THE DRYING OF RUBBER

BY

J. H. PIDDLESDEN

Introduction

The design and operation of buildings for the drying and smoking of rubber has attracted considerable attention in the last few years. Several smoke-houses which shew improvements in the ease of handling the rubber, reductions in the time required to dry it, and a minimised risk of fire, have been designed. These advances have been largely empirical, and it was deemed advisable to carry out investigations into the fundamental mechanism involved, before attempting to study the effect of minor alterations in the technique of preparing and smoking sheet rubber.

(A) THEORY OF DRYING

The practice of drying varies widely according to the material which is being treated, but there are certain fundamental considerations which are applicable to all drying problems.

If a very wet solid is exposed to air, it immediately commences to lose water by evaporation. The rate at which this occurs depends upon the condition of the surrounding air, and the surface area exposed. While the surface remains completely wet the rate at which water is removed is independent of the moisture content of the solid. Thus, if the external conditions are maintained constant, drying proceeds at a constant rate, and while this persists the temperature of the solid surface will be the wet-bulb temperature of the air. This "constant rate period" as it is called continues until dry patches are formed on the surface. At this point, which is termed the "critical water content," the drying enters a so-called "falling rate period." This, in turn, may be divided into two portions. The first is the "zone of unsaturated surface drying," in which the external atmospheric conditions are still an important factor, but are modified by the consideration that, as drying proceeds the area of effective wet surface diminishes. The second portion of the falling rate period is the zone in which internal liquid diffusion takes control. At this stage the nature of the material being dried is of major importance, and the condition of the surrounding air has little or no effect. The rate-of-drying curve is thus divided into at least three portions, each controlled by different sets of variables.

These are:—

(i) *The Constant Rate Period*

This, as was stated above, obtains while the surface remains uniformly wet. The rate remains constant only if certain "drying conditions" are maintained constant. A study of these will indicate the method for obtaining the best rate during this phase of the drying. Evaporation from the free liquid surface at the wet surface of a solid is analogous to that which occurs at an air-liquid interface whenever the vapour pressure in the air is below that of the liquid, at the temperature of the surface, and is due to this difference. The evaporation of the liquid abstracts heat from the system.

The first objective, if a high drying rate is required, must be to establish the maximum possible vapour pressure difference between the surface of the wet body, and the air in contact with it. Here a further factor is introduced. The layer of air in contact with the surface soon becomes saturated with moisture, and evaporation is therefore limited by the rate at which the moisture can diffuse through this layer. This in turn depends upon the thickness of the layer, which may readily be reduced by increasing the air velocity across the surface.

The partial pressure of water vapour in the air must be as far below the saturation pressure as possible. The ratio between these two values is expressed as the percentage relative humidity. As the capacity of air for carrying water vapour increases very rapidly with increase of temperature, this provides a very simple method of reducing the relative humidity. For example, air containing .02 lb. water vapour per lb. of dry air (a normal figure for Malaya) is saturated at approximately 76°F and if cooled below this point will deposit dew; whereas this same mixture raised to 130°F has a relative humidity of about 22 per cent, and will absorb nearly 400 per cent more water before condensation occurs. Thus for rapid evaporation, not only must the air velocity be high, but the relative humidity must be low. These conditions may be achieved by using a constant stream of fresh air at high temperature. The surface area must also be as large as possible. Finally, since the process absorbs heat, a continuous supply of heat must be maintained in order to prevent the temperature of the whole system from falling.

(ii) *Zone of Unsaturated Surface Drying*

The zone of unsaturated surface drying constitutes the first portion of the falling rate period. It commences when dry patches begin to occur on the surface, and continues until the rate of

diffusion becomes the controlling factor. The rate of drying at this stage is also controlled by evaporation. The variables affecting this rate are therefore the same as those given above, except that in this case the wet surface area is diminishing as the drying proceeds. During this phase the area of wet surface, and consequently the drying rate, usually decrease in approximately direct proportion with the moisture content of the solid.

(iii) *Period Controlled by the Rate of Internal Liquid Diffusion*

The rate of diffusion of moisture from the interior to the surface of a wet slab decreases with the water content of the material. A second "critical point" therefore occurs when the rate of diffusion can no longer keep pace with the rate of evaporation from the surface. When the moisture content is below this critical value the rate of diffusion controls the rate of drying. The diffusion of liquids through solids follows closely laws governing the diffusion of heat. The rate of drying under these conditions may therefore be expressed as a Fourier series, based on the general equation[1]

$$\frac{dM}{dT} = k\frac{d^2 M}{d s^2}$$

where M is the free moisture content *i.e.* the total moisture minus the equilibrium moisture

T is the time

s is the thickness of the material

k is the diffusion factor.

The value of the diffusion factor (k) is determined by the permeability of the particular substance being dried, and by the temperature at which the drying is carried out. The time required for drying may be reduced by increasing the temperature, or by so modifying the material that it is more permeable to water. Either of these expedients will increase the value of the diffusion factor (k). It can also be shewn[2] from the theoretical equation that the drying time is proportional to the thickness squared.

(B) APPLICATION TO RUBBER OF THE THEORY OF DRYING

It will be seen from the foregoing that for rapid drying the sheet rubber should be as thin and porous as possible, high temperatures should be used throughout and, in the early stages, high air velocity should be advantageous. There are obviously practical limitations to the application of these conditions. Unduly high temperatures will damage the sheet by blistering. If the sheet is machined too thin, the cost of machining, the space required in

the smoke-house, and the difficulties in handling are all increased. Finally, to use high air velocities, and at the same time to maintain an adequately high temperature, would necessitate a large expenditure on smoke-house fuel, unless some mechanical system for the recirculation of air were used. The first object of our experiments was therefore to determine at what stage diffusion became the controlling factor in the rate of drying, since prior to this the velocity and humidity of the air are important factors, whereas afterwards the sheet thickness becomes of major importance.

Van Harpen[3] found for certain rubber samples, that the total drying time for each was proportional to the square of its thickness. From the foregoing it will be seen that this implies that the whole drying period is controlled by the rate of diffusion, and that the initial constant rate period during which ventilation is the important factor occupies a negligible proportion of the total time.

Experimental

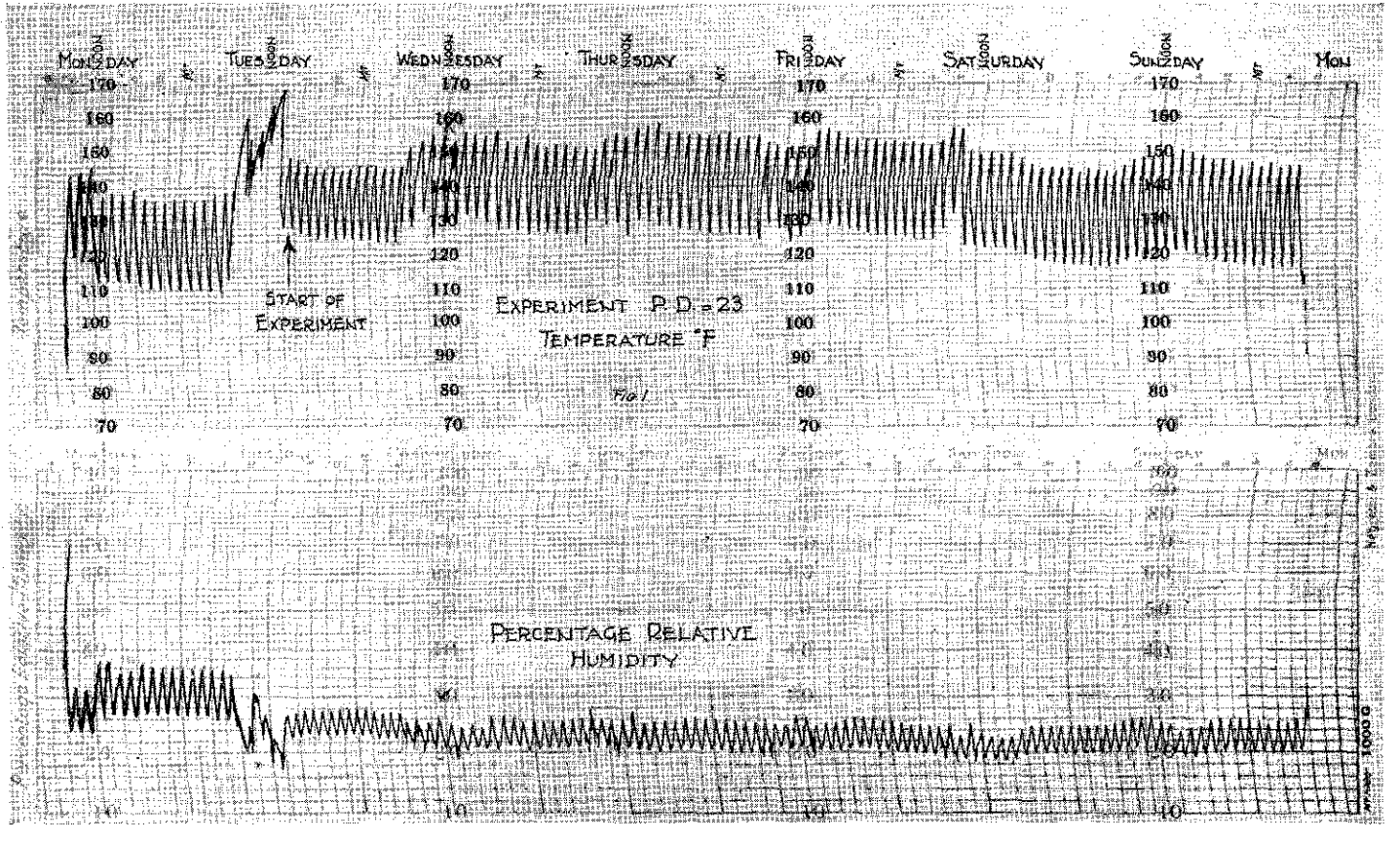
A few rough preliminary trials soon indicated that the last traces of water were difficult to remove from rubber. Thus, if small samples of rubber were used, extremely accurate weighing was necessary, to follow the drying in the later stages. Such weighings could not be carried out rapidly, since it was first necessary to cool the sample, and the delay so caused made the time and temperature records inaccurate.

To overcome these objections an attempt was made to construct a recording weighing machine, which could be placed in the drying cabinet. Sufficient accuracy could not be achieved by this device, and it had the further objection that the number of samples which could be handled simultaneously was limited by the number of machines.

It was therefore decided to use full-sized pan sheets, which could be weighed very rapidly to the nearest 0.1 gm. on a decimal balance. It was soon found that the use of a marking roll introduced variability owing to the different depth of impression made on sheets of different thicknesses.

As a result of these preliminary trials the following procedure was adopted. Latex was coagulated in pans each holding one gallon of liquid containing 15 per cent of dry rubber. The coagulum was machined next morning to the required thicknesses through rolls with calibrated adjusting screws, two sheets being rolled at each setting. After varying periods of soaking and dripping, the sheets were dried in a thermostatically-controlled, electrically-heated drying cupboard. The temperature and humidity

FIGURE 1


MONDAY
TUESDAY
WEDNESDAY
THURSDAY
FRIDAY
SATURDAY
SUNDAY
MON
NOON
MT
START OF EXPERIMENT
EXPERIMENT P.D. = 23
TEMPERATURE °F
PERCENTAGE RELATIVE HUMIDITY

of the air inside were recorded automatically, and the sheets were removed and weighed at intervals until dry. Dryness was assumed when there were no longer any opaque patches in the sheet.

Owing to the intermittent method of weighing, the actual point at which the rubber became dry could not be determined very accurately. Overnight an interval of 18 hours elapsed between weighings. The rate of drying was however very slow during the final stages and the curve of percentage moisture plotted against time was very flat and approximated closely to a straight line. It was also frequently found that there were small inequalities in the sheet and that very small wet patches sometimes persisted for a considerable time after the rest of the sheet was dry. Therefore, although drying was continued until complete transparency was achieved, and this was regarded as the dry weight, the end point of the drying was taken to be the point at which the rubber contained 0.1 per cent moisture and the drying time was obtained by extrapolation or interpolation to this point, from the few weighings taken on each sheet immediately before dryness was perceived. This procedure largely eliminated the errors due to very small wet patches, and to the possibility that complete transparency was not noted until a few hours after it had occurred.

Since the heating load was heavy and no relay was available the thermostatic control was rather insensitive and the temperature and humidity charts obtained were similar to those shewn in Fig. 1. The average temperature and humidity ruling throughout each experiment was obtained by summing all the points of inflexion and calculating the mean.

For each experiment, curves of moisture-content against time were plotted, and in each case the lower portion was replotted on a magnified moisture-content scale. A typical example is shewn in Figs. 2 and 3. As was predicted, the first portion of the curve was very steep and practically straight, but by the time that 10 per cent moisture-content was reached, diffusion appeared to have become the controlling factor, and this figure was therefore taken as the second critical moisture-content. A careful study of all the curves indicated that this was a good average value. It was immediately obvious from the curves that this diffusion portion of the drying occupied the greater part of the total time involved.

FIGURE 2

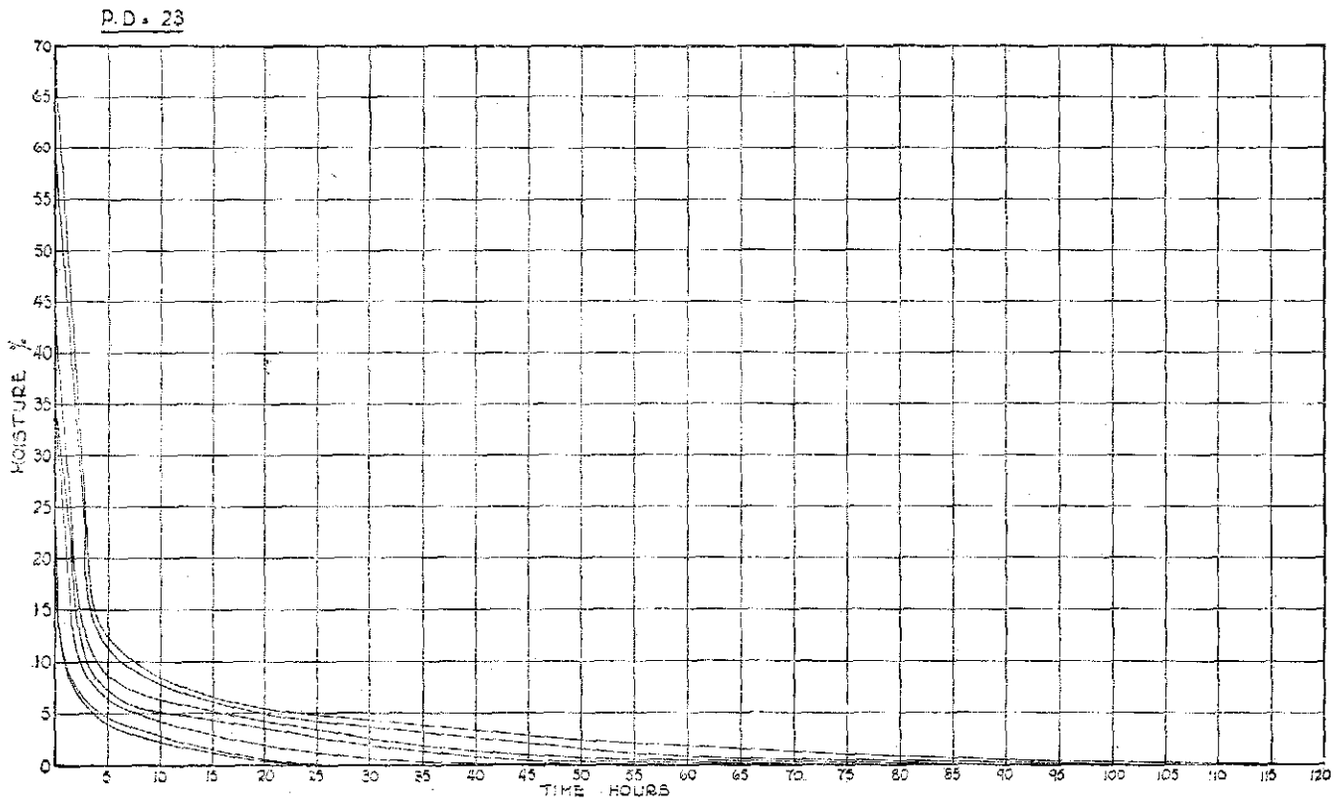
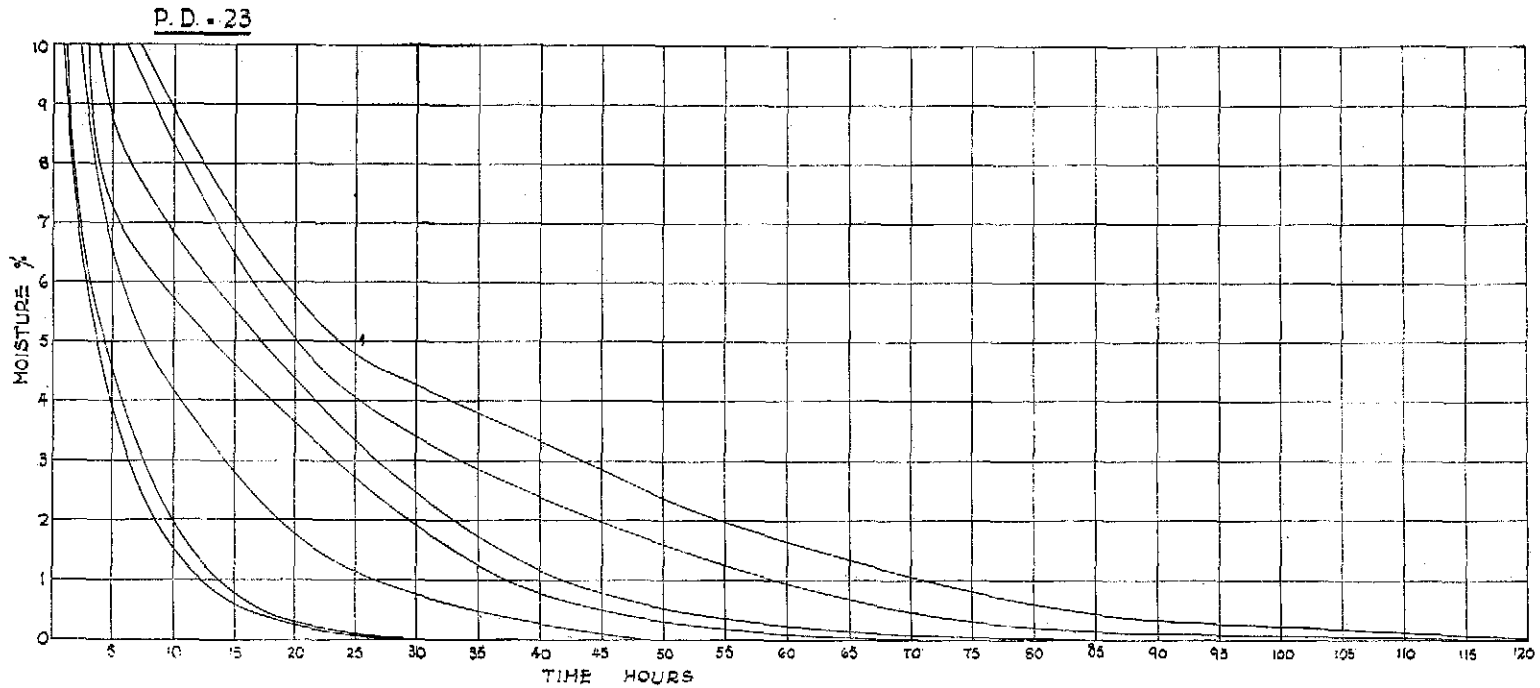

P.D. 23
MOISTURE %
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
TIME - HOURS

FIGURE 3


P. D. - 23
MOISTURE %
TIME HOURS
0
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2
3
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5
6
7
8
9
10
5
10
15
20
25
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90
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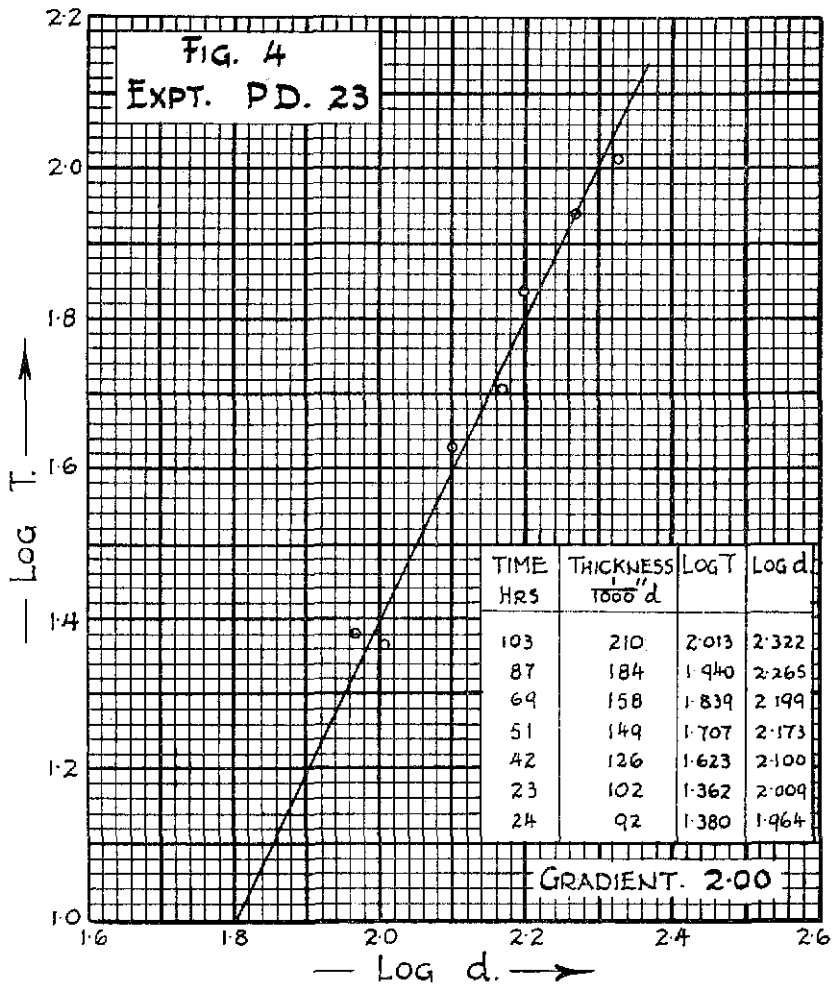
100
105
110
115
120

FIGURE 4



DIFFUSION-CONTROLLED PERIOD

(i) *General Analysis*

To confirm the view that the drying from 10 per cent moisture was controlled by diffusion, the logarithm of the time taken to dry from 10 per cent to 0.1 per cent moisture-content was plotted against the logarithm of the thickness, as shewn in Fig. 4. In each case the curve approximated closely to a straight line of gradient 2. The gradients for all experiments were determined and appear in Table I, together with an analysis of the probable error.

TABLE I

Experiment No.	Gradient	Difference from mean	Difference²
13	1.49	.58	.336
14	2.06	.01	—
15	2.33	.26	.067
18A	2.04	.03	.001
18B	2.18	.11	.012
20	2.12	.05	.003
22	1.91	.16	.026
23	2.00	.00	—
24	2.09	.02	—
25A	2.33	.26	.067
25B	2.04	.03	.001
26A	2.08	.01	—
26B	2.28	.21	.044
27A	2.13	.06	.004
27B	1.87	.20	.040
28A	1.85	.22	.048
28B	1.82	.25	.063
29A	1.89	.18	.032
29B	2.22	.15	.023
31A	2.00	.07	.005
31B	1.76	.31	.096
32A	2.50	.43	.184
32B	2.30	.23	.053
TOTAL	47.29		1.105
MEAN	2.056		

$$\text{Standard Deviation} = \sqrt{\frac{1.105}{22}} = 0.224$$

$$\text{Probable Error} = \frac{0.224}{\sqrt{23}} = \underline{0.047}$$

Since a straight line of gradient 2 is obtained by plotting logarithms of the general parabolic equation $y = kx^2$, it is seen that the results agree closely with the theoretical deduction, that when diffusion is the controlling factor the time required to dry a material through any given moisture-range is proportional to the square of the thickness. This agreement confirms the conclusion that diffusion is the controlling factor in the drying of rubber below 10 per cent moisture-content.

The differential equation for diffusion quoted earlier may be expanded into the following series for the slab, according to Newman *(loc. cit)*.

$$\frac{w-C_1}{C_0-C_1}=\frac{8}{\pi^2}\left[e^{-\left\{\frac{k\theta}{a^2}\right\}\left\{\frac{\pi}{2}\right\}^2}+\frac{1}{9}e^{-9\left\{\frac{k\theta}{a^2}\right\}\left\{\frac{\pi}{2}\right\}^2}+\frac{1}{25}e^{-25\left\{\frac{k\theta}{a^2}\right\}\left\{\frac{\pi}{2}\right\}^2}+\cdots\right]$$

where the following notation is used:—

- k is the diffusivity constant expressed as pounds per hour flowing across one square foot when the concentration-gradient is one pound per cubic foot per foot length in the direction of flow. It has absolute dimensions of square feet per hour.
- θ is the time in hours
- a is half the thickness of the slab in feet
- w is the final average liquid concentration in lb. per cubic foot
- C_1 is the equilibrium liquid concentration in the same units
- C_0 is the initial uniform liquid concentration in the same units.

The term $\frac{w-C_1}{C_0-C_1}$ is therefore a numerical ratio and is independent of the units used, provided they are consistent for the three terms. In the present case the moisture-contents are expressed as percentages on the dry weight of rubber. This ratio may be denoted by "E." A table of values for the term $\frac{k\theta}{a^2}$ for various values of E has also been published by Newman *(loc. cit.)*

Sherwood[4] has pointed out that the above analysis is based on the assumption of a uniform distribution of moisture across the thickness of the slab or sheet, at the beginning of the diffusion period. Unless drying is started exactly at the critical point the assumption of uniform moisture distribution cannot be valid. It is further suggested by Sherwood that if the constant rate drying period is sufficiently long, a parabolic moisture-distribution is set up across the sheet, and he derives equations for this case. The same author also draws attention to a limiting case, which occurs when the initial drying is very rapid, and there is not time in the short constant rate period for a parabolic moisture-distribution to be reached before the surface concentration of moisture is reduced

to zero, and the following series is given as the equation for this case:—

$$E^1 = \frac{96}{\pi^4}\left[e^{-\left\{\frac{k\theta}{a^2}\right\}\left\{\frac{\pi}{2}\right\}^2} + \frac{1}{81} e^{-9\left\{\frac{k\theta}{a^2}\right\}\left\{\frac{\pi}{2}\right\}^2} + \frac{1}{625} e^{-25\left\{\frac{k\theta}{a^2}\right\}\left\{\frac{\pi}{2}\right\}^2} + \cdots \right]$$

E^1 in this equation corresponds to the value denoted previously by E. *It is the ratio of the free-water-content at time θ to the free-water-content at the critical point.*

Sherwood *(loc. cit.)* has calculated values of E^1 for various values of $\frac{k\theta}{a^2}$ and these results are reproduced in table II A.

Further values obtained by the writer are given in table II B.

TABLE II A

$\frac{k\theta}{a^2}$	E^1
0	1.0
.02	.951
.05	.880
.10	.775
.15	.684
.20	.605
.30	.473
.50	.290
1.0	.086

TABLE II B

$\frac{k\theta}{a^2}$	E^1
.60	.224
.65	.198
.70	.175
.75	.154
.80	.137
.90	.106
.95	.094
1.05	.0738
1.10	.0640
1.15	.0576
1.20	.0505
1.30	.0396
1.40	.0310
1.50	.0143

Sherwood[5] has also suggested the use of a special graph paper with a uniform abscissa scale, but having the ordinate scale adjusted to force the above theoretical equation into a straight line. This technique is extremely helpful since experimental values for E^1 can be plotted directly against θ or against θ/a^2 and in both cases the results should fall on straight lines. Rapid comparison is thus possible between the theoretical derivation and the observed values, and the value of the diffusivity constant (k) is easily determined.

As previously stated, this analysis depends on the assumption that drying proceeds very rapidly in the period controlled by evaporation, and that the surface is dry by the time that the critical point is reached. Rubber approximates closely to these conditions. The high rate of drying of sheet in the early stages is shewn in Fig. 2, and it is common knowledge that the surface of wet rubber is dry to the touch after a very short period of drying. The results were therefore set out using this method and compared with Sherwood's theoretical equation.

Curves shewing the total moisture content at various times during the drying had already been plotted as shewn in Figs. 2 and 3. For the earlier experiments each curve represented the mean results from two sheets of rubber, both machined at the same settings, from the same latex. Whereas in the later ones the results for each sheet were plotted separately, and each batch of sheets was divided into two series of identical sheets, (A) and (B), which were submitted to slightly different soaking and dripping treatments before being dried together. From each curve the time taken for the moisture content to fall from 10 per cent to certain arbitrary levels was taken and a table prepared of this time divided by the thickness squared. An example is given in Table III. This provided the necessary data for plotting E^1 against θ/a^2 according to the method outlined above. This example was typical of the whole series of experiments. The values of θ/a^2 for each value of E^1 in each experiment were reasonably constant and were averaged as shewn in the table. Values of this variable for thin sheets and for all sheets at high values of E^1, were those most liable to error since the time intervals were short.

Table IV shews the mean values of θ/a^2 determined as in the above example, for the whole series of experiments involving the drying of approximately 250 sheets. The average temperature in the drying cabinet is also given for each test. The results are arranged in ascending order of temperatures.

TABLE III

Experiment PD 23

Curve No.		1		2		3		4		5		6		7		
Thickness $\frac{\text{ins.}}{1000}$		210		185		158		149		126		102		92		
$\left\{\frac{\text{Thickness}}{2}\right\}^2$ ft. $\times 10^5 = a^2$		7.60		5.85		4.32		3.84		2.74		1.80		1.46		Mean
Moisture Per cent.	F^1	Time θ	θ/a^2	Time θ	θ/a^2	Time θ	θ/a^2	Time θ	θ/a^2	Time θ	θ/a^2	Time θ	θ/a^2	Time θ	θ/a^2	$\frac{\theta}{a^2} \times 10^{-5}$
8	0.8	3	0.395	3	0.513	2	0.463	1	0.360	0.5	0.183	1	0.556	1	0.684	0.451
6	0.6	10	1.316	8	1.367	7	1.622	4	1.042	2	0.730	2	1.111	2	1.369	1.222
5	0.5	16	2.105	13	2.241	11	2.549	8	2.084	5	1.826	3	1.667	2.5	1.711	2.026
4	0.4	26	3.421	21	3.588	16	3.702	13	3.385	7	2.555	4	2.222	3.5	2.395	3.038
3	0.3	36	4.737	29	4.959	22	5.090	19	4.949	11	4.015	6	3.334	5	3.424	4.358
2	0.2	49	6.443	40	6.830	30	6.942	27	7.035	16	5.842	9	5.000	8	5.479	6.224
1	0.1	65	8.555	55	9.404	38	8.802	36	9.382	23	8.395	14	7.770	13	8.895	8.743
0.5	0.05	78	10.260	65	11.105	46	10.650	42	10.940	29	10.580	18	10.000	17	11.640	10.739
0.3	0.03	87	11.445	72	12.305	52	12.040	47	12.240	34	12.410	20	11.110	20	13.690	12.177

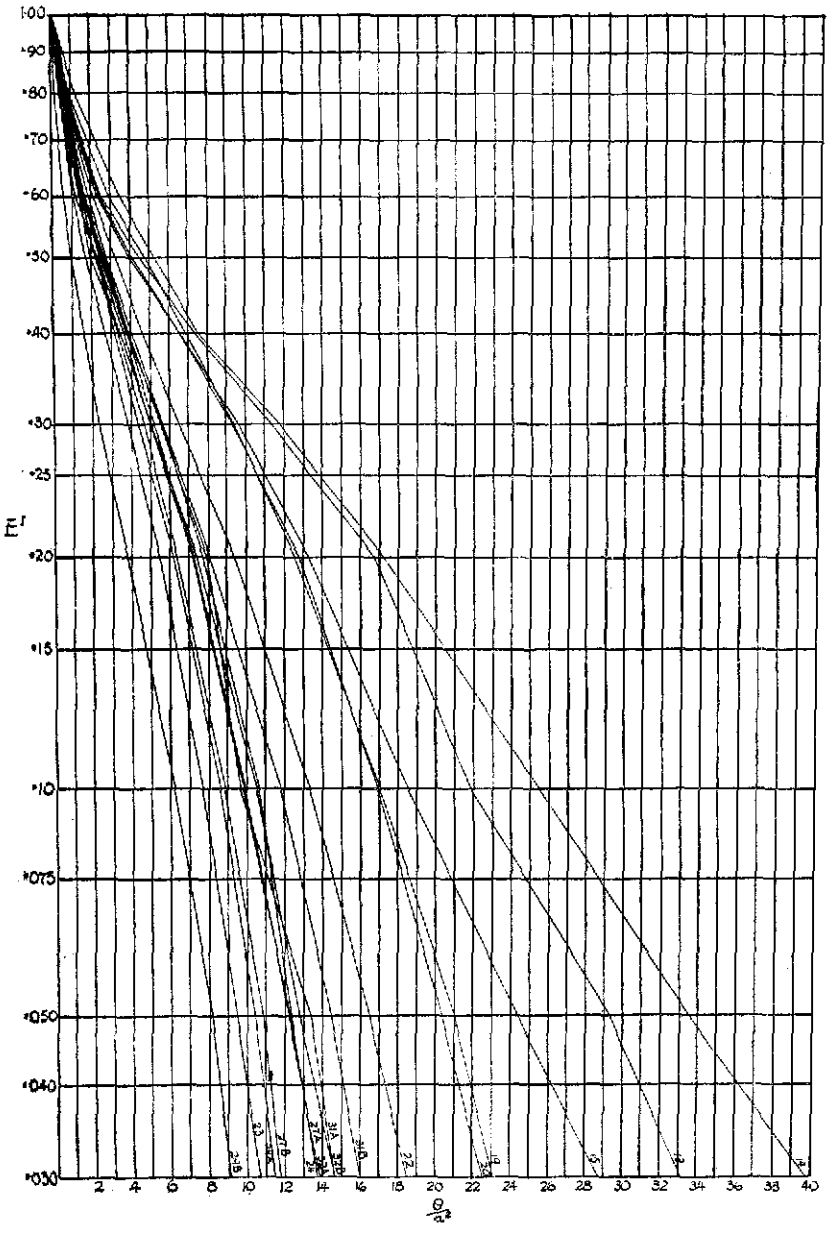
TABLE IV

$$\frac{\theta}{a^2} \times 10^{-5}$$

Expt. No.	Temp. °F	Values for E^1								
		.8	.6	.5	.4	.3	.2	.1	.05	.03
13	117.0	0.78	2.46	4.47	7.38	11.41	16.73	21.85	29.21	33.08
14	117.7	1.22	3.35	—	7.44	11.88	17.16	25.47	33.52	39.75
15	121.6	0.62	2.38	4.07	6.48	9.65	13.23	18.50	24.36	28.72
18 A	122.8	0.31	1.22	2.72	4.47	6.88	9.70	13.66	18.54	20.97
18 B	122.8	0.94	2.60	3.99	6.06	8.50	11.50	15.63	18.44	19.68
20	129.0	0.66	2.30	3.98	6.46	9.30	12.73	16.96	20.34	22.53
31 A	129.5	0.54	1.65	2.55	3.82	5.50	7.84	9.59	13.31	14.65
31 B	129.5	0.38	1.47	2.42	3.81	5.63	8.08	11.83	14.46	15.99
19	130.5	0.84	2.89	4.67	6.80	9.32	12.47	17.02	20.99	23.05
32 A	131.5	0.44	1.17	2.23	3.62	5.00	7.22	9.86	12.31	13.89
32 B	131.5	0.41	1.29	1.95	3.41	4.98	7.26	10.45	12.85	14.71
22	132.3	0.63	2.05	3.17	4.62	6.46	9.33	13.34	16.49	18.37
24	132.3	0.58	1.85	2.75	4.03	5.61	7.61	10.59	12.33	13.71
23	134.8	0.45	1.22	2.03	3.04	4.36	6.22	8.74	10.74	12.18
26 A	138.4	0.60	1.74	2.58	3.75	5.09	6.94	9.36	11.76	13.28
26 B	138.4	0.43	1.15	1.99	3.12	4.46	6.59	9.40	11.78	13.00
25 A	138.8	0.44	1.32	2.01	3.07	4.30	5.90	8.69	10.99	12.39
25 B	138.8	0.25	0.86	1.69	2.44	3.91	5.78	8.30	10.17	11.36
27 A	140.0	0.60	1.62	2.56	3.76	5.20	7.19	9.90	12.21	13.89
27 B	140.0	0.50	1.44	2.17	3.27	4.66	6.37	8.82	10.86	11.79
28 A	144.6	0.20	0.70	1.06	1.87	2.99	4.45	6.57	8.16	9.05
28 B	144.6	0.23	0.65	1.08	1.75	2.62	4.00	5.94	7.51	8.37
29 A	150.6	0.45	1.45	2.12	3.11	4.22	6.10	8.58	10.42	11.54
29 B	150.6	0.20	0.48	0.92	1.56	2.29	3.76	6.17	8.14	9.13

These values were then plotted on the specially constructed graph paper, suggested by Sherwood, on which the theoretical relationship between E^1 and $k\theta/a^2$ gives a straight line. Any deviations must be due either to variations in the diffusion factor (k) during the drying, or to errors in the experimental determination of the term θ/a^2. Of the two measurements involved here, namely the time, and the thickness, the former is more liable to error since it was obtained by interpolation from the original curves.

FIGURE 5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2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40

FIGURE 6

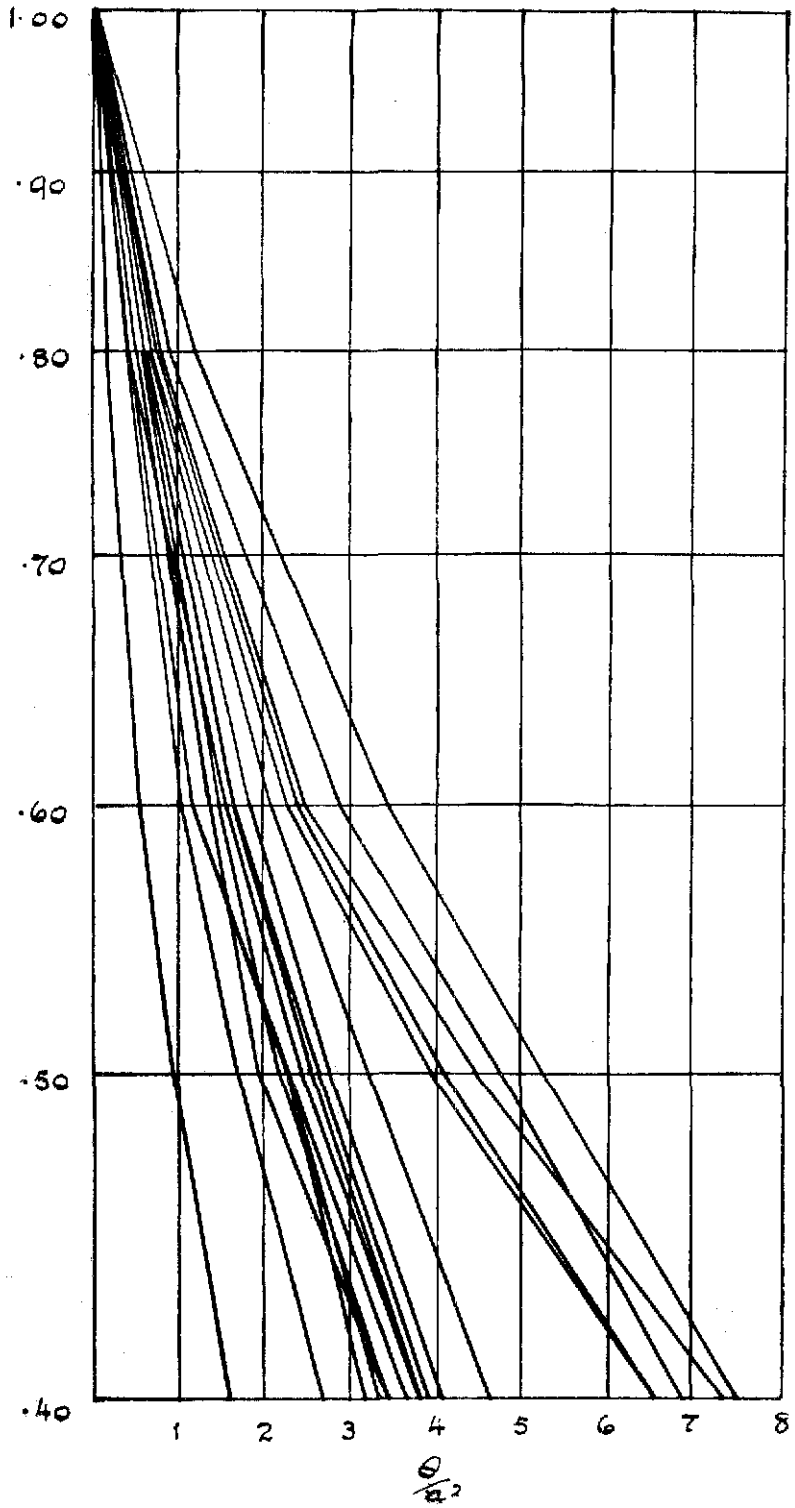

Fig. 5 shews a number of the results from Table IV, plotted by this method. Fig. 6 is an enlargement of the upper portion of the same curves. It will be observed that, considered over the whole range of values of E^1, from 1.0 to 0.03 the lines are reasonably straight, hence the assumption that the surface of the rubber sheet is already dry at the critical moisture content of 10 per cent is not very far from the truth. Fig. 6 however shews that the top portion of the lines are concave upwards. This deviation from the straight line is small, but consistent, and is therefore likely to be due to variations in the value of the diffusion constant (k) rather than to experimental errors. As the drying progresses the curves tend to be slightly convex upwards. These deviations indicate that the diffusion rate at first falls off and then, when the rubber is nearly dry the rate rises slightly again. It is probable that the first decrease is due to the shrinkage of rubber during drying. The same phenomenon has been observed in the case of clay[4]. The later rise is not well marked and may be illusory. One possible explanation, however, is that although the air temperature remained constant throughout, when the rubber was approaching dryness the heat lost through the evaporation of the diffused moisture would decrease, and the small amount of radiation from the shielded heating elements may then have been sufficient to raise the sheet temperature a little above that of the surrounding air.

The value for the diffusivity factor (k) is determined by dividing the value of $k\,\theta/a^2$ from Table II A or II B for any given value of E^1, by the figure for θ/a^2 for the same value of E^1 from Table IV. This was done for values of E^1 corresponding to 6 per cent, 3 per cent and 1 per cent moisture content, and the results are shewn in Table V.

(ii) *Effect of External Condition on Diffusion Constant*

It will be observed from Tables IV and V that the value of the diffusion constant (k) increases fairly regularly and rapidly with rise of temperature, for any particular value of E^1. The deviations from this regularity are at least partially explicable by the variation in

(a) ventilation conditions
and (b) draining periods at air temperature from experiment to experiment.

(a) *Ventilation conditions*

It is seen that the values of the diffusion constant (k) increased gradually with increase of temperature but over that portion of the range where natural ventilation was used, the values of (k) were

TABLE V

Values of k

Expt. No.	Mean Temp. °F.	Soaking Period after Machining Hrs.	Natural or Forced Draught.	Time of Dripping in Air Hrs.	$E^1 = .6$ $k\theta/a^2 = .215$		$E^1 = .3$ $k\theta/a^2 = .485$		$E^1 = .1$ $k\theta/a^2 = .922$		Mean Relative Humidity.
					$\frac{\theta}{a^2} \times 10^{-5}$	$K \times 10^5$	$\frac{\theta}{a^2} \times 10^{-5}$	$K \times 10^5$	$\frac{\theta}{a^2} \times 10^{-5}$	$K \times 10^5$	
13	117.0	2	Forced	2	2.46	.0874	11.41	.0425	21.85	.0422	—
14	117.7	2	„	2	3.35	.0642	11.88	.0409	25.47	.0362	—
15	121.6	2	„	2	2.38	.0904	9.65	.0503	18.50	.0499	—
18A	122.8	2	„	2	1.22	.1762	6.88	.0706	13.66	.0675	27.1
18B	122.8	2	„	2	2.60	.0826	8.50	.0571	15.63	.0590	27.1
20	129.0	1	„	0	2.30	.0936	9.30	.0522	16.96	.0544	28.1
31A	129.5	1	Natural	0	1.65	.1303	5.50	.0882	9.59	.0962	24.7
31B	129.5	1	„	3	1.47	.1462	5.63	.0862	11.83	.0780	24.7
19	130.5		Special Treatment See Table 6		2.89	.0744	9.32	.0521	17.02	.0542	—
32A	131.5	1	Natural	0	1.17	.1838	5.00	.0971	9.86	.0935	24.2
32B	131.5	1	„	3	1.29	.1667	4.98	.0974	10.54	.0875	24.2
22	132.3	1	„	0	2.05	.1049	6.46	.0751	13.34	.0692	27.6
24	132.3	1	„	0	1.85	.1161	5.61	.0865	10.59	.0871	26.7
23	134.8	1	„	0	1.22	.1762	4.36	.1112	8.74	.1057	24.1
26A	138.4	1	Forced	0	1.74	.1236	5.09	.0953	9.36	.0986	19.8
26B	138.4	1	„	3	1.15	.1870	4.46	.1086	9.40	.0982	19.8
25A	138.8	1	„	0	1.32	.1628	4.30	.1128	8.69	.1061	22.7
25B	138.8	1	„	3	.86	.2501	3.91	.1240	8.30	.1111	22.7
27A	140.0	1	„	0	1.62	.1327	5.20	.0943	9.90	.0932	21.0
27B	140.0	1	„	3	1.44	.1492	4.66	.1040	8.82	.1045	21.0
28A	144.6	1	„	0	.70	.3072	2.99	.1622	6.57	.1402	18.7
28B	144.6	1	„	3	.65	.3308	2.62	.1851	5.94	.1552	18.7
29A	150.6	1	„	0	1.45	.1482	4.22	.1149	8.58	.1074	17.5
29B	150.6	1	„	3	.48	.4482	2.29	.2119	6.17	.1495	17.5

consistently slightly higher than would have been expected from those obtained in the experiments using forced draught. This cannot be due to any humidity difference, since the forced draught system merely withdrew air from the top of the cabinet and returned it to the bottom, at such a rate that the air was completely circulated once every three minutes, with approximately 7 per cent rejected at each circulation. For the tests in which the blower was not employed, ventilators were arranged to change the air once every 40 minutes. The same amount of air was thus admitted to the cabinet in either case. Throughout the experiments it was found that after the first two or three hours, the moisture content of the air in the drying chamber was almost exactly that of the surrounding atmosphere. The relatively higher values of the diffusion factor (k) obtained when using natural ventilation may have been due to one or both of two factors. First, although the heaters were shielded by asbestos board, a certain amount of radiation on to the sheet may have occurred. This would tend to raise the sheet temperature above that of the air from which the temperature records were derived. A higher air velocity in these circumstances would minimise possible differences between the temperature of the sheet and that of the air. Evidence in support of this theory is provided by the finding that when forced draught was used, higher drying temperatures could be employed with less risk of damage to the sheet by blistering. The second possibility is that a dry impervious skin may have been formed on the surface of the sheet rubber during drying. A high air velocity would tend to increase this effect.

(b) *Draining periods at air temperature*

Another variable in the drying conditions was the period for which the sheet was hung in the air before being transferred to the heated cupboard. For purposes of calculation this period was regarded as part of the drying time. The results quoted in Table V shew that for high values of E^1 the value of (k) was usually higher for those sheets placed in the hot chamber immediately after soaking. As drying proceeded, and E^1 diminished, this difference practically disappeared. Further evidence for the effect of the draining period on the value of (k) was derived from the results of experiment 19 which appear in Table VI.

Here two of the sheets were left out in the air for the first 22 hours of the drying time and the moisture content was reduced to just over 5 per cent., whereas similar sheets which had been drained for shorter periods before being placed in the drying cupboard reached 3 per cent moisture in the same time. Yet the total time taken to dry these two sheets was if anything slightly less than

TABLE VI

Experiment No. 19

Sheet	No. 1	No. 2		No. 3		No. 4		No. 5		No. 6		No. 7		No. 8	
Thickness	0.123 in.	0.121 in.		0.124 in.		0.127 in.		0.129 in.		0.134 in.		0.122 in.		0.125 in.	
Soaked	0.5 Hr.	0.5 Hr.		0.5 Hr.		0.5 Hr.		2 Hrs.		2 Hrs.		2 Hrs.		2 Hrs.	
Drained	3 Hrs.	3 Hrs.		1.5 Hr.		1.5 Hr.		1 Hr.		1 Hr.		22 Hrs.		22 Hrs.	
Time	Moisture Per cent	Time	Moisture Per cent	Time	Moisture Per cent	Time	Moisture Per cent	Time	Moisture Per cent	Time	Moisture Per cent	Time	Moisture Per cent	Time	Moisture Per cent
0	33.13	0	33.74	0	31.81	0	30.51	0	27.89	0	25.89	0	27.98	0	28.20
3	11.90	3	11.25	1.5	22.24	1.5	22.03	1	20.56	1	18.39	3	12.95	3	15.37
5	7.43	5	7.20	5	7.51	5	7.59	3.5	8.57	3.5	7.63	22	5.35	22	5.18
23	3.12	23	2.85	23	3.38	23	2.98	21	3.58	21	3.89	24.5	4.31	24.5	4.02
26	2.82	26	2.70	26	2.80	26	2.53	24.5	3.12	24.5	3.44	27.5	3.57	27.5	3.28
29	2.52	29	2.25	29	2.35	29	2.23	27.5	2.65	27.5	3.28	45	0.74	45	0.89
47	1.18	47	0.60	47	0.74	47	0.60	45	0.78	45	1.20	51	0.74	51	0.45
53	0.74	53	0.60	53	0.74	53	0.60	51	0.78	51	0.75	69	0.15	69	0
71	0.15	71	0	71	0	71	0.30	69	0.16	69	0	73	0	73	0
74	0	—	—	74	0	74	0.15	73	0.16	73	0	—	—	—	—
—	—	—	—	—	—	98	0.15	97	0	—	—	—	—	—	—
—	—	—	—	—	—	119	0	—	—	—	—	—	—	—	—

that required by those sheets which had spent almost the whole period at a higher temperature. Thus the value of the diffusion constant (k) for sheets dried for the first 22 hours in air must have been higher than that for those drained for shorter periods. Although it is dangerous to draw conclusions from such limited evidence, this is an indication that the speed of the early part of the drying affects (k) thus supporting the view that a dry surface film, which hinders further drying, may be formed on the rubber. This is a well-known phenomenon with other materials and is usually termed surface checking. Although Table V indicates that ventilation and draining conditions do have an effect on the value of the diffusion constant (k) it also indicates that the effect of these variables is not sufficiently great for them to be of major importance in practice.

(c) *Effect of Compression during Rolling*

There is one further point on which the results offer certain evidence. It may be expected that the increased rolling necessary to produce a thinner sheet would reduce the porosity of the rubber sufficiently to produce an adverse effect on the diffusivity factor (k). This would produce a deviation from the theoretical relationship that drying time is directly proportional to the square of the thickness. A study of the values of θ/a^2 for the whole range of experiments, indicated that this ratio did tend to increase slightly as the sheet thickness diminished. The detailed example which forms Table III is typical. The effect was small, however, and was far outweighed by the reduction in time secured by producing thin sheet.

(d) *Effect of Surface Area of Sheet*

It will be observed that none of the foregoing deductions take into consideration the area of the sheet. This omission is justifiable since the thickness of the sheet was so small in comparison with its other dimensions that no error was involved in neglecting the edge effects and regarding the behaviour as similar to that of a sheet of infinite area.

(e) *Effect of Relative Humidity of Air*

The effect of the relative humidity of the air has also not been taken into account in calculating the results. As was pointed out earlier, this cannot affect the rate of drying so long as it is sufficiently low to permit moisture to evaporate faster than it can diffuse to the surface. Since the rate of diffusion has been shewn

to control the rate of drying over the major portion of the total time required, the relative humidity of the air did not affect the calculations.

(iii) *Summary*

Summarising at this stage, it may be said that the greater portion of the time taken to dry normal sheet rubber is occupied in drying beyond a 10 per cent moisture content, and that the rate at which this drying occurs is controlled by the rate of diffusion. The two principal means by which drying time can be reduced are by increasing the temperature and reducing the thickness of the sheet. There are indications that surface checking occurs but the experiments so far carried out give no clue as to its severity. The available evidence indicates either that effect is so small as to be unimportant in practice, or the phenomenon is so pronounced that simple practical measures, such as drying slowly at atmospheric temperatures for the first few hours, which should alleviate the trouble, have little effect. It is hoped that further experimental work will be possible to decide the extent of this surface checking. It is feared, however, that even if it is found to be important, the only method likely to expedite the drying will be humidity control irrespective of temperature, which would probably prove impracticable for an estate factory. In this connection it should be borne in mind that the relative humidity of the atmosphere is very high in rubber-growing countries, and that the sheet is normally dripped for a few hours at atmospheric temperature before it is transferred to the smoke-house, where the temperature is raised gradually. Thus sheet rubber is in practice dried slowly and at high humidity in the early stages. Further improvements on these lines are therefore unlikely.

CONSTANT RATE PERIOD

Attention up to this stage has been directed mainly to the diffusion-controlled portion of the drying. As was pointed out in reference to Fig. 2, the evaporation-controlled period during which the rubber dried down to 10 per cent moisture-content occupied a small proportion of the total time. Actually the thickest sheets in the experiment plotted in Fig. 2 were 0.21 inch thick and contained initially 67 per cent of free moisture. Their total drying time was 115 hours, but the moisture content had fallen below 10 per cent in less than eight hours. The thinnest sheets in the same series were 0.092 inch thick and had an initial moisture content of about 21 per cent and a drying time of 25 hours. Here the moisture-content reached 10 per cent in less than 1½ hours.

Further confirmation may be obtained from Table VI. The conditions controlling the constant-rate phase of the drying were stated in the preliminary discussion, and have been well established by the work of Hinchley and Himus,[6] and others. Since they are independent of the nature of the material being dried, except in so far as it may be hygroscopic, and since the technique used in this work did not permit of the measurement of drying over short intervals of time, it is not proposed to offer any experimental results for this evaporation-controlled period. It may be mentioned, however, that all the graphs of moisture-content against time were nearly straight over this region, as they should be according to the theory.

ZONE OF UNSATURATED SURFACE DRYING

Mention of the initial portion of the falling rate period, which is referred to in the preliminary discussion as the "zone of unsaturated surface drying" has also been omitted from the experimental analyses. It occurs between the first and second critical moisture contents. At first sight there appears to be no reason for the existence of this period under the conditions of this experiment, since a uniform smooth surface was exposed and there was thus no cause to expect one portion of the surface to be dry before the remainder. In contradiction to this it must be pointed out that the rubber was hung over bars and drainage of the surface film of water towards the lower edges would therefore occur, causing the film to be thicker at these points.

When it is remembered that in this zone the rate of drying is still controlled by the rate of evaporation, which has already been shewn to be very much larger than the rate of diffusion, it will be apparent that the effect of this period on the total drying time must be small. Further, there is no extraneous factor apart from those already considered in relation to the constant-rate period which can affect the drying rate in this zone, and there is thus little to be gained from a study of it. Owing to the intermittent weighing method adopted during these tests, it was found impossible in practice to locate the first critical point, and the zone of unsaturated surface drying; since the slight difference in rate which it could be expected to cause, from that of the constant rate period, was within the limits of experimental error. It was therefore regarded as part of the constant-rate evaporation-controlled period.

Comparison of Results with those Previously Published [3]

Although the evaporation-controlled period was short it was not negligible, and should be sufficient to produce an appreciable

deviation from the relationship stated by Van Harpen *(loc. cit.)*, namely, that the total drying time is proportional to the square of the thickness. To check this, the logarithm of the time required to dry from the initial moisture content to 0.1 per cent moisture content was plotted against the logarithm of the thickness in a manner similar to that used for Fig. 4. Once again the lines were straight and the gradient was almost exactly 2. The actual results are given in Table VII, which is comparable with Table I, except that in this case those experiments which were previously divided into A and B portions are here treated as one.

TABLE VII

Total Time versus Thickness Squared

Expt. No.	Gradient	Difference from mean	Difference²
13	1.57	0.41	0.168
14	1.90	0.08	0.006
15	2.13	0.15	0.025
18	2.25	0.27	0.073
20	2.08	0.10	0.010
22	1.75	0.23	0.053
23	1.96	0.02	0.000
24	1.89	0.09	0.008
25	1.92	0.06	0.004
26	2.18	0.20	0.040
27	2.08	0.10	0.010
28	2.02	0.04	0.002
29	1.89	0.09	0.008
31	1.68	0.30	0.090
32	2.38	0.40	0.160
TOTAL	29.68		0.657
MEAN	1.98		

$$\text{Standard Deviation} = \sqrt{\frac{0.657}{14}} = \sqrt{0.0470} = 0.217$$

$$\text{Probable Error} = \sqrt{\frac{0.0470}{15}} = 0.056$$

It has thus been shewn that the total drying time, and the time to dry from 10 per cent moisture content are both proportional to the square of the thickness. Also it was stated that the rate of drying from the initial moisture content down to 10 per cent moisture was constant and independent of the thickness. These facts can be reconciled only if the initial moisture content minus 10 per cent is proportional to the square of the thickness.

The experimental results were examined to test this conclusion. It was found to be approximately correct as is shewn in Table VIII.

TABLE VIII

Experiment PD 23

Initial Moisture Minus 10 per cent. = M	Thickness Inches = d	$\frac{M}{d^2} \times 10^{-3}$	Number of Machinings
56.98	0.211	1.28	3
48.07	0.185	1.41	3
31.72	0.158	1.27	4
24.41	0.150	1.09	4
20.69	0.126	1.30	5
12.60	0.102	1.21	5
10.94	0.092	1.29	5
		Mean 1.26	

The results from a number of other experiments selected at random were closely similar. It was found, however, that for thin sheets which had been passed many times through the machine there was a deviation from the mean. Experiment 13 of which details are given in Table IX was the one in which the highest number of passes through the machines was used, and affords the best illustration of this finding.

It will be seen that the ratio between the initial moisture content minus 10 per cent, and the square of the thickness is only approximately constant but a high order of accuracy is not necessary to explain the evident relationship between Van Harpen's

findings, and the deductions in this paper, since, in any case, the time taken for the initial, evaporation-controlled portion of the drying is small, in comparison with the total time required.

TABLE IX.

Experiment 13

Initial Moisture Minus 10 per cent. = M	Thickness Inches = d	$\frac{M}{d^2 \times 10^{-3}}$	Number of Machinings
74.6	0.250	1.19	2
55.2	0.214	1.20	3
47.5	0.195	1.25	4
39.7	0.196	1.04	5
43.2	0.195	1.14	6
44.1	0.175	1.45	7
23.8	0.150	1.07	8
16.1	0.133	0.91	9
8.0	0.116	0.59	10
6.1	0.109	0.52	11

Conclusions

The relationship stated by Van Harpen that the total time required to dry sheet rubber is proportional to the square of the thickness has been shewn to be an accurate working rule, although it did not at first sight appear to accord with general drying theory. By far the greater proportion of the time in drying rubber is controlled by diffusion, and approximate values of the diffusivity constant are given. A high order of accuracy is not claimed, since the critical moisture-content was difficult to determine, and although 10 per cent appeared a good average value it may have varied slightly for different experiments and even for different samples in the same test run. The two main methods by which drying time can be reduced are:—

(i) the production of thinner sheet
(ii) the use of higher temperatures.

There is an initial period of the drying during which the rate is controlled by the rate of evaporation. Here the time may be reduced by increasing the air velocity. There is little advantage to be gained in this way, firstly since the initial period represents a small proportion of the total time, and secondly because there is some evidence that surface checking occurs. This effect is increased by rapid drying in the early stages and it has an adverse effect upon the diffusion rate. The effect of various marking patterns on the drying time is another important aspect which remains to be investigated.

Practical Applications

The production of thin sheet and the use of high temperatures have been stressed as the two main methods available for reducing the time required to dry sheet rubber. There are obvious limitations to the extent to which either can be applied in practice.

(i) *Sheet Thickness*

Attempts to produce extremely thin sheet lead to a number of difficulties, some of which are listed below.

(a) The width of the dry sheet should be limited to 19 inches for easy packing, and if very thin sheet is to be produced without exceeding this width, the depth of latex used in the coagulating tanks may need to be restricted.

(b) The production of very thin sheet imposes added work on the sheeting battery. The output per hour is decreased, partly due to the increase in area required per pound of rubber and partly to the increased slip which occurs between the rubber and the rolls. All play must be eliminated from the rolls and bearings. Unless the number of pairs of rolls is increased in proportion to the reduction of thickness required, a greater squeezing effect must be obtained from each pair, and under these conditions difficulty may be experienced in making the rubber enter the nip. It may even be found that the thickness required is beyond the powers of the battery, in which case it becomes necessary to reduce the dry rubber content at which the latex is coagulated. This in turn necessitates the provision of a larger number of coagulating tanks for the same crop.

(c) Very thin sheets are limp and difficult to handle. They tear easily and are liable to stick together when piled or when hanging in the smoke-house. They also require increased smoke-house space per unit weight of rubber.

Modern sheeting batteries have proved capable of producing satisfactory sheet 0.10 inch thick from coagulum prepared from

latex containing 1.5 pounds of rubber per gallon, in standard tanks. This represents the practical limit, beyond which the above difficulties become important. It should be emphasised that a batch of rubber is not dry until the thickest portion of the thickest sheet is dry. Uniformity of thickness is therefore of vital importance, and in practice there is frequently more scope for reduction of the total drying time by attempts to eliminate thick patches and odd thick sheets in the batch, than there is in attempting to reduce the average thickness of the whole crop.

(ii) *Temperature*

The maximum temperature which can be used is limited by the danger of forming blisters on the sheet. It has been found that the safe maximum increases as drying proceeds, and it is therefore desirable to increase the temperature gradually during drying. In a separate paper elsewhere in this *Journal* will be found a description of two forms of a successful modern smoke house, together with notes which have been compiled from experience on the operation of this type. It will be observed that a four-days drying period is recommended and that the temperature is increased gradually from 100°F to 140°F. Higher temperatures have been used but these leave a very small margin of safety.

(iii) *Drying Time*

Although four days is the recommended period, there is little difficulty in drying sheet 0.10 inch thick in three days in the "Subur" smoke-house if desired, and there are special patented dryers capable of drying thin sheet rubber in 48 hours. In the smoke-house, however, two processes are in operation, for while being dried, the rubber absorbs certain ingredients from the wood smoke, and becomes coloured. Some users prefer a well-smoked sheet to one which is very pale in colour. The smoke not only acts as a disinfectant which renders the rubber somewhat less liable to mould attack, but it also appears to improve the ageing properties of the rubber after vulcanisation[7]. If rubber is dried too rapidly, difficulty may be experienced in producing sheet sufficiently dark in colour to meet with the approval of certain manufacturers. It has been found in practice, however, that rubber absorbs very little smoke when it is nearly dry. This is the reason for the recommendation of a four days' drying period, with comparatively low temperatures for the first 48 hours. It is also a further argument against attempts to carry the reduction of thickness to extremes.

It therefore appears unlikely that there will be any radical change in the method of drying rubber so long as smoked sheet, of the type now produced almost universally, remains the main form in which rubber is exported. It is considered that there is still room for minor improvements in the design and thermal efficiency of smoke-houses, and possibly for some small reduction in the time required to dry and smoke the rubber, but it is feared that the automatic machine which can convert the wet rolled coagulum into dry smoked sheet in a few hours, will remain unrealised.

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