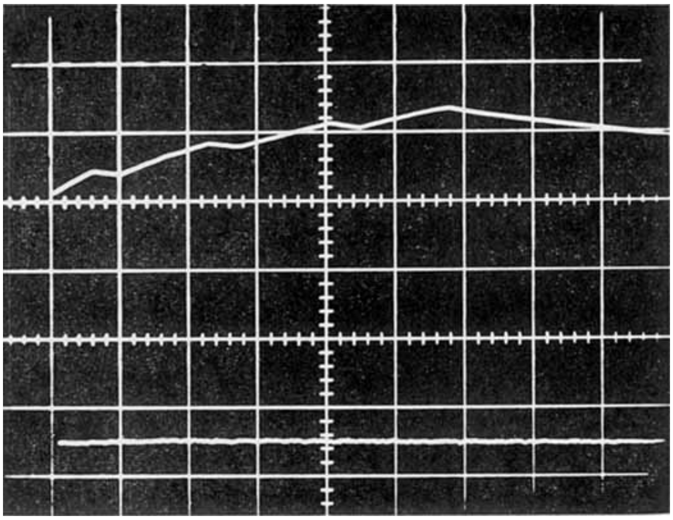
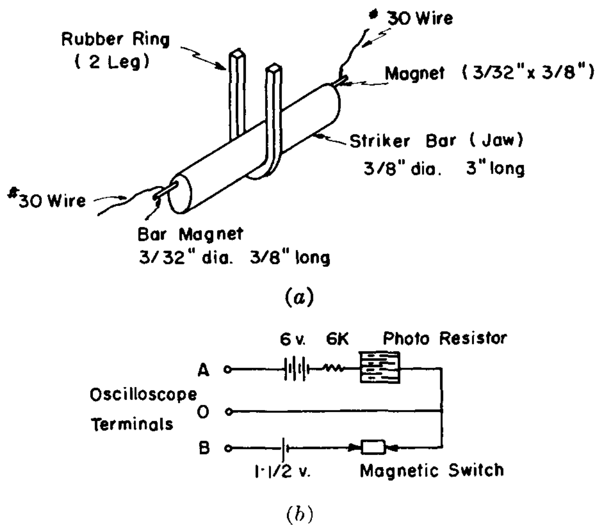


Fig. 9. Polaroid print of timing signal (upper trace). Grid lines have a spacing of 1 cm. on the oscilloscope mask. All dimensions refer back to the original size, i.e., 2 msec./cm. *on the original screen*. Full size but negative taken at 0.9 ×.



(a)

(b)

Fig. 10. (*a*) Schematic view of magnetic switch. (*b*) Schematic electrical circuits.

case (that is in a dummy setup in which the weight was lowered slowly until it made contact with the striker bar), it was felt important to check this measurement in dynamic operation. The author wanted to make sure that the contact point of the sample was known within about 2×10^{-4} sec. or 0.1 in. Hence, the arrangement shown schematically in Figure 10 was set up as a separate experiment. Two small weak magnets were stuck to the striker bar, one at each end. These magnets in turn were soldered to wires which were part of the photo-input circuit. The magnets on the striker bar were the equivalent of knife blades on a switch, since any movement of the bar itself jarred the

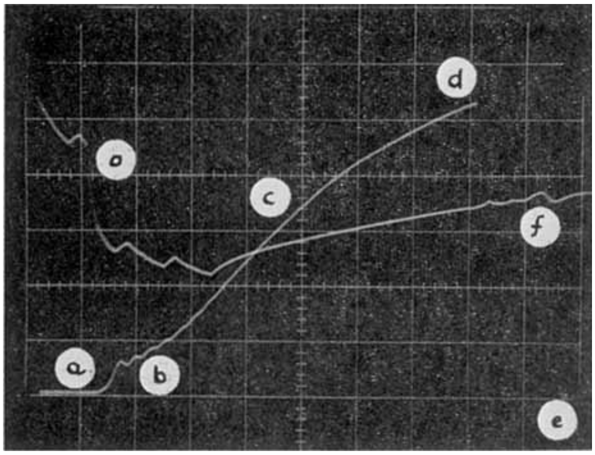
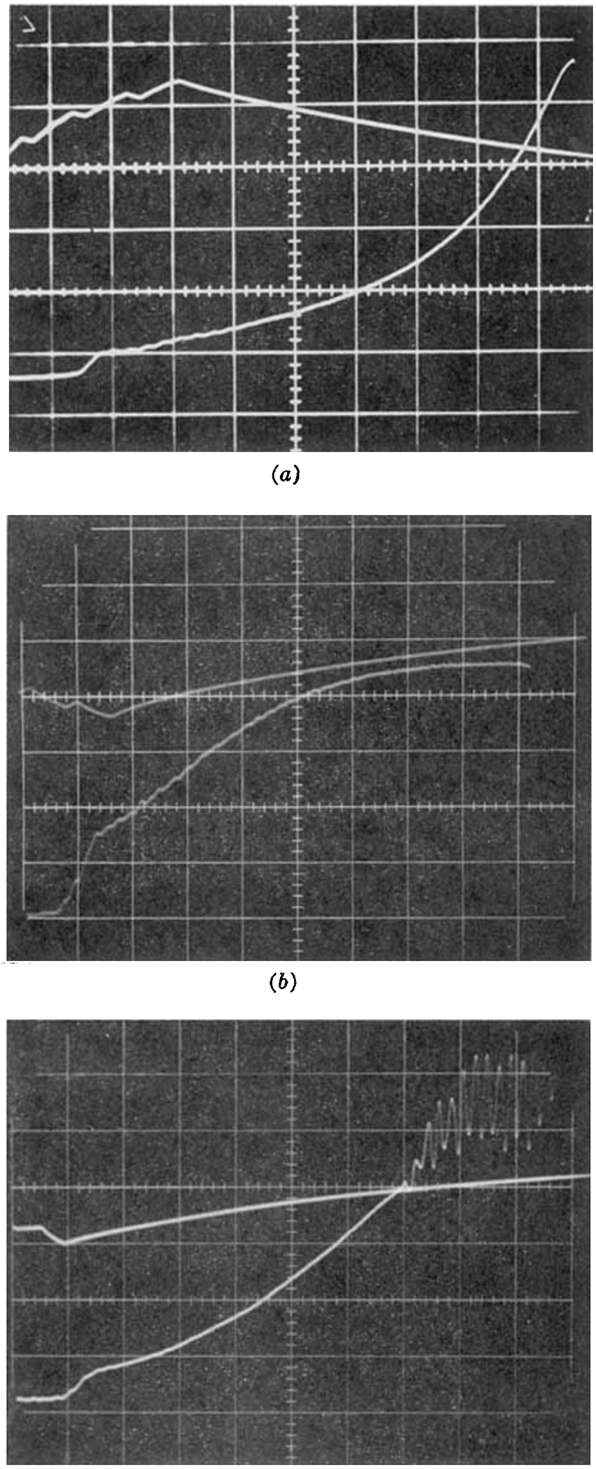


Fig. 11. Polaroid print record (original record). Upper curve is the trigger circuit, showing contact with the striker bar and the weight record. Lower curve is the load-time curve for the sample, an SBR tread recipe. Trigger: 1 v./cm. Load: 22 lb./cm.



(*a*)

(*b*)

(*c*)

Fig. 12. (*a*) High speed load-time curve for pure gum stock: X, 2 msec./cm.; Y_1, trigger 1 v./cm.; Y_2, beam 1 mv./cm. Four leg. (*b*) High speed load-time curve for oil-extended SBR tread: X, 2 msec./cm.; Y_1, trigger 1 v./cm.; Y_2, beam 1 mv./cm. two leg. (*c*) High speed load-time curve showing tower hit: X, 2 msec./cm.; Y_1, trigger 1 v./cm.; Y_2, beam 1 mv./cm.

magnets loose, immediately opening the circuit. This action registered as an abrupt drop or change in voltage on the scope. Typical curves illustrating this action on a sample record are shown in Figure 11. The upper signal curve, reversed in polarity from the example of Figure 9, shows the typical signal derived from the falling weight abruptly displaced (by $1^1/_2$ v.) at the time that the "contact switch" was broken, point *o*. The lower curve is the record curve of the load on the sample. Since the photosignal starts the traces a moment before any load is registered, the original load curve shows no load or establishes zero. There is an abrupt rise in the load curve *a*, a small amount of vibration *b*, and a subsequent rise in the curve *c*, to break *d*, followed by some free vibration of the beam *e*. The photocurve also shows a rare event at this moment *f* as the broken sample unwinds through the light beam, reflecting a small amount of light back into the photosystem. The abrupt rise in load *a* is a new phenomenon that comes in at the high speeds of this experiment. The small amount of vibration in the vicinity of *b* is simply parasitic vibration of the strain-gage beam stronger in some curves than in others, but not significant in the results of the experiment. The downward curvature of the stress-strain curve is real. The abrupt ending of the curve *d* is the true endpoint. It will be noted that the contact point of the bar *o* and the first rise of load *a* registered from the strain-gage beam, differ by a significant time—about 1 msec. This interval is well above the resolving time of this type of experiment, estimated as about $^1/_3$ msec. This time difference is real and will be discussed in considerable detail in subsequent sections. For a ring sample arranged in a four-legged loop, each centimeter on the time scale corresponds to 42.7% extension. Hence the total elongation of the sample measured from the first contact determined electrically is 14.1 msec. or 602%. The load curve, as determined from calibration is 11 lb./mv., which for the beam setting of 2 mv./cm., results in a scale factor 22 lb./cm. The tensile load value, 5.25 cm. (net displacement), gives a tensile strength 2900 psi. Other items of interest on the curve can be scaled from these data. A computation form has been drawn up to help standardize the computation and reporting of data.

Curves for samples of a "pure gum" recipe and an oil-extended tread stock are presented as Figures 12*a* and 12*b*. The long-range low modulus characteristics of the pure gum are obvious, as well as the abrupt rise in tensile properties at high elongations. In contrast to this, the flattening of the load curve for the oil-extended recipe should be noted. Not every run or drop gives a usable curve. Slight differences in the way the impulse-weight falls or the way in which it strikes the sample sometimes lead to an obvious "tower hit" shown in Figure 12*c*. In early experiments, this expression literally true; tower hits resulted in considerable damage, usually to the strain gages themselves. At present, a more accurate term would be "tower scrape," in that the falling weight often is twisted to one side, after it begins to stretch the sample, to rub along the tower support legs for a short distance. The resulting vibrations are obvious, but do no harm.

Sonic Pulses—Foot of the Stress-Strain Curve

When rubber is stretched at ordinary speeds or under ordinary conditions, any small stretch of the rubber is immediately accompanied by a back retractive force. The load-time curves obtained from the high drop experiment do not show this relationship. There is a distinct time delay between the moment when the sample is first stretched and the moment when the load is recorded on the strain-gage beam. This delay is not due to resolving power of the beam, although close to that limit. Time delays of the order of magnitude of 1 to 2 msec. respectively for the four-legged and two-legged arrangements have been found. The beam itself has a resonance frequency approximately 5000 cycles/sec., corresponding to less than a quarter of a millisecond delay when excited by a step function.

In these experiments we are stretching the sample so rapidly that the top, restrained by the strain-gage beam, does not know that the bottom has been moved until some time later. This means that the sample is not stretched uniformly throughout its length. The initial deformation starts or concentrates at the lower jaw, then propagates upward at the speed of sound in the rubber. Only when the deformation front reaches the upper jaw does a pulse register on the strain-gage beam. The delay between the start of stretching and the first load then is the time required for a longitudinal sonic pulse to travel that length of sample.

If the rubber is not being stretched uniformly, the load-elongation curve actually recorded does not have the same meaning as a stress-strain curve recorded under slow test conditions, where the

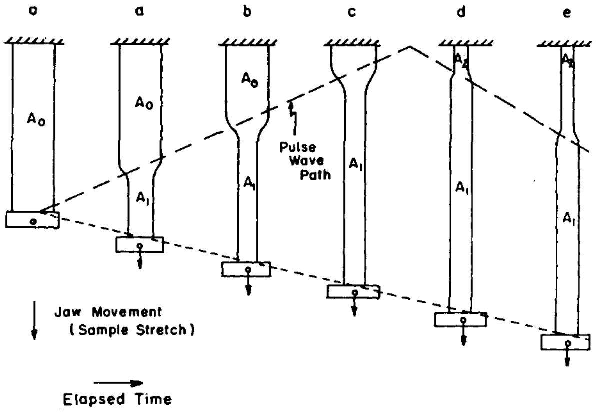
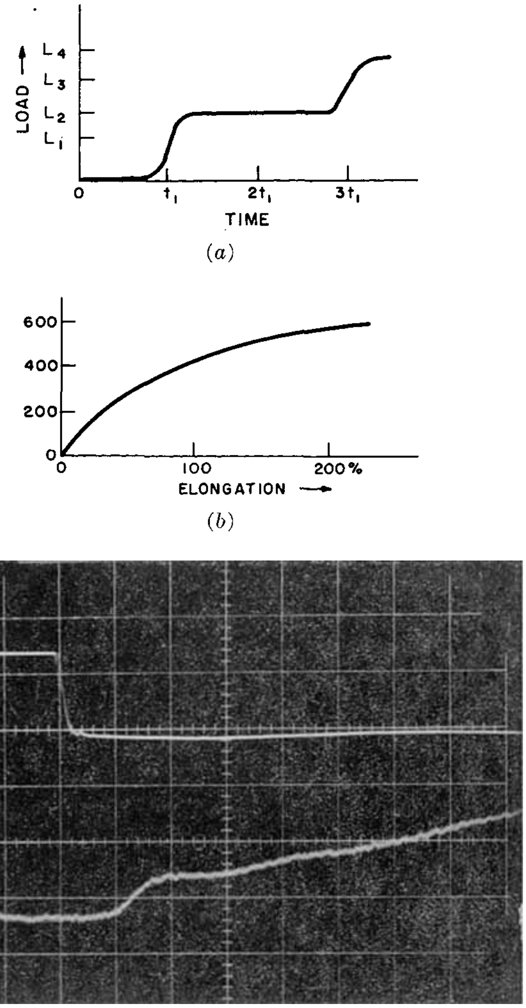


Fig. 13. Illustration of nonuniform extension at high rates of stretching.

whole rubber sample is close to equilibrium at all times. That is, if these assumptions are true and if the experiment is as indicated, then we have reached a practical limit in the high speed testing of rubber; i.e., the stress-strain curve has changed its meaning in the sonic transition region.

The nonuniform nature of stretching as proposed in this assumption is illustrated in Figure 13. This figure shows a sketch of a sample at regular intervals during a rapid stretch. The bottom end of the sample (the bottom jaws) is being moved at a speed comparable to but less than the speed of sound in the rubber. Jaw speed is 500 in./sec. in our experiment compared to about 1250 in./sec. sonic velocity. Since the rubber is not in equilibrium (does not have time to respond uniformly), most of the strain will take place immediately at the lower jaw. This strain or reduction in area forms a neck, very similar to the "neck" in polyethylene, which propagates along the length of the sample. The undeformed rubber (above the neck) bears no load. Hence there is no signal to be recorded from the upper end at this time. Elongation in the usual sense has no meaning, since the sample has two areas or two amounts of elongation. One portion has zero elongation, the other has a large elongation, roughly 100% as illustrated. The proportion of rubber in these two conditions changes smoothly during the stretch. When all of the rubber between the grips has been reduced in area or now shares the same strain, a load is registered on the strain-gage beam.

The pulse or neck traveling along the sample is a wave phenomena and will reflect from the upper jaw to give an increased elongation or an increased reduction in area as a second step. This second neck now propagates from the upper jaw down to the lower. This reflection of traveling waves means that individual portions of the sample are elongated stepwise even though the end is moving smoothly and continuously. These steps travel the length of the specimen and it is only when a step reaches either jaw that the load curve will show a gain in value. This step type of reduction in area, or stepwise elongation of rubber samples, has been photographed at the Quartermasters Corps Depot at Natick, Massachusetts using a strip-frame camera having an effective speed roughly equivalent to 100,000 frames/sec.[11] As many as four or five reflections of the wave front have been photographed in gum rubber samples stretched at rates up to



(a)

(b)

(c)

Fig. 14. (a) Load-time curve at high rates of elongation. (b) Stress-strain curve at equilibrium conditions. (c) Load-time curve. Gum thread—high rate.

1200 in./sec. using a tensile machine which is basically a giant slingshot.

The sharp neck illustrated represents a condition only found in a low loss material typical of a pure gum stock. In a normal black recipe the neck would become so diffuse after a relatively short movement that it would disappear quickly. While two recognizable reflections or load-steps have been found in the load curves of gum stocks by this technique, only one step has been seen in tread recipes.

Figure 13, frames *d*, *e*, . . . illustrate one more high speed phenomenon not encountered in more familiar situations. The wave pulse shown in frames *a*, *b*, *c* travels upward at the velocity *c* measurable on "static" or bench specimens. The pulse after reflection, however, moves downwards with a higher velocity since it is now moving through a rubber bar which *itself is moving* with velocity *v*. In addition, the sonic pulse velocity *c* is raised to a higher value *c′* since the elastic properties of the stretched material differ from those of the unstretched specimen.

The nature of the load-time curve obtained at high rates of elongation is illustrated in Figure 14*a*, compared to Figure 14*b*, a stress-strain curve, taken at almost equilibrium conditions. An actual load-time record for a sample of golf ball thread is further shown as Figure 14*c*. The step nature of the curve at the early stages of elongation is clearly visible.

References

1. Roth, F. L., and W. L. Holt, *J. Research Natl. Bur. Standards*, **23**, 603 (1939).

2. Villars, D. S., *J. Appl. Phys.*, **21**, 565 (1950); D. S. Villars and D. C. Scott, Jr., ASTM Special Tech. Publ. No. 185, 62–71, 1956.

3. Fromandi, G., R. Ecker, and W. Heidemann, *Proc. Intern. Rubber Conf.*, Washington, D. C., 1959, p. 177.

4. Kainradl, P., F. Händler, *Kautschuk u. Gummi*, **12**, 239, 284, 336 (1959); reprinted in *Rubber Chem. and Technol.*, **33**, 1438 (1960).

5. Miller, R. F., and J. G. Slaby, *SAE Symposium*, Chicago, June 1960.

6. Schallamach, A., *Trans. Inst. Rubber Ind.*, **28**, 256 (1952).

7. Vickers, H. H., and S. B. Robinson, *Proc. Intern. Rubber Conf.*, Washington, D. C., 1959, p. 128.

8. Stambough, R. B., M. Rohner, and S. D. Gehman, *J. Appl. Phys.*, **15**, 741 (1944).

9. Mrowca, B. A., S. L. Dart, and E. Guth, *J. Appl. Phys.*, **16**, 8 (1945).

10. Bueche, A. M., and A. V. White, *J. Appl. Phys.*, **27**, 980 (1956).

11. Hoge, H. J., and M. Pilsworth, Quartermasters Research and Eng. Command, U. S. Army, Natick, Mass.

Synopsis

A high speed stress-strain apparatus has been constructed to measure the strength and elongation of rubbery materials at extension rates roughly 250 and 550 in./sec. The test sample is stretched by falling weight which catches a protruding lug on the lower jaw of the sample. The weight falls from a magnetic grip at one of two selected stations. The potential energy of the falling weight is large compared to the energy under the stress-strain curve in order to avoid appreciable slowing of the weight during the period of stretch. The excess energy is dissipated in several kinds of damping mechanisms without damage to other than expendable crash pads. The tensile load on the rubber sample is carried by a stiff-strain-gage beam, the output of which is displayed on an oscilloscope for photographic recording. Stress-strain curves of rubber recorded for stretch rates about 550 in./sec. show evidence of sonic wave pulses in the early portions of the extension cycle. Ultimate tensile and elongation values differ somewhat from values obtained using conventional test machines.

Résumé

On a construit un appareil de tension à grande vitesse pour mesurer la résistance et l'élongation de substances caoutchouteuses à des vitesses d'extension d'environ 250 et 550 pouces/seconde. L'échantillon d'essai est étiré par la chute d'un poids s'accrochant à un oeillet en saillie à la partie inférieure de l'échantillon. Le poids tombe d'une poignée magnétique située à l'une ou l'autre position choisie. L'énergie potentielle du poids qui tombe est grande, comparée à l'énergie par courbe de la tension, ceci enfin d'éviter un ralentissement appréciable du poids durant la périods d'étirement. L'excès d'énergie est dirigée par diverses sortes de mécanismes d'amortissement sans dommage pour autre chose que pour les tampons amortisseurs. La charge exerçant la tension sur l'échantillon de caoutchouc est supportée par le fléau rigide d'une jauge de tension dont la puissance est communiquée à un oscilloscope pour enrégistrement photographique. Des courbes de tension de caoutchouc enrégistrées pour des vitesses d'étirement d'environ 550 pouces/seconde, mettent en évidence des oscillations d'ondes sonores dans les premières parties du cycle d'extension. Les dernières valeurs de tension et d'élongation difèrent quelque peu des valeurs obtenues en employant les machines d'essais habituelles.

Zusammenfassung

Ein Hochgeschwindigkeits-Spannungs-Verformungsapparat zur Messung der Festigkeit und Dehnung von Kautschukmaterialien bei Dehnungsgeschwindigkeiten von rund 250 und 550 Zoll/Sekunde wurde konstruiert. Die Testprobe wird durch ein fallendes Gewicht gedehnt, das auf einen Vorsprung am unteren Probenbacken auftrifft. Das Gewicht fällt von zwei ausgewählten Stellungen aus einer magnetischen Haltevorrichtung. Die potentielle Energie des Fallgewichtes ist gross im Vergleich zur Energie unter der Spannungs-Dehnungskurve, um eine merkliche Verlangsamung des Gewichtes während der Dehnungsperiode zu vermeiden. Die Überschussenergie wird in verschiedenen Dämpfungsmechanismen, ohne weiteren Schaden anzurichten, verzehrt. Die Zugbelastung des Kautschuk

wird durch eine Messvorrichtung zur photographischen Registrierung auf ein Oszilloskop übertragen. Spannungs-Dehnungskurven, die an Kautschuk bei Streckgeschwindigkeiten von etwa 550 Zoll/Sekunde registriert wurden, zeigen in den Frühstadien des Dehnungszyklus Anzeichen für Schallwellenimpulse. Die Zerreissspanungs- und -dehnungswerte unterscheiden sich etwas von den mit den konventionellen Testapparaten erhaltenen.

Discussion

Question: In the two-legged and four-legged sections, where did the samples break?

Answer: We took Fastex pictures to find out where they broke. They break at, or very close to, the rod themselves.

Question: The influence of the support rod on the stretch, especially with larger diameters, should be very important with the four-legged sample.

Answer: The sample ring that I use is about 2 in. in diameter. It is folded over a $^3/_8$-in. rod to get the four-legged configuration. I have tried using $^1/_4$-in. rod, $^1/_2$-in. rod, and once a 1-in. rod, but there appeared no difference in results. I agree that it is important theoretically, but it is probably not practically. However, greasing makes a big difference: there are much lower values for extension and tensile strength when the rod is dry. Castor oil or silicone grease works well.

Question: Would not that account for the early-stage elongation? For instance, you showed a stepwise change. Could this be accounted for by the fact that the load changed by slippage over your grips?

Answer: It could be, but I doubt it. Again, we have Fastex records to show that the rubber seems to stretch fairly uniformly. A theoretical description can be given of the size of the expected load pulse based on the sonic properties of the rubber. This is an involved computation, but we get what we believe are the proper orders of magnitude for these steps. I would say the theory gives us more confidence than an experiment.

Question: Have you ever observed the bars attached to the moving grip accelerating ahead of the falling weight after the first contact?

Answer: Yes, this was observed once. The bar can be bumped. That is why now we always use lead sleeves; it lessens the impact.

Question: What materials have you tried besides lead as shock absorbers?

Answer: I have tried several plastics, and butyl rubber. Lead works well.

Question: How long did the lead last?

Answer: For two or three times. Originally, I got a large lead sheet, cut it into strips, and dropped little "U" 's over the bar. Later I got 100 ft. of lead pipe, $^3/_8$ in., and cut it into 1-in. lengths.

Question: Can you comment further on the step time?

Answer: Yes, in the two-legged configuration the sample is twice as long. The delay time is twice that which we observe in the four-legged sample. Rings that had a smaller diameter gave a proportionately different time interval. The load curve and, in particular, the load step depend upon the kind of rubber and its compounding. The size of step also depends upon the striking velocity.

Question: Don't you get a change in the velocity on using a lead sleeve on contact?

Answer: The lead sleeve used on the bar starts out at approximately $^1/_{16}$ in. in thickness. It is smashed down to about half that thickness. Thus, there is an initial uncertainty in contact, perhaps of $^1/_{32}$ in. This is a very small error at a velocity of 500 in./sec. and also small compared with other quantities being observed.

Question: I have two questions. You have shown a sample breaking and then the retraction. First, can you calculate the speed of the retraction?

Answer: Yes, we have done so. This is the linear velocity of propagation, not the sonic velocity we are used to observing in bulk mode transmission. There are two velocities of sound in rubber. They correspond to propagation computed from bulk modulus and that computed from linear modulus. All this work involved linear modulus velocities.

Question: Could you give a percentage per second of that weight velocity?

Answer: No, because it does not have meaning as such. There are two different areas in the sample, i.e., the non-uniform stretch. Sam Gehman and co-workers some years ago presented some excellent Fastex pictures concerning this (see Ref. 8). His work still stands.

Question: My second question is: Did you attach your strain gauge to the bumper, as you got your curves for stress?

Answer: No. Wires would have to be put on the lower jaw and kept there while the weight stretches the sample. Perhaps you can tell me a way of doing this. One of my co-workers and I have tried to figure out a way of doing this because we would like to make such measurements. For example, I should like to record a load curve showing a difference in load at the top and bottom of the sample during the first portion of the stretch, i.e., during the "step."

Question: Can you give some velocities for the stress load which you use? For example, what was the velocity at retraction?

Answer: The velocity of sound in rubber is about 1250 in./sec. This is longitudinal velocity and the velocity of retraction.

Question: With no strain?

Answer: No, rather, this is the velocity of the sonic pulse, the longitudinal pulse in unstrained rubber.

Question: What is the actual physical retraction? You said you retracted in two directions; what is the distance of that motion?

Answer: I should like to discuss this later.

Question: Your weight must accelerate until it strikes the lead at the bottom.

Answer: Yes.

Question: That means it is still accelerating while it pulls your sample down.

Answer: Yes, that is perfectly true. As the weight passes over the sample, it is traveling another 6 in. It has already traveled 35 ft. The change in velocity in this interval as it strikes the sample is less than 1%. I am more worried about the change in velocity in the negative sense, as the rubber slows it down. By the way, this is the practical lower limit in drop test technique. A weight dropping through a height of 1 ft. only has 1 ft.-lb. of energy per pound. A sample of the kind we are using takes 20 or 30 ft.-lb. of energy as it is stretched to break. If we are to use dropping weights at low velocities, they must be large. A 100-lb. weight is very great; there is enough trouble with one weighing only a few pounds.

Question: In connection with the first question asked in this discussion, in using multiple legs do you ever get multiple breaks?

Answer: Yes.

Question: In connection with the little wear pattern that you showed, can you make a comment on how it arises in the first place?

Answer: That is another topic I should be pleased to discuss later. It concerns a theory of mine which several of my rubber-compounder and tire-wear co-workers criticize.

Question: How do you account for the energy absorbed by the lead sleeves on the cross-bar? It is an error which would have to be considered.

Answer: Yes, but it is so small that I have never noticed it.

Question: It may be considered negligible?

Answer: Yes.

Question: I noticed in one of the groups of Fastax pictures that the weight seemed to stop moving before the sample broke.

Answer: That is just an artifact of photographic reproduction. We had to enlarge each individual frame, then paste it on a second sheet, and finally rephotograph. Depending upon where the enlargements were lined up, the weight may look as if it had gone to the bottom and then come up a little bit. Measurement on the individual frames, in the original film, shows a smooth, continuous movement of the weight well past the broken sample, until the time that it hits the lead bumpers.