Aggregate Temperature and Moisture Prediction From Asphalt Plant Data

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A method of combining more than 40 aggregate
drying variables into three primary variables
is outlined in this report. The three primary
variables are (a) aggregate heat absorption (the
heating rate of a given aggregate at a given
temperature during drying), including secondary
variables such as initial moisture content, satura-
tion, pore structure, and solid thermal char-
acteristics; (b) temperature gradient (the effec-
tive temperature profile of dryer gases from
entrance to exit), including variables of burner
rate, flame position, and veil density; and (c)
exposure time (the time a given aggregate is
exposed to the temperature gradient), including
the variables of dryer slope, length, rotation,
and aggregate size.

The control of these three variables during
the drying operation makes aggregate temperature
at discharge predictable. To arrive at this find-
ing, the results of 250 laboratory tests on three
aggregate types (sized 3/4 to sand) were coupled
with the conclusions of previous aggregate dry-
ing research at the Ohio State University. Tempera-
ture gradient and exposure time had been isolated
as significant variables in aggregate drying. The
three primary variables were found by adding the
results of lab tests on heat absorption rates to
data from previous studies.

● THE PURPOSE of this study is to develop a method of predicting aggregate tempera-
ture and moisture during the drying operation under controllable asphalt plant opera-
tions. The relationships of aggregate-dryer variables would then be used to evaluate
their effects on dryer operations. The study was undertaken in cooperation with the
Bureau of Public Roads on aggregate heating and drying economics at asphalt plants.

Analyses of dryer operations are complicated by different dryer designs, sizes,
and heating operations. As a result, complicated interactions exist between aggre-
gates, hot gases, and dryer designs. Any analysis must reduce over 40 dryer-
aggregate variables to some fundamental parameters in terms of the dryer function—
aggregate temperature increase and moisture loss.

Dryer operations are considered to be controllable when the aggregate-dryer varia-
tions can be measured quantitatively. Some important variations are moisture, ex-
posure temperature, and exposure time. During dryer operations these variations affect
aggregate drying and heating.

Moisture content is not consistent in aggregates at dryer entrance. This is apparent
in one aggregate source at one plant or over a number of plants where thousands of ag-
gregate types and moisture combinations exist. Data illustrating moisture content at
several dryers are shown in Figure 1 (Reprint from (9)). These data were obtained in

1960 in an earlier study with the Bureau of Public Roads. Each data point represents the average moisture content of 3 to 6 samples taken during one day of operation at each dryer. Other past data indicate that feed moisture contents for each aggregate size per dryer will vary, sometimes up to 2 to 3 percent, over the operational season. Because moisture content variations of 1 or 2 percent can effectively influence dryer production, dryer evaluation for each aggregate-moisture combination appears necessary throughout the operational season.

The time of aggregate exposure or passage through the dryer also varies. Even during steady operation, exposure times will vary within an aggregate size group; and each size group will vary. For example, prototype dryer data indicate that for average coarse aggregate exposure times of 2 min, sand exposure time is 2 $\frac{1}{2}$ min. When increasing the average coarse aggregate exposure time to 4 $\frac{1}{2}$ min, sand time increases to 6 min. Therefore, for the size groups of bituminous concrete mixtures, differences of exposure times will exist.

The third complexity is "temperature gradient." This is a function of burner rate, flame shape, aggregate moisture, veil resistance, and dryer design and airflow. The burner rate and aggregate veil usually vary during dryer operation. The temperature gradient as a function of two variables is shown in Figure 2. When the same burner rate is used (A, A', or A''), variations of veil density (A-A') or variations of hottest flame location (A-A'') produce changes in temperature gradients. If the burner rate is increased from A to B, the temperature gradient increases in a parallel manner.
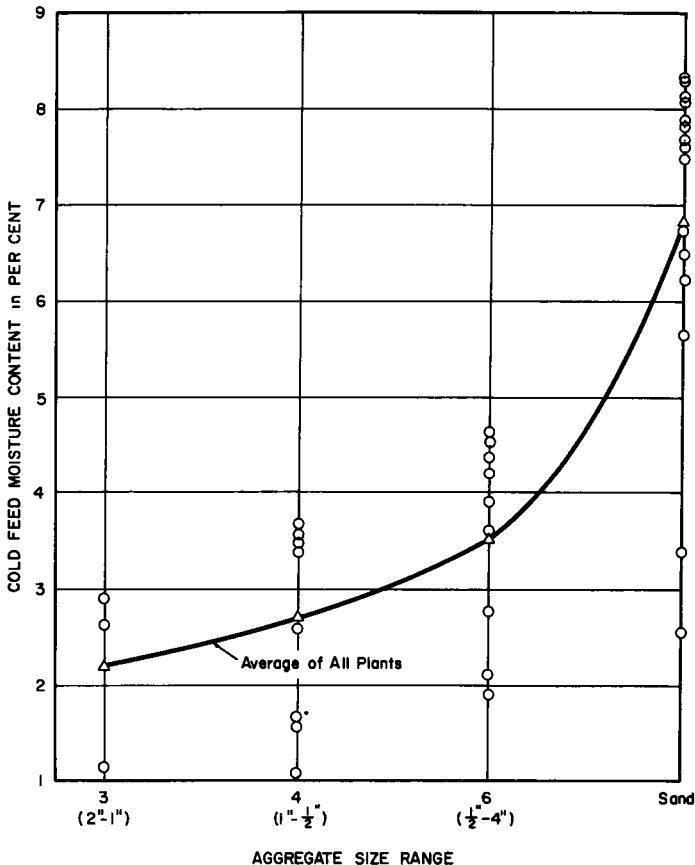

Figure 1. Aggregate size vs moisture content.

Sufficient aggregate exposure is necessary because moisture loss and temperature are dependent on exposure time. The time in the veil (maximum heat exposure) is relatively short. It is necessary for heat to penetrate to the aggregate centers during the periods of flight and cascading contact near the drum walls. Under these exposure conditions, the interaction of the dryer hot gases and aggregate becomes a function of the dryer and burner design. Dryer dimensions usually influence the amount of aggregate heated. However, irrespective of the dryer design, aggregate heating is accomplished by exposure time. For a given aggregate temperature, required exposure time is inversely proportional to the exposure temperature.

In his investigation, Pagen (8) found that all initially wet aggregates exposed to heat go through a drying cycle. Drying cycle changes were shown due to aggregate type and moisture differences. Fischmann (8) in the same paper pointed out that aggregate heating rate is directly dependent upon the thermal conductivity of the solid. Tests by other physical investigators have shown that thermal conductivity increases as moisture increases in porous materials. For aggregate heating aggregate temperature consists of aggregate solid temperature plus the temperature of the interior water in the aggregate pores. From this reasoning one would expect a decreasing thermal conductivity and thus a decreasing heating rate as aggregates dry under a given exposure temperature.

Baker and Lottman (1) conclude drying cycle phases are dependent on exposure temperature. Their data from several drying cycles of saturated aggregates show that
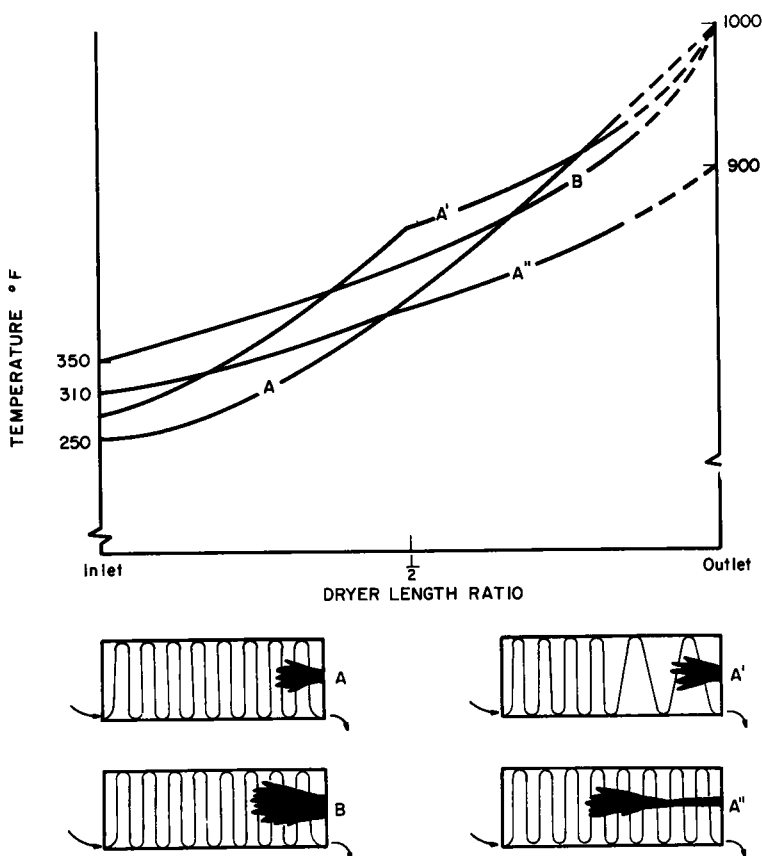
Temperature Gradient Variation by Changes of Veil and Burner

Figure 2. Dryer length vs effective temperature.

temperatures, time durations, and rates of moisture loss are related. Although their data relate to moisture loss, aggregate heating dependency on drying cycles is implied. In a later study, Deming (6) found aggregate heat absorption rate was related to the drying cycle.

Prototype dryer studies were later performed to evaluate aggregate characteristics, temperatures, and exposure times. Smeins (5) found changes in initial saturation levels produced different heating rates for aggregates. When varying initial moisture content, Smeins found greater aggregate discharge temperatures for lower initial moisture contents. The discharge temperatures of porous aggregates were found to be highly dependent on initial saturation. Also, for initial saturations over 50 percent, gravel aggregate was discharged from the dryer at greater temperatures than other aggregate types.

Smeins found also in the prototype that greater percentages of sand in the dryer aggregate lowered the temperature of the aggregate at discharge. He found the temperature of the aggregate combination dropped from 500 to 250 F when the percentage of sand increased from 25 to 75. This was due to the increased moisture to be removed and the greater veil density or resistance to heat flow from the increased surface area. The following are three implications derived from Smeins' study:

1. For heating a given aggregate, a greater initial moisture content will decrease its heat absorption rate regardless of the particular drying cycle phase under consideration.
2. The location of moisture content, surface or interior water, may be an important factor in aggregate heating.
3. For a given dryer set-up, a desirable gradation range may exist for maximum heating outside of which excessive aggregate surface areas or diameters produce less than maximum heating rates.

Lovejoy (2) checked prototype drum temperatures under varying air flow, burner rates, slopes, and feed rates. Drum temperatures were measured by thermocouples at points that divided the drum length into three equal parts. He found the $\frac{1}{3}$-point temperature gradients usually reflected thermal efficiency. Relatively small temperature differentials between the $\frac{1}{3}$-points proved efficient operation, although moisture removed and discharge temperatures were low. The second $\frac{1}{3}$-point temperature varied more than the first with different dryer settings. As a result, the second $\frac{1}{3}$-point temperature usually indicated aggregate discharge temperature. The discharge temperatures in turn were found to be directly proportional to the percentage of moisture removed. Providing drum temperatures reflect aggregate-hot gas temperatures along the dryer, one implication for current rotary dryer operation is that greater thermal efficiencies can be obtained when aggregate discharge temperature is decreased by proper dryer operational changes.

Exposure time was found to be important for utilizing available burner heat to heat and dry aggregate. Both Uehling (4) and Lovejoy (2) found greater exposure times, produced by flatter prototype drum slopes, resulted in greater thermal efficiencies. With a constant burner rate, their data implied increased thermal efficiency with increases in aggregate exposure times and weights in the drum.

The temperature-size distribution within aggregate samples at dryer discharge was observed by Uehling (4) and Middleton (3). Although temperature variation was apparent when measuring several samples from each size group, the over-all observation was that groups of the larger sizes were usually cooler than those with the smaller ones. Maximum differentials of 110 F from the 2-in. range to sand were found. Both investigators concluded that temperature differentials will usually exist in the discharged aggregate whenever aggregates of different sizes are heated.

The past conclusions imply aggregate size, type, and moisture content are several of the primary factors that determine rate of heat absorption. When considering the effects of exposure times and temperatures on aggregates, the conclusions indicate an aggregate heating solution is possible.

In conduction, convection, or radiation, the rate of heating is represented by a heat absorption coefficient. Aggregate heating involves all three methods of heat

transfer. Aggregate size, type, and moisture characteristics, the limitations of instrumentation, and the critical sensitivity of thermal measurements needed to determine heat coefficients are difficult to collect and apply to the aggregate heating problem. As a result, a laboratory oven heating test has been used to determine over-all heat absorption rate coefficients. To some extent heat absorption plots describe aggregate ability to heat; they can be used to predict and analyze the heating of aggregates in asphalt plant dryers.

The study has been undertaken as a practical investigation of aggregate heating characteristics for use in field conditions. Aggregate temperature was evaluated in terms of generalized analytical approaches to dryer-aggregate combinations. Several quantitative solutions and heating considerations were attempted to predict aggregate temperature on the basis of fundamental characteristics of aggregate and dryers. These fundamental characteristics or variables are (a) aggregate heat absorption rate, (b) dryer temperature gradient, and (c) dryer exposure time.

The method used in this study includes a laboratory heating test to identify aggregate heating characteristics and a field test to measure exposure times and temperature gradients. These variables are then used as the factors for predicting aggregate temperature. Also, they may serve as a future basis for dryer efficiency and design.

GENERAL PROCEDURE

Laboratory Heating Test

The test work was based on the assumption that a heating test for aggregates could combine all the important aggregate variables. Test results would then represent quantitatively heat transfer during the drying cycle. A preliminary investigation of drying cycle changes during heating added two other variables to the test—oven temperature and initial saturation. The variables considered in the aggregate heat absorption experiments were (a) drying cycle phases, (b) oven temperature, and (c) initial aggregate saturation.

The following steps were used in the laboratory procedure:

1. Samples of stockpile aggregates representing each hot-bin size range were obtained for a laboratory oven-heating test. The moisture content of each aggregate size range was determined as it existed in the stockpiles.
2. Samples were heated to oven temperature. The "dry" specific heat values of the aggregates were then determined by a calorimeter.
3. Drying curves were plotted at constant temperature for each aggregate size at its stockpile moisture content.
4. Phases of the drying cycles were found and the corresponding oven times recorded. The oven temperature (300 F+) was also recorded.
5. Drying cycles were repeated for each aggregate size. The cycles were interrupted at the terminal point of each phase.
6. The aggregates were immediately placed in a calorimeter and a temperature rise noted. The moisture remaining in the aggregates at each terminal point was determined from the drying cycle and used to compute the "wet" specific heat of the aggregates. Heat absorption rates (Btu/min) were then calculated from heat exchange laws.
7. When heat absorption rates for all aggregate sizes were calculated at each phase of the drying cycle, they were plotted with oven temperature on a semi-log scale.

The data from laboratory heating tests are plotted in Figures 3, 4, and 5. In general, there is a straight-line relationship for Btu/min absorption and oven temperature at each drying cycle phase. Also, at lower oven temperatures sand heat absorption is less than stone heat absorption at each drying cycle phase. As oven temperature increases, the sand heat absorption rates approach the stone rates. As aggregates dry, heat absorption rates generally lower.

It is hypothesized that all heat-drying cycle lines form a dry aggregate temperature curve above the working temperature of the oven. The temperature at which this occurs
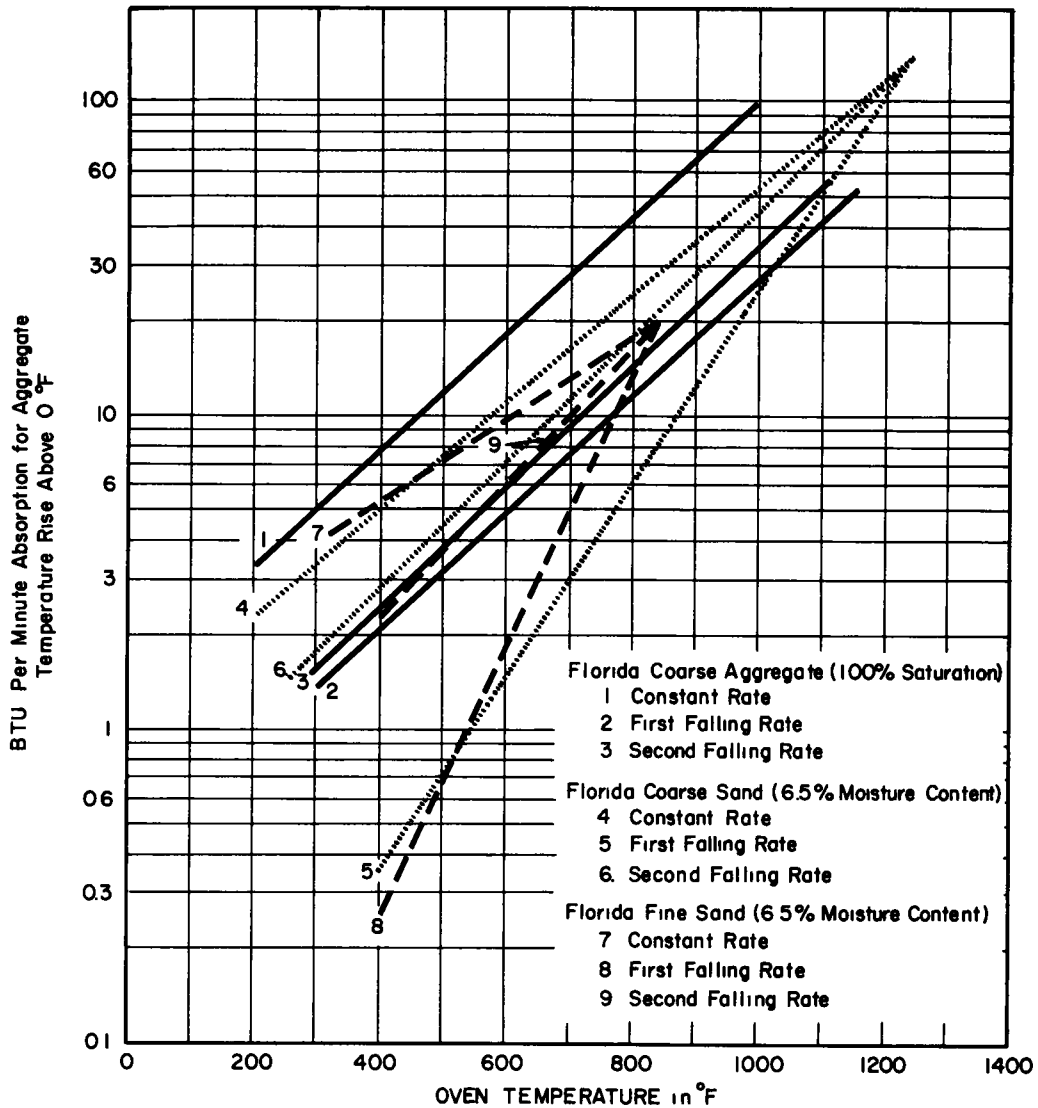
Figure 3. Oven temperature vs heat absorption for Lakeland, Fla., limestone.

apparently depends on aggregate size. For example, in Figure 3 fine sand lines join at 850 F, coarse sand at 1,250 F, and coarse aggregate probably at a much higher temperature outside the graph. At the temperatures beyond which aggregate drying lines join, heat absorption of wet aggregates may be independent of the drying cycle. In practice, these temperatures may never be reached, at least in the first portion of the dryer.

Figures 4 and 5 are heat absorption plots of a coarse limestone and a slag sand. In these figures the initial moisture content or saturation was varied. The limestone plot shows that some initial moisture (60 percent saturation) is required for the greatest heat absorption rate in each drying period. Observations of the slag sand plot show that initial moisture has a variable effect on heat absorption rate. At the lower oven temperatures, the greatest heat absorption rates occur in the constant rate periods (where most aggregate moisture exists during drying).
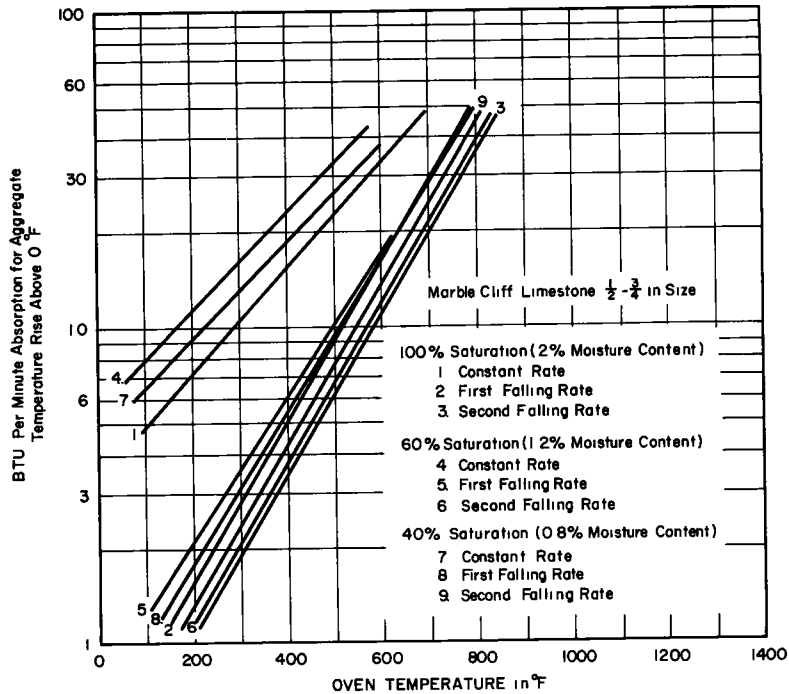
Figure 4. Oven temperature vs heat absorption for Marble Cliff limestone.
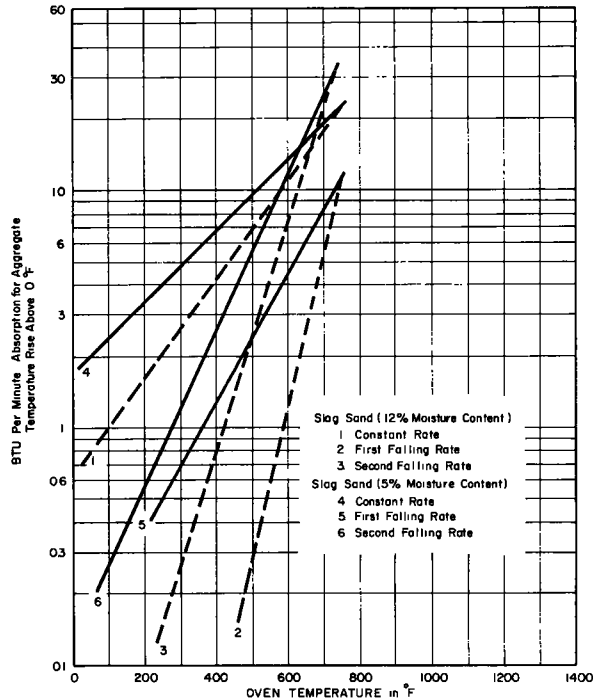

Figure 5. Oven temperature vs heat absorption for slag sand.

Field Test

Laboratory tests showed that drying phase and exposure temperature will determine aggregate heat absorption rates. Heat absorption is found from drying phase, exposure temperature, and aggregate exposure time at asphalt plant dryers. The field measurement of these three variables is described generally by the following procedure:

1. The average exposure time for each aggregate size is found by use of colored aggregate tracers representing each size.
2. Temperature measurements of the dryer exterior are taken at $\frac{1}{8}$-points from entrance to discharge. The profile of drum temperature indicates the aggregate mass heating curve and the drying cycle. Stack temperature, gas velocity and burner rates are recorded. Dryer heat balance or aggregate moisture loss tests will give gas temperature gradient along the drum interior.
3. It is assumed the temperature profile shows how much of dryer is taken up by each drying cycle phase.
4. The temperature gradient gives the exposure temperature for each drying phase.

Application of Lab and Field Test to Determine Aggregate Discharge Temperature

The application of aggregate heat absorption rates, exposure times, and temperature gradients is outlined in the following procedure:

1. Using each aggregate size's average exposure time, and assuming this exposure time is a uniform summation of exposure times along the dryer, the exposure time for each drying cycle phase can be calculated using the drum temperature profile.
2. With the laboratory heat absorption rates (Btu/min) for each drying phase, exposure time, and average gas temperature for each drying cycle phase, the aggregate heat absorption for each drying cycle phase is calculated. Total heat absorption, or Btu rise, for the given aggregate size is determined. The discharge temperature is then found for this aggregate size. (This step is repeated for the other aggregate sizes, to determine their temperature rise.)

Details of the method are outlined in the Appendix. Computations of aggregate heating characteristics, temperature gradients by both heat balance and average moisture loss methods, and exposure times for the drying zones are included for the Ohio State prototype dryer and for a field dryer. The heat balance method was not used for the field dryer due to the absence of burner-rate data.

Average values of exposure time, temperature gradient, and moisture content are used in the Appendix. The effects of their variations on aggregate discharge temperature and moisture content can be determined by the Appendix method when replacing average values by the variation extremes of each value. For greater practical meaning, statistical data of these variations could find the probability of different levels of each value. These levels could be used to find the normal or expected distributions of discharge temperature and moisture content.

Calorimeter Device

Temperature measurements of aggregates during drying were necessary in this study. Earlier cooperative studies at Ohio State with the Bureau of Public Roads made use of the calorimeter principle when special water containers and thermometers were used. Their accuracy was greater than thermometers—especially when finding coarse aggregate temperature. Rapid temperature measurement is needed to hold aggregate cooling effects to a minimum during drying sampling. The calorimeter principle was a significant improvement over other thermal sensing principles.

Subsequent development led to the design of the calorimeter used in this study. It is illustrated with a 2-lb sample of coarse aggregate in Figure 6. It utilizes the principle of heat exchange between aggregate and water. When a sample is placed in the screen basket (suspended inside the casing) and rotated by means of the crank handle, heat transfer occurs between aggregates and water. The tumbling action
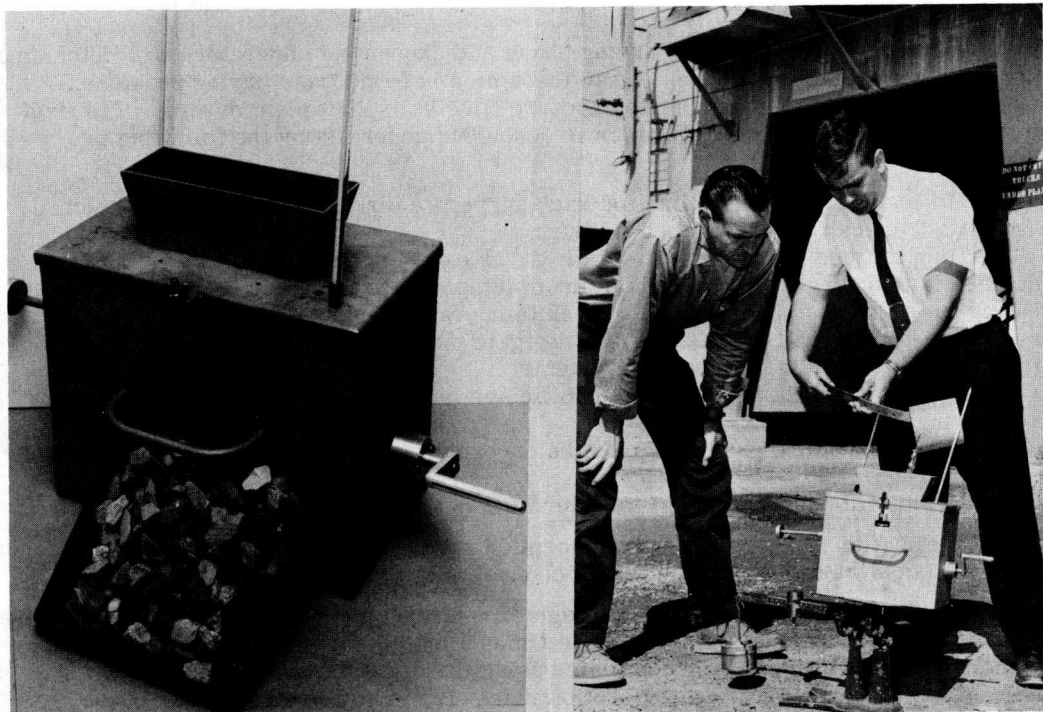
Figure 6. Aggregate calorimeter.

causes maximum surface exposure to churning water. In 20 to 30 sec, equilibrium temperature is reached. Initial aggregate temperature is calculated from water and aggregate weights, initial water temperature, final water temperature, and specific heat of the two media. Specific heat of aggregate can also be calculated by a similar procedure when initial aggregate temperature is known. This can be established by several hours of oven heating at a constant temperature. In addition, the calorimeter measures heat input to aggregate. This is usually measured during drying; the procedure is the same as aggregate temperature determination. The details of the laboratory heating test described previously refer to the use of this device.

Aggregate Heating Considerations

The method for predicting aggregate temperature can be applied to the evaluation of dryer variables. There are many variables that influence these three primary variables. The following is a partial list of variables and the primary variable they influence:

1. Aggregate heat absorption.—initial moisture content, saturation, pore, structure, solid thermal characteristics, size.
2. Exposure time.-dryer slope, length, rotation, aggregate size.
3. Temperature gradient. —burner rate, flame position, fuel type, veil density.

With the method used in this report, the effects of aggregate heat absorption, exposure time, and temperature gradient appear to have equal influence on aggregate temperature. Figure 7 shows the extremes of presently available data. When seeking aggregate temperature, Figure 7 suggests equal emphasis be given all three variables. Temperature gradients and exposure times may need to be established for each aggregate type. Undoubtedly there are combinations that can minimize excessive heat losses, aggregate temperature differentials, discharge moisture contents, and low production rates.
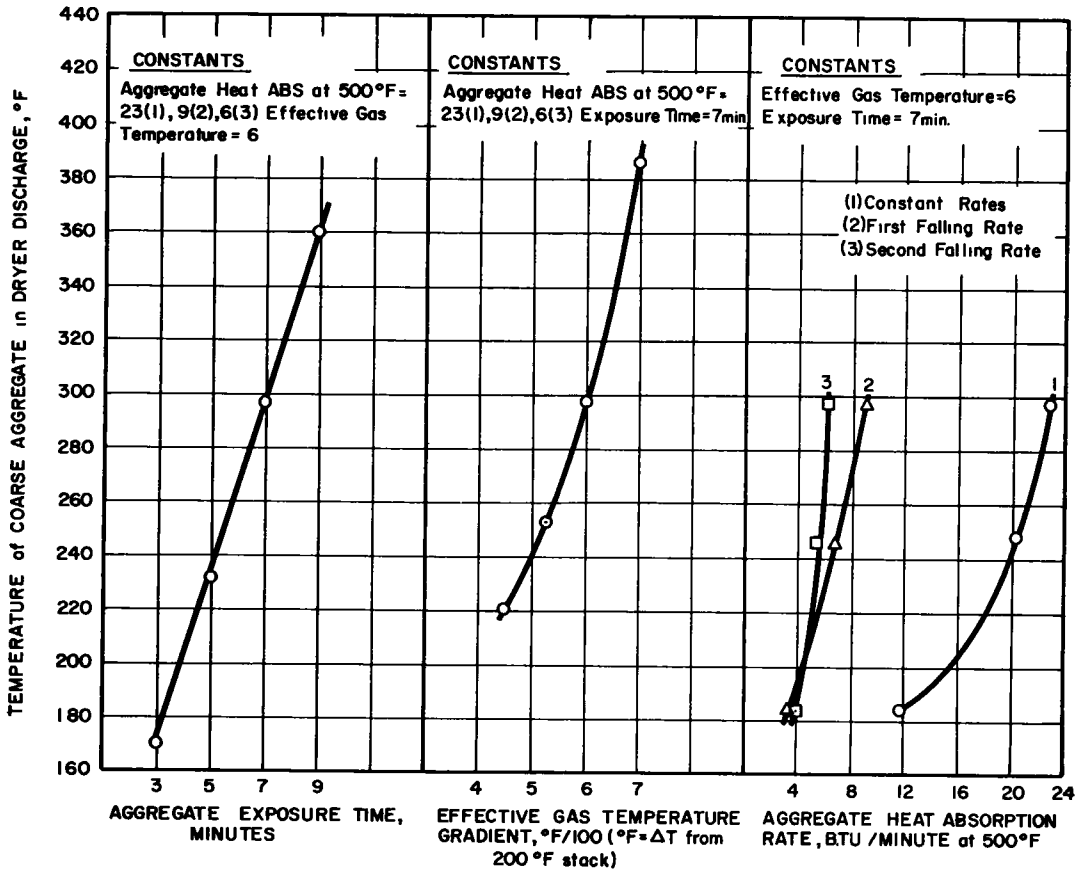
Figure 7. Effect of variables on coarse aggregate temperature.

The effect of temperature gradient and exposure time on aggregate discharge temperature for Marble Cliff limestone is shown in Figure 8. These plots were based on heat absorption curves using the three-value method, and for a constant aggregate weight in the drum. Figure 8 shows that high temperature gradients are required for aggregate temperatures of 300 F when exposure times are relatively small. Slopes of gradients show that changes of exposure time produce greater changes of aggregate temperature on high temperature gradients than on low temperature gradients. In Figure 8 the data indicate very high temperature gradients produce very high production rates. However, exposure time must be tightly controlled at high temperature gradients.

When considering thermal efficiency, past data on rotary dryers show long exposure times and low temperature gradients produce efficient conditions. The selection of economical combinations of variables is limited for present dryers. Exposure time controls and burner capacity should be considered with thermal efficiency when setting production rates.

Data from Figure 8 were re-plotted for Figure 9. Combinations of temperature gradients and exposure times were selected for each aggregate temperature. Plots obtained are a family of curves from which temperature gradients and exposure times can be found for the coarse aggregate temperature desired. As exposure time approaches zero, the required temperature gradient for the aggregate temperature approaches infinity. For aggregate temperatures over 200 F, exposure times approach infinity when temperature gradients of zero are used. This is based on a steady stack temperature of 200 F.
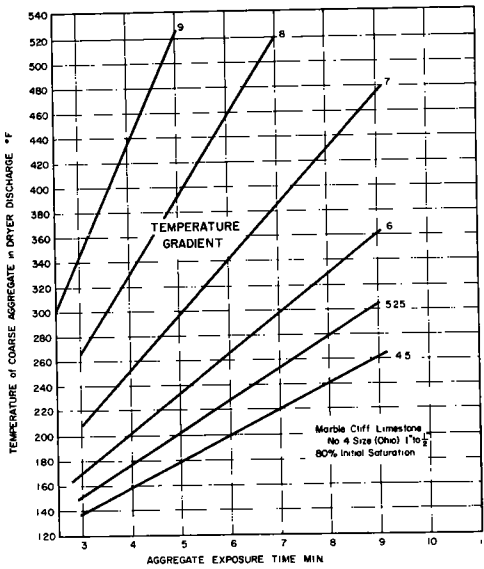
Figure 8. Effect of temperature gradient and exposure time for coarse aggregate discharge temperature.

Figure 9. Effective temperature gradient vs exposure time for coarse aggregate discharge temperature.

A smaller increase in temperature gradient is required to increase already high aggregate temperatures at a given exposure time. However, when decreasing exposure time at a uniform rate, a greater rate of increase in temperature gradient is required to give the same aggregate discharge temperature.

The validity of the method used to aid in dryer evaluation requires extensive additional laboratory and field data. The preliminary studies show that the approach has merit; definite data required for dryer evaluation can be stipulated. This will be of great value to the consumer, producer, and research interest. The method will eventually allow selection of an economical combination of dryer-aggregate variables.

CONCLUSIONS

1. Aggregate temperature can be found by combining dryer exposure time, dryer temperature gradient, and aggregate heat absorption rate when aggregate moisture loss is known. Similarly, aggregate moisture loss can be found from aggregate discharge temperature under these conditions.

2. Many combinations of temperature gradients and exposure times for a given aggregate result in the same aggregate temperature.

3. Aggregate heat absorption rates change during drying for a given aggregate and initial moisture content.

4. For the same drying phase, different aggregates at the same initial saturation level have different heat absorption rates. Similarly, the same aggregates at different initial saturations have different heat absorption rates.

5. For some porous aggregates, initial moisture may increase heat absorption rates during the early stages of aggregate drying when aggregate temperatures are less than 300 F.

6. Aggregate heating comparisons can be found from the heat absorption test when changing aggregate type and/or initial moisture.
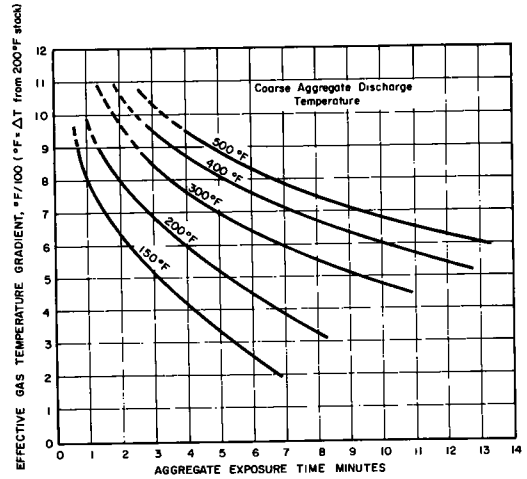
Appendix

DETAILS OF LAB AND FIELD TEST TO DETERMINE AGGREGATE DISCHARGE TEMPERATURE

A. Laboratory Heating Test for Aggregate Heat Absorption Rate

The general procedure for these tests has been outlined. The following, including Tables 1, 2, and 3, is a sample calculation of aggregate heat absorption values.

Aggregate:	Lakeland, Fla., limestone
Size:	$\frac{3}{4} - \frac{1}{2}$ in.
Initial Saturation:	100 percent
Initial Moisture Content:	4.5 percent
Oven Temperature:	760 F

TABLE 1

CALORIMETER TEST DATA

Drying Cycle Interruption	Wt. of Cal. + Water + Agg.	Wt. of Cal. + Water	Wt. of Cal.	Wt. of Agg.+ Water	Wt. of Water in Cal.	Temperature	
						Initial	Final
(min)	(lb)	(lb)	(lb)	(lb)	(lb)	(°C)	(°C)
1 ½	33.45	31.43	9.00	2.02	22.43	13.45	14.75
						13.30	14.60
4	33.86	31.85	9.00	2.01	22.85	14.20	16.70
						14.00	16.40
6	33.74	31.83	9.00	1.91	22.83	16.50	19.20
						16.25	18.95
10 ½	33.69	31.86	9.00	1.83	22.86	20.90	25.70
						20.60	25.45
15	33.63	31.73	9.00	1.90	22.73	19.00	25.35
						18.75	25.10

Figure 10 shows divisions of the drying cycle curve into the various zones for computing heat absorptions during drying.

TABLE 2

MOISTURE IN AGGREGATE AT POINTS OF INTERRUPTION IN DRYING CYCLE

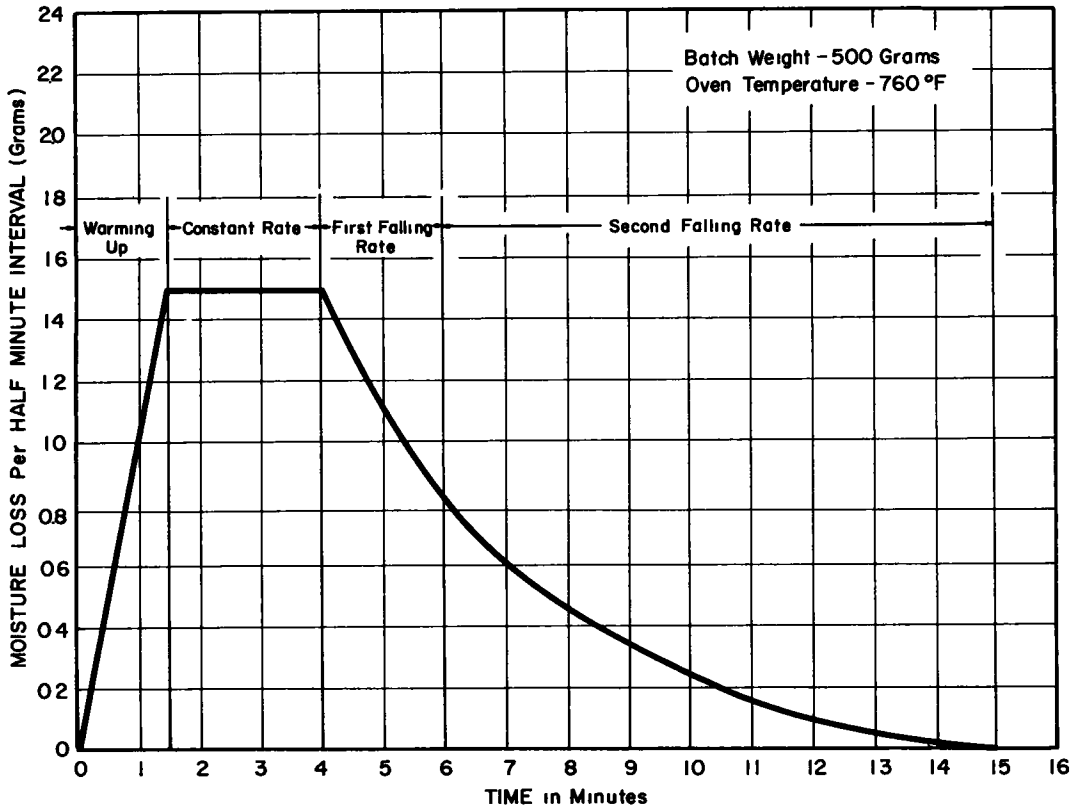| Time (min)	Moisture per Unit Wt.	Aggregate Moisture (lb)
1 ½	41.74 × 0.0008 = 0.03339	0.03339 × 2.02 = 0.0674
4	22.99 × 0.0008 = 0.01839	0.01839 × 2.01 = 0.0370
6	11.64 × 0.0008 = 0.00931	0.00931 × 1.91 = 0.0178
10 ½	1.54 × 0.0008 = 0.00123	0.00123 × 1.83 = 0.0023
15	0	0

Figure 10. Aggregate moisture loss vs oven exposure time.

TABLE 3
BTU COMPUTATIONS

Time (min)	Wt. of Water in Cal. (lb)	T_f (°F)	T_i (°F)	W_{agg} + W_{moist}	W_{moist} (in Agg)	W_{agg} Dry	C_{Pagg}	Btu	Btu per Min.	
									Last Reading	Avg.
1½	22.43	58.41	56.07	2.02	0.0674	1.9526	0.218	81.29	54.19	
4	22.85	61.79	57.38	2.01	0.0370	1.9730	0.218	129.00	19.34	36.76(C.R.)
6	22.83	66.33	61.92	1.91	0.0178	1.8922	0.218	130.00	0.50	9.92(F.F.R)
10½	22.86	78.03	69.35	1.83	0.0023	1.8277	0.218	229.69	22.33	12.05(S.F.R.)
15	22.73	77.40	65.97	1.90	0	1.9000	0.218	291.86	13.82	

The following formula is used for Btu absorption:

$$Btu = W_{w\text{-}cal}\,(T_f - T_i) + T_f\,(C_{Pagg} \times W_{agg} + C_{pw} \times W_{w\text{-}agg}) \tag{1}$$

in which

$W_{w\text{-}cal}$ = weight of water in calorimeter (lb);
W_{agg} = weight of dry aggregate (lb);
$W_{w\text{-}agg}$ = weight of moisture in aggregate (lb);
T_f = temperature, final of water in calorimeter (°F);

$$T_i = \text{temperature, initial of water in calorimeter } (^0\text{F});$$
$$C^i_{Pagg} = \text{specific heat of dry aggregate; and}$$
$$C_{Pw} = \text{specific heat of water (assume unity).}$$

Eq. 1 determines one point on each of the constant rate, first falling rate, and second falling rate period curves. One additional set of computations based on calorimeter test data at a different oven temperature determines the position of the CR, FFR, and SFR curves. These curves are shown in Figure 3.

Additional curves at different moisture contents for different aggregates (coarse and fine) are shown in Figures 4 and 5. The following examples will use the curves shown in Figure 4 for Marble Cliff limestone.

B. Computation of Temperature Gradient in Dryers

1. Prototype Dryer

(a) Moisture Method

Data:

Mix proportion	40 percent sand
	60 percent No. 46 stone
Moisture before	4.94 percent sand
	1.28 percent No. 46 stone
Moisture after	0.09 percent combination

Average exposure time in dryer for stone and sand = 3.7 min.

Drying curves for 60 percent saturated (1.28 percent) Marble Cliff limestone at 300, 400, and 550 F are obtained (see Fig. 4). Sample weight = 500 g.

Drying curves for sand with 4.94 percent moisture content at 400, 600, and 760 F can also be obtained. Sample weight = 500 g.

Temperature gradient by the moisture method is shown in the following steps:

Step 1. To find actual moisture removed in the average exposure time of 3.7 min.

Assuming a total batch weight of stone + sand = 500 g, stone = 0.6×500 = 300 g, and sand = 0.4×500 = 200 g, then initial moisture in stone $1.28/100 \times 300$ g = 3.84 g and initial moisture in sand $4.94/100 \times 200$ g = 9.88 g, with an initial total = 13.72 g. Final moisture (stone + sand) $0.09/100 \times 500$ g = 0.45 g, with moisture removed = 13.27 g.

Step 2. To find average dryer gas temperature.

Figure 11 shows the drying curves for the stone at temperatures 300, 400, and 550 F. Figure 12 shows the drying curves for the sand at temperatures 400, 600, and 760 F. Area under each curve gives moisture, in grams, removed per 500 g of aggregate. This area for each curve up to 3.7 min is given in Table 4.

These values are plotted into a graph (Fig. 13) of moisture removed against temperature. Values for sand for exposure time of 3.7 min (see Table 5) are also plotted in Figure 13.

TABLE 4

AREA UNDER CURVES IN FIGURES 11, 12, AND 13 FOR EXPOSURE TIME OF 3.7 MIN

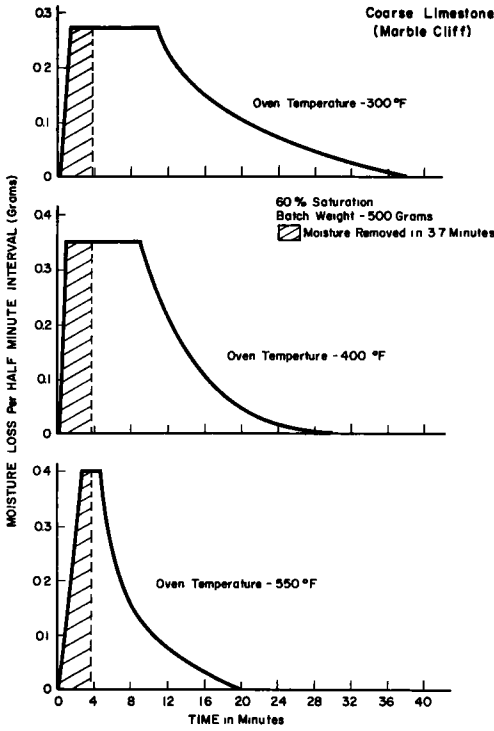| Temp. (°F)	Area			
	No. 46 Stone		Sand	
	Per 500 G	Per 300 G[a]	Per 500 G	Per 200 G[a]
300	1.548	0.93		
400	2.31	1.39	5.56	2.22
550	3.33	2.00		
600			23.22	9.29
760			32.86	13.14

[a]By proportion.

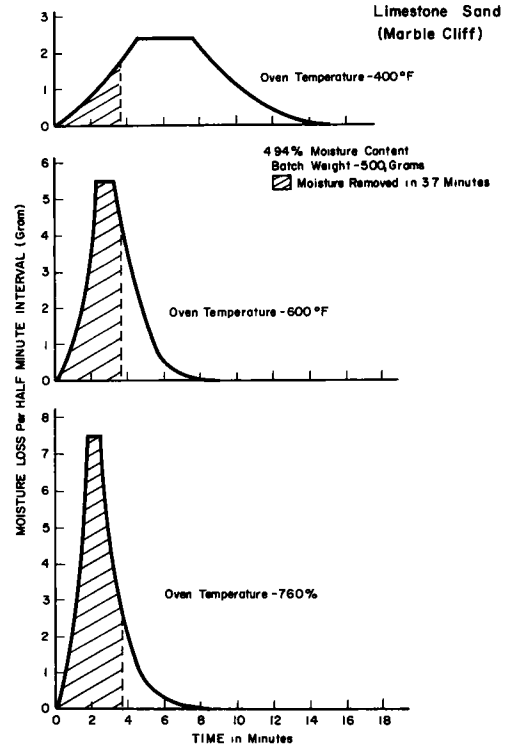Figure 11.   Coarse aggregate drying curves.
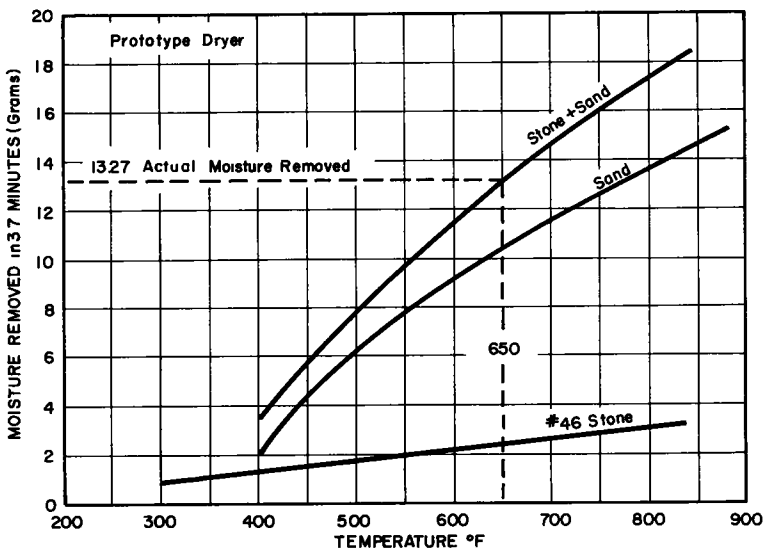

Figure 12.   Fine aggregate drying curves.

Figure 13.   Oven temperature vs moisture loss.

The preceding graphs are compounded to obtain the curve of total moisture removed (in 3.7 min. from 500 g of stone plus sand) against effective dryer gas temperature. On this curve, the temperature corresponding to 13.27 g (actual moisture removed) is 650 F. This is an estimate of the average dryer gas temperature.

Step 3. To find the point along dryer where average drum temperature exists.

This point can be assumed to be located by the use of the drum shell temperature gradient. A vertical line through this point divides the area under the gradient curve into two equal parts. In this example, the average drum temperature point will be assumed to exist at 0.67L. This point also determines the location of the average dryer gas temperature. The location of this point P with coordinates (0.67L, 650 F) on a plot of effective dryer gas temperature is shown in Figure 14. A line is extended both ways from P to the stack temperature (260 F). This line indicates the temperature gradient of the dryer gases.

(b) Dryer Zone—Heat Balance Method as Shown by Parr (7)

Data:

Fuel gas consumption per hour at atmospheric pressure and 60 F = 12.50 cu ft.

Heat value of fuel gas   = 1,200 Btu per cu ft at 60 F
Rate of feed of aggregate   = 85 lb per min
Initial moisture content   = 5.30 percent
Final moisture content   = 0.75 percent
Air flow through the dryer   = 1,245 cfm
Stack gas temperature   = 250 F
Ambient temperature   = 75 F

Assumption:

1 mol of fuel gas   = 379 cu ft at 60 F
1 mol of water   = 18 lb
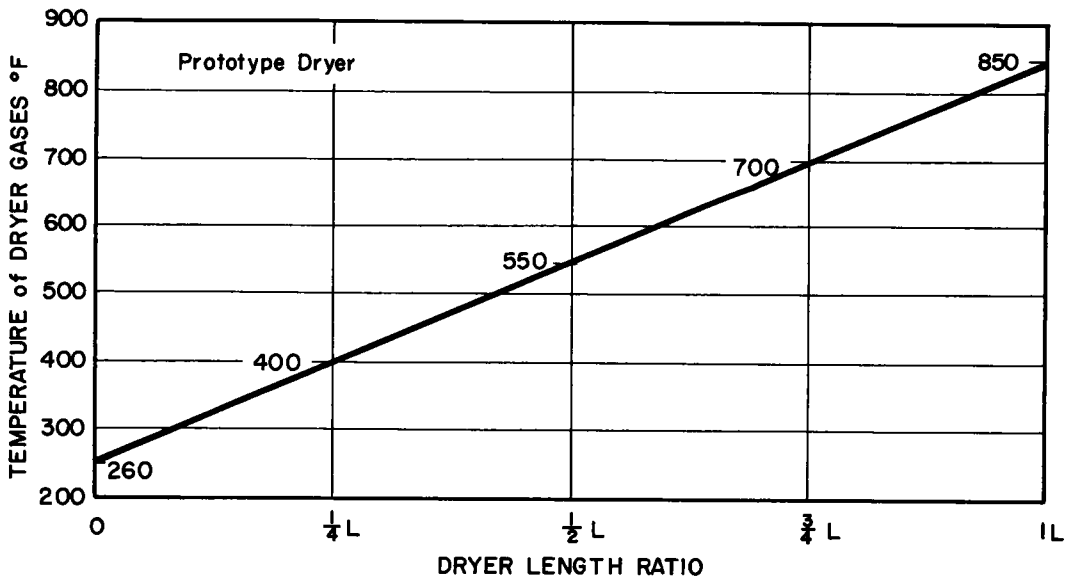1 mol of stack gas   = 359 cu ft at 32 F

Figure 14. Prototype dryer temperature vs dryer length ratio—moisture method.

For 1 mol of fuel gas:

   1.995 mol O_2 required for combustion
   1.022 mol CO_2 formed
   1.952 mol H_2O formed
   0.065 mol N_2 formed (from fuel gas)
   7.50 mol N_2 formed (from combustion air)

Specific heat of stack gas analysis:

   CO_2 = 9.7 Btu per mol per F
   H_2O = 8.1 Btu per mol per F
   O_2 = 7.2 Btu per mol per F
   N_2 = 7.0 Btu per mol per F
   Air   = 7.04 Btu per mol per F

The assumption for first trial that over-all aggregate temperature at discharge is 350 F is subject to correction, if necessary, after the temperatures of the coarse and fine aggregate are individually determined. The solution is as follows: Fuel gas burned per hour = 12.50 × 60 = 750 cu ft at 60 F = 750/379 = 1.97 mol.

For 1.97 mol of fuel gas per hr:

   1.97 × 1.995 =   3.93 mol O_2 required per hour for combustion.
   1.97 × 1.022 =   2.01 mol CO_2 formed per hour
   1.97 × 1.952 =   3.84 mol H_2O formed per hour
   1.97 × 0.065 =   0.13 mol N_2 formed per hour (from gas fuel)
   1.97 × 7.50   = 14.80 mol N_2 formed per hour (from combustion air)
                     20.78 mol combustion gases formed per hour

Aggregate discharged = 85 × 60 = 5,100 lb per hr; and water evaporated = (5.30 - 0.75)/100 × 5,100 = 232 lb per hr = 232/18; i.e., 12.9 mol per hr. Total computed stack gas = 20.78 + 12.9 = 33.7 mol per hr. Stack gas temp. = 250 F = 710 F Abs. and 1 mol of stack gas = 359 cu ft at 32 F = 519 cu ft at 250 F.

   Total computed stack gas volume = 519 × 33.7 = 17,460 cu ft per hr at
       250 F
   Actual stack gas volume = 1,245 × 60 = 74,700 cu ft per hr
   Excess air in stack gas = 74,700 - 17,460 = 57,240 cu ft per hr
   Actual air required for combustion = 14.80 + 3.93 = 18.73 mol per hr
                                     = 18.73 × 519   = 9,700 cu ft per hr
   Excess air percentage = 57,240/9,700 = 590 percent
   Stack gas analysis:

   CO_2 = 2.01 mol per hr
   H_2O = 12.9 + 3.84 = 16.74 mol per hr
   N_2 = 14.80 + 0.13 = 14.93 mol per hr
   Excess
      Air   = 57,240   =110.30 mol per hr
               ───────   ─────────────────
                 519   143.98 mol per hr

Total air in = 110.3 + 18.73 = 129.03 mol per hr at 75 F

Heat Balance (Datum = 60 F):

Heat in
   Heat in fuel = 750 × 12,000   = 900,000 Btu per hr
   Heat in aggregate = 5,100 × 0.2 × (75 - 60) = 15,300 Btu per hr
   Heat in moisture = 232 × 1.0 × (75 - 60)   =   3,485 Btu per hr
   Heat in air to dryer = 129.03 (7.04)(75 - 60) = 13,630 Btu per hr
              Total heat in   ─────────────────
                                                932,415 Btu per hr

Heat out
Heat in aggregate   = 5,100 × 0.2 × (350-60) = 296,000 Btu per hr
Heat in water   = 16.74 × 18 × (1,164-28) = 342,000 Btu per hr
Heat in CO_2 = 2.01 × 9.7 × (250-60) =   3,700 Btu per hr
Heat in N_2 = 14.93 × 7.0 × (250-60) = 19,850 Btu per hr
Heat in excess air = 110.3 × 7.04 × (250-60) = 147,300 Btu per hr
        Total heat out   808,850 Btu per hr

Heat loss = 932,415-808,850 = 123,565 Btu per hr or
                              125,000 Btu per hr

The dryer is divided into three zones to correspond approximately to the three stages in the drying cycle for constant rate, first falling rate and second falling rate periods. In this example 0 to ½ L, ½ L to ¾ L and ¾ L to L are suitably assumed as the three zones.

The heat loss of 125,000 Btu per hr at 25 percent in Zone I, 50 percent in Zone II, and 25 percent in Zone III is allocated. As Zone II aggregate temperature of 210 F is assumed. Aggregate feed = 5,100 lb per hr. Aggregate moisture = 232.0 lb per hr. Stack gas temperature = 250 F, over-all aggregate discharge temperature = 350 F, room temperature = 75 F. Stack gas = 143.98 mol per hr.

Zone I   Heat absorbed
            by aggregate = 5,100 × 0.2 × (210-75) = 137,500 Btu per hr
          Heat absorbed
            by moisture = 323 × 1 × (210-75)   = 31,300 Btu per hr
          Heat loss = ¼ (125,000)   = 31,250 Btu per hr
                                                      200,050 Btu per hr

          Heat balance for Zone I
            200,050 = 143.93 × (7.04) × Δ T
                 Δ T = 198 F
               Stack gas temperature = 250 F
                      ΔT = 198 F

       Temperature of dryer gases at interface of
            Zones I and II = 448 F

Zone II   Assume 80 percent moisture evaporation in Zone II
          Moisture evaporated = 0.80 × 232.0   =   186 lb per hr
          Total heat of saturated
            steam at 212 F, 14.7 psi   =   1,150 Btu per lb
          Total heat in water at 210 F   =   178 Btu per lb
            Heat absorbed in Zone II by moisture   =   972 Btu per lb
          Heat absorbed by moisture = 186 × 972   = 180,500 Btu per lb
          Heat loss = ½ (125,000)   = 62,500 Btu per lb
                                                      243,000 Btu per lb

          Heat balance for Zone II
            243,000 = 134 × (7.04) × Δ T
                 ΔT = 258 F

       Temperature of dryer gases at interface of Zones I and II = 448 F
                                                   ΔT = 258 F
       Temperature of dryer gases at interface of Zones II and III = 706 F

Zone III
          Moisture evaporated = 0.20 × 232.0   =   46 lb per hr
          Heat absorbed by moisture = 46 × 972   = 44,700 Btu per hr
          Heat absorbed by aggregate = 5,100 × 0.2 ×
            (350-210)   = 143,000 Btu per hr
          Heat loss = ¼ (125,000)   = 31,250 Btu per hr
                                                      218,950 Btu per hr

Heat balance for Zone III
$$218,950 = 131.5 \times (7.04) \times \Delta T$$
$$\Delta T = 236 \text{ F}$$

Temperature of dryer gases at interface of Zones II and III = 706 F

ΔT = 236 F

Temperature of dryer gases at burner   = 942 F

The temperature gradient is plotted for each zone interface temperature in Figure 15.

2. Dryer No. 2 at Marble Cliff Quarries Co. by Moisture Method

Data: Mix proportion

- 40 percent sand
- 40 percent No. 6 stone
- 15 percent No. 4 stone
- 5 percent asphalt

Moisture before

- 6.16 percent sand
- 1.81 percent No. 46 stone
- 0.18 percent combination

Average exposure time in dryer for stone and sand = 7.9 min.
Recorded drum temperature:

Stack end	= 175 F
1/8 L	= 175-200 F
1/4 L	= 175-200 F
3/8 L	= 175-200 F
1/2 L	= 200-225 F
5/8 L	= 250-275 F
3/4 L	= 400-450 F
7/8 L	= 550-600 F
Burner end	= 550-600 F

Drying curves for 60 and 100 percent saturated Marble Cliff limestone at 300, 400, and 550 F, are known (Fig. 4). Sample weight = 500 g. Drying curves for sand with 6.5 percent moisture content at 400, 600, and 760 F, are known. Sample weight = 500 g. The initial moisture content of stone (1.81 percent) was found to correspond to 80 percent saturation. Hence, data for 80 percent saturation are found by interpolation from known data of 60 and 100 percent saturations.

The solution is given by the following steps:

Step 1. To find actual moisture removed in the average exposure time of 7.9 min.

It is assumed that a total sample weight of stone + sand = 500 g. Stone = $55/95 \times 500$ = 290 g and sand = $40/95 \times 500$ = 210 g. Initial moisture in stone $1.81/100 \times 290$ = 5.25 g and initial moisture in sand $6.16/100 \times 210$ = 12.94 g. Therefore, total initial moisture = 18.19 g and total final moisture (stone and sand) = $0.18/100 \times 500$ = 0.90. Moisture removed = 17.29 g.

Step 2. To find average dryer gas temperature. Area under drying curve gives moisture, in grams, removed per 500 g of aggregate. This area, for the relevant curves up to 7.9 min, is given in Table 5.

The figures for moisture removed in 7.9 min for 290 g of stone and 210 g of sand are shown in Figure 16. The two plots are compounded to obtain curve for total moisture removed (from stone + sand). From this compounded curve the temperature corresponding to 17.29 g (actual moisture removed) is 590 F. This is assumed to be the average dryer gas temperature.

TABLE 5
AREA UNDER DRYING CURVE FOR EXPOSURE TIME OF 7.9 MIN

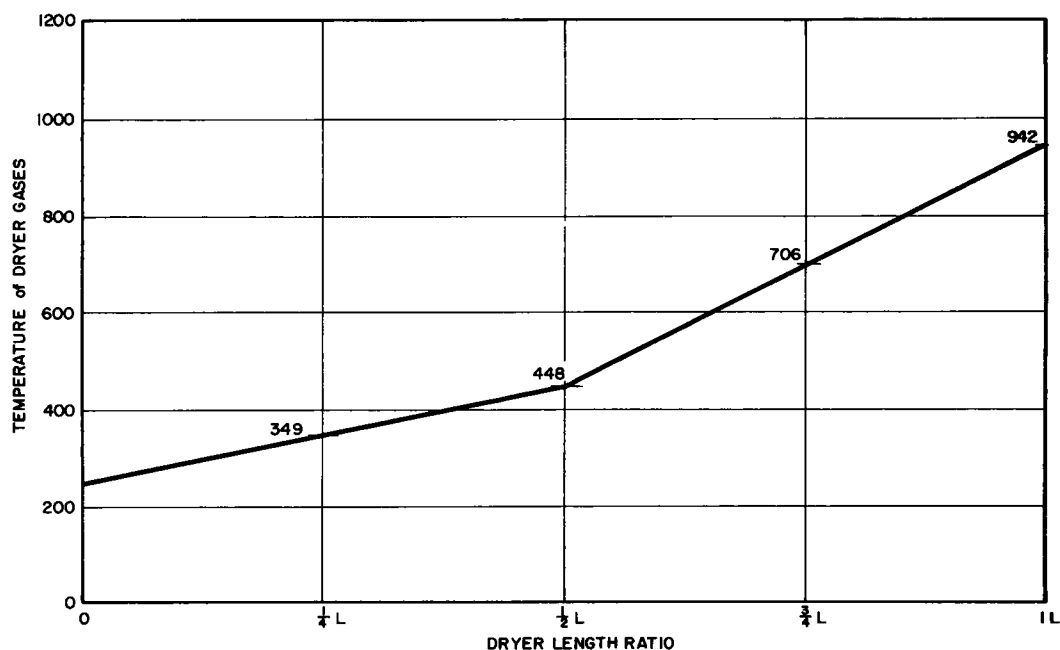| Temp. (°F)	Area						
	No. 46 Stone					Sand	
	Per 500 G		Per 290 G[a]			Per 500 G	Per 210 G[a]
	100% Sat.	60% Sat.	100% Sat.[a]	60% Sat.[a]	80% Sat.[b]		
300	4.030	3.988	2.34	2.32	2.33		
400	5.120	5.320	2.97	2.32	3.02	25.04	10.50
500	6.212	4.412	3.61	2.56	3.08		
600						34.14	14.30
760						38.78	16.30

[a] By proportion.
[b] By interpolation.

Figure 15. Prototype dryer temperature vs dryer length ratio—heat balance method.

Step 3. To find the point along dryer where average drum temperature exists.

The area under average drum shell temperature curve is found in Figure 17. This area is divided into two equal parts by a vertical line AB. This line is determined at 0.67 L for this case.

Step 4. Point C with coordinates (0.67 L, 590 F) is located in Figure 17. The stack temperature (200 F) is joined to 590 F. The line obtained represents the temperature gradient of the dryer gases.
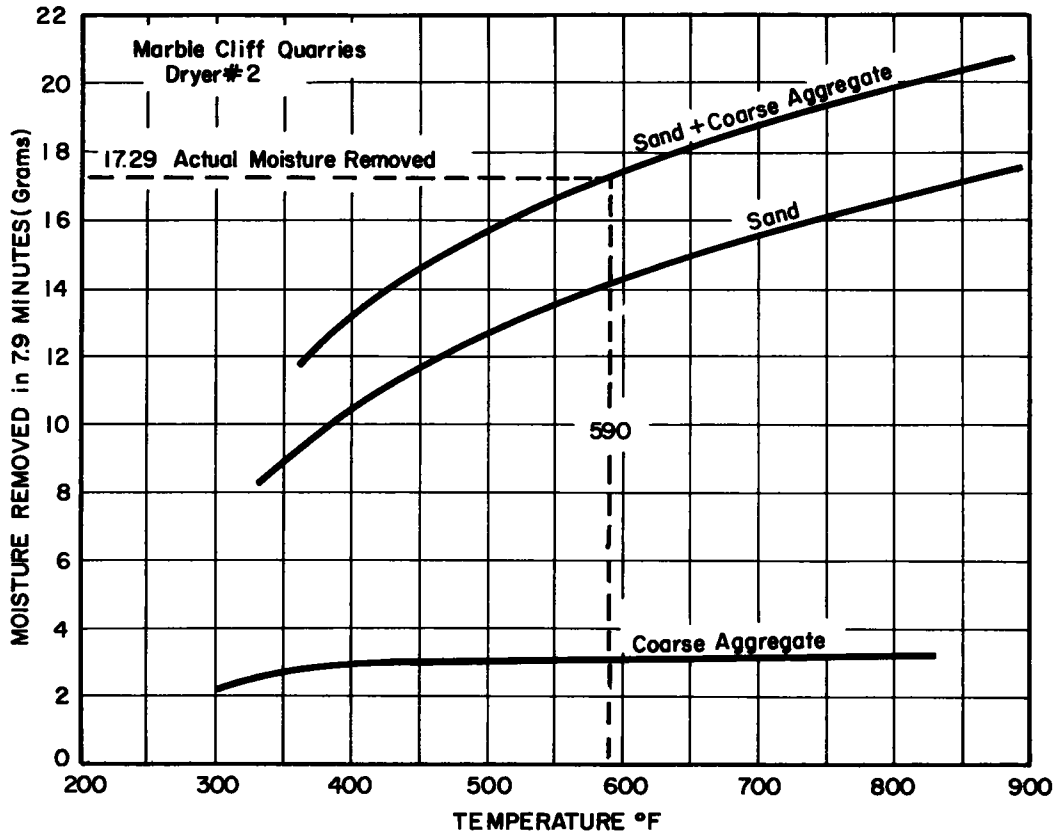
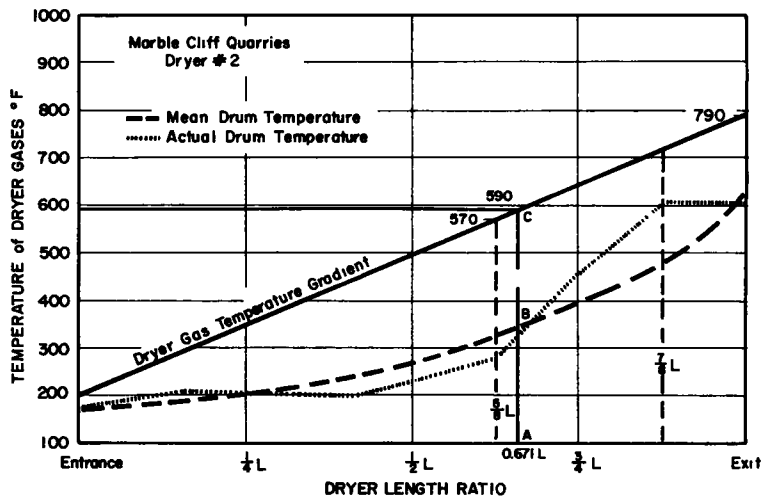Figure 16. Moisture removed vs oven temperature.

Figure 17. Dryer temperature vs dryer length ratio for Marble Cliff dryer 2.

C. Computation of Aggregate Temperature at Dryer Discharge

The computation of aggregate temperature at dryer discharge is given in Table 6. Temperatures of other sizes including sand may be computed in the same manner using oven heat absorption curves and dryer exposure times for each size. The same temperature gradient of dryer gases may be used for all other size temperature determinations.

The over-all temperature of the aggregate combination may be computed by the following relation when specific heat values of each size group are nearly equal:

$$\frac{P_1T_1 + P_2T_2 + P_3T_3 + \ldots\ldots\ldots\ldots +P_nT_n}{100}$$

TABLE 6
COMPUTATION OF AGGREGATE TEMPERATURE
AT DRYER DISCHARGE

Property	Prototype Dryer		Dryer No. 2[c] Marble Cliff Quarries
	Method A[a]	Method B[b]	
Spec. heat	0.200	0.200	0.246
Avg. expos. time (min)	3.70	3.70	7.9
Oven sample wt. (lb)	2.0	2.0	2.0
Drying cycle (L):			
Constant rate	0 to $\frac{2}{4}$	0 to $\frac{2}{4}$	0 to $\frac{5}{8}$
1st falling rate	$\frac{2}{4}$ to $\frac{3}{4}$	$\frac{2}{4}$ to $\frac{3}{4}$	$\frac{5}{8}$ to $\frac{7}{8}$
2nd falling rate	$\frac{3}{4}$ to $\frac{4}{4}$	$\frac{3}{4}$ to $\frac{4}{4}$	$\frac{7}{8}$ to $\frac{8}{8}$
Drying cycle time (min):			
Constant rate	$\frac{1}{2} \times 3.70 = 1.85$	$\frac{1}{2} \times 3.70 = 1.85$	$\frac{5}{8} \times 7.9 = 4.94$
1st falling rate	$\frac{1}{4} \times 3.70 = 0.92$	$\frac{1}{4} \times 3.70 = 0.92$	$(\frac{7}{8} - \frac{5}{8}) \times 7.9 = 1.97$
2nd falling rate	$\frac{1}{4} \times 3.70 = 0.92$	$\frac{1}{4} \times 3.70 = 0.92$	$(\frac{8}{8} - \frac{7}{8}) \times 7.9 = 0.98$
Avg. effec. gas temp. (°F):			
Constant rate	400	349	$200 + \frac{370}{2} = 385$
1st falling rate	625	577	$570 + \frac{130}{2} = 635$
2nd falling rate	775	824	$700 + \frac{90}{2} = 745$
Heat absorp. rate (Btu/min):			
Constant rate	25	21	16.5
1st falling rate	21	16	20.5
2nd falling rate	39	51	29.0
Total heat absorp. (Btu):			
Constant rate	1.85 × 25.0 = 46.2	1.85 × 21.0 = 38.9	4.94 × 16.5 = 81.7
1st falling rate	0.92 × 21.0 = 19.4	0.92 × 16.0 = 14.7	1.97 × 20.5 = 40.4
2nd falling rate	0.92 × 39.0 = 36.0	0.92 × 51.0 = 46.4	0.98 × 29.0 = 28.5
Total	101.6	100.5	150.6
Total temp. rise[d] (°F)	$\frac{101.6}{2.0 \times 0.2} = 255$	$\frac{100.5}{2.0 \times 0.2} = 253$	$\frac{150.6}{2.0 \times 0.246} = 306$
Temp. meas. by calorimeter	250 to 276	250 to 276	301 to 320

[a]Based on temperature gradient obtained by moisture method.
[b]Based on temperature gradient obtained by heat balance method.
[c]Based on effective gas temperature gradient obtained by moisture method.
[d]ΔT, above 0 F.

in which

P_j = percent by weight of aggregate size group in gradation, and
T^j_j = temperature of aggregate size group in gradation.

D. Computation of Aggregate Moisture at Dryer Discharge

1. Dryer No. 2 at Marble Cliff Quarry Co. — The computation of aggregate moisture at dryer discharge is based on effective gas temperature gradient plot in Figure 8 and dryer data from Tables 5 and 6.

For aggregate exposure time of 7.9 min and stone temperature of 306 F, required temperature gradient (by interpolation) is 5.9, or 590 F (ΔT from 200 F stack). Temperature gradient is therefore 200 F at stack and 790 F at burner. A straightline gradient over dryer length is assumed (see Figure 17). Using these data, the average dryer temperature is found from steps 3 and 4 in section B2 to be 590 F.

The procedure now is the reverse as shown in section B2. Drying curve plots (from lab oven tests) are used to develop the curves in Figure 16 by step 2, section B2. The average dryer temperature of 590 F is used in Figure 16 to find the moisture removed in the stone (coarse aggregate), sand or stone and sand combination by known initial moisture contents and blend proportions.

Figure 16 and step 1, section B2, show the check of 17.29 g of moisture removed per 500 g of aggregate (stone and sand), or 3.5 percent.

REFERENCES

1. Baker, R. F., and Lottman, R. P., "Practical Implications of the Theory for Heating and Drying of Aggregates." Proc., AAPT (Jan. 1960).
2. Lovejoy, D. R., "Investigation of Burner Operation in an Asphalt Plant Dryer." Report CE 15-2, Transportation Engineering Center, Ohio State Univ. (Nov. 1960).
3. Middleton, L. M., "Investigation of Temperature Variation in Prepared Aggregates as Asphalt Plants." Report CE 15-4, Transportation Engineering Center, Ohio State Univ. (Nov. 1960).
4. Uehling, G. E., "Several Dryer Operational Effects Upon Aggregate Preparation." Report CE 15-3, Transportation Engineering Center, Ohio State Univ. (Nov. 1960).
5. Smeins, V. G., "Investigation of the Effect of Changes in Aggregate Characteristics on the Dryer Discharge." Report CE 15-5, Transportation Engineering Center, Ohio State Univ. (Nov. 1960).
6. Deming, H. R., "Implications of the Drying Cycle as Concerned with Aggregate Preparations for Bituminous Mixes." Report CE 15-1, Transportation Engineering Center, Ohio State Univ. (Nov. 1960).
7. Parr, W. K., "The Drying and Heating of Aggregates, Basic Theory and Practical Application." Canad. Tech. Asphalt Assoc., Montreal (Nov. 1960).
8. Fischmann and Pagen, "Drying of Bituminous Concrete Aggregates." Bull. 173, Engineering Experiment Station, Ohio State Univ. (Jan. 1959).
9. Lottman, R. P., "Aggregate Heating and Drying Variations in Asphalt Plants." Proc., AAPT (Jan. 1961).
10. Cox, K. L., "Investigation of Residence Time in the Prototype Aggregate Dryer." Engineering Experiment Station, Ohio State Univ. (Dec. 1959).
11. Plummer, D. D., "Investigation of Temperature Conditions of Bituminous Concrete Aggregate." Engineering Experiment Station, Ohio State Univ. (Dec. 1959).
12. Lewis, R. D., "Investigation of the Drying Characteristics of Bituminous Concrete Aggregate." Engineering Experiment Station, Ohio State Univ. (Dec. 1959).
13. Lonsberry, D. O., "Investigation of Moisture Loss for Bituminous Concrete Aggregates after Interruption of the Drying Process." Engineering Experiment Station, Ohio State Univ. (Dec. 1959).

14. Lara-Tomas, M., "Statistical Methods Used in the Investigation of Aggregate Drying Characteristics." M.Sc. thesis, Ohio State Univ. (1958).
15. Bryant, J.W., "A Study of a Prototype Dryer." M.Sc. thesis, Ohio State Univ. (1958).
16. Flinn, M.L., "A Study of the Drying of Aggregates for Bituminous Concrete." M.Sc. thesis, Ohio State Univ. (1955).