TABLE I SUCCESSIVE CRUSHING OF −½"+3/8" DOLOMITE.

SIEVE SIZES	% BY WEIGHT	CUM.% RET.	% BY WEIGHT	CUM.% RET.	% BY WEIGHT	CUM.% RET.	% BY WEIGHT	CUM.% RET.
	1.		2.		3.		4.	
3/8"	66.2	66.2	46.1	46.1	37.5	37.5	29.2	29.2
No.4	22.0	88.2	28.5	74.7	28.9	66.4	29.7	58.9
No.10	8.1	96.3	15.4	90.1	18.6	85.0	21.1	80.0
U.S.40	2.5	98.8	6.8	96.9	10.3	95.3	12.8	92.8
No.100	0.5	99.3	1.1	98.0	1.7	97.0	2.5	95.3
PAN.	0.7	448.8	2.0	405.8	3.0	381.2	4.7	356.2
	100.0		100.0		100.0	100.0	100.0	
CRUSHING RATIO =	$\frac{448.8}{500.0}$	=0.898	$\frac{405.8}{448.8}$	= 0.905	$\frac{381.2}{405.8}$	=0.938	$\frac{356.2}{381.2}$	=0.935
	5.		6.		7.		8.	
3/8"	24.5	24.5	17.8	17.8	15.3	15.3	12.4	12.4
No.4	28.5	53.0	29.8	47.6	28.3	43.6	27.0	39.[illegible]
No.10	22.5	75.5	23.5	71.1	24.1	67.7	24.7	64.1
U.S.40	15.1	90.6	17.5	88.6	18.6	86.3	20.5	84.6
No.100	3.2	93.8	3.8	92.4	4.7	91.0	5.1	89.7
PAN.	6.2	337.4	7.6	317.5	9.0	303.9	10.3	290.2
	100.0		100.0		100.0		100.0	
CRUSHING RATIO	$\frac{337.4}{356.2}$	=0.948	$\frac{317.5}{337.4}$	= 0.942	$\frac{303.9}{317.5}$	=0.957	$\frac{290.2}{303.9}$	= 0.956
	9.		10.		11.		12.	
3/8"	8.8	8.8	8.9	8.9	8.9	8.9	6.3	6.3
No.4	26.4	35.2	24.1	33.0	22.2	31.1	22.0	28.3
No.10	26.3	61.5	25.9	58.9	26.0	57.1	26.4	54.7
U.S. 40	21.3	82.8	22.2	81.1	23.3	80.4	24.1	78.8
No.100	5.6	88.4	6.1	87.2	6.1	86.5	6.9	85.7
PAN.	11.6	276.7	12.8	269.1	13.5	264.0	14.3	253.8
	100.0		100.0		100.0		100.0	
CRUSHING RATIO	= $\frac{276.7}{290.2}$	=0.955	$\frac{269.1}{276.7}$	=0.972	$\frac{264.0}{269.1}$	=0.983	$\frac{253.8}{264.0}$	=0.962
	13.		14.		15.		16.	
3/8"	5.2	5.2	5.2	5.2	3.9	3.9	3.3	3.3
No.4	20.0	25.2	19.0	24.2	19.5	23.4	18.6	21.9
No.10	27.4	52.6	26.4	50.6	25.1	48.5	24.9	46.8
U.S.40	24.8	77.4	25.4	76.0	26.5	75.0	27.3	74.1
No.100	7.0	84.4	7.2	8[illegible].2	7.5	82.5	7.5	81.6
PAN.	15.6	244.8	16.8	239.2	17.5	233.3	18.4	227.7
	100.0		100.0		100.0		100.0	
CRUSHING RATIO	= $\frac{244.8}{253.8}$	=0.965	$\frac{239.2}{244.8}$	=0.976	$\frac{233.3}{239.2}$	=0.976	$\frac{227.7}{233.3}$	= 0.976

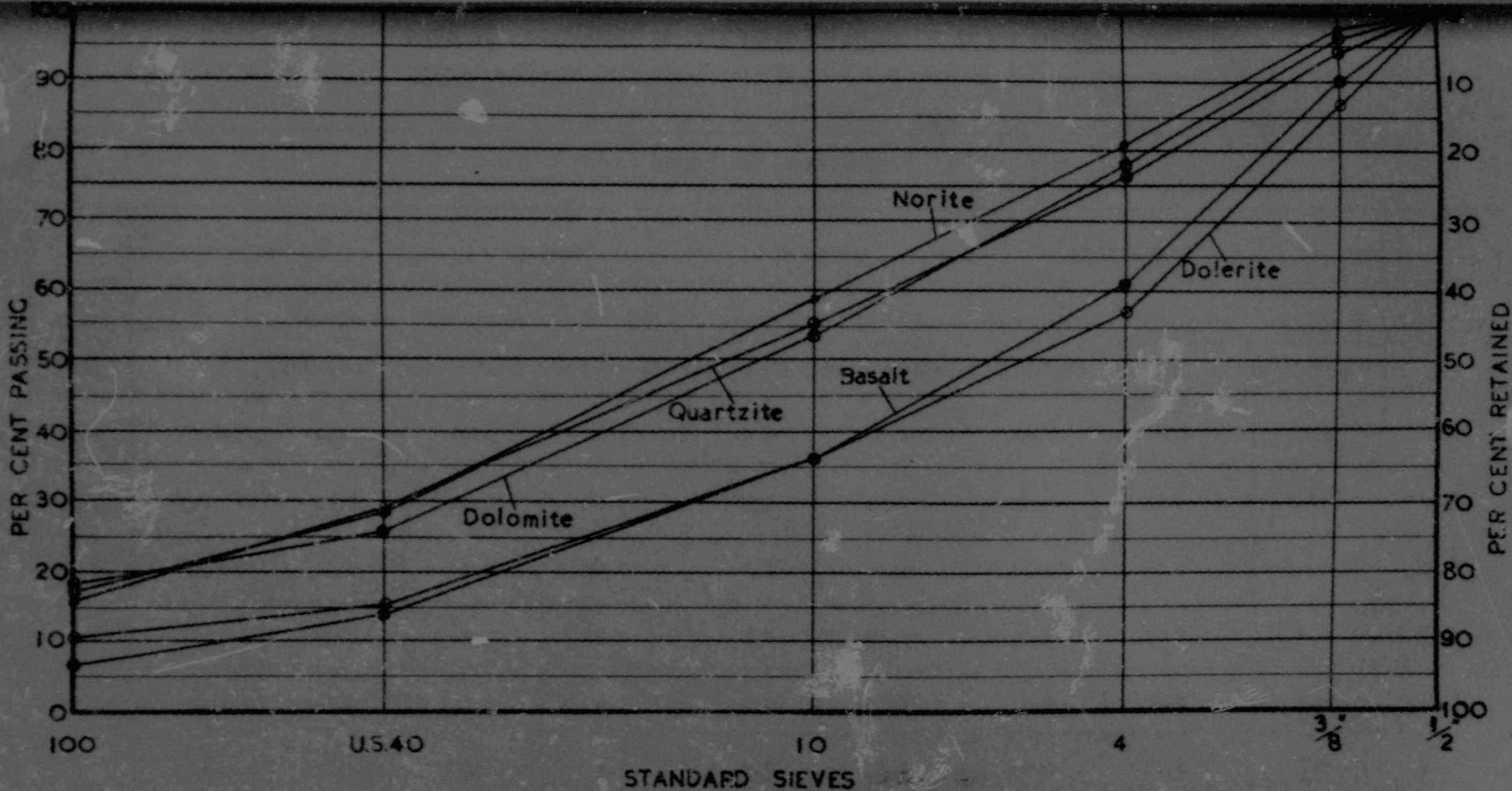

FIGURE 2. Final Gradings after 16 Cycles of Degradation.

TABLE II COMPARISON OF FIVE TYPES OF AGGREGATE IN THE CRUSHING TEST.

(NOTE: For sake of brevity only the 1st and 16th cycles are shown here)

	TYPE OF AGGREGATE									
	DOLERITE		BASALT		DOLOMITE		QUARTZITE		NORITE	
SIEVE	1st Cycle	16th Cycle	1st Cycle	16th Cycle	1st Cycle	16th Cycle	1st Cycle	16th Cycle	1st Cycle	16th Cycle
SIZE	(The quantities given below have been calculated as percentages by weight retained on the sieves).									
3/8"	85.8	13.2	70.1	10.1	66.2	3.3	59.9	6.0	37.6	2.4
No.4	10.0	29.5	22.3	28.7	22.0	18.6	19.8	17.6	34.6	17.1
No.10	2.8	21.6	4.8	24.6	8.1	24.9	11.1	20.9	13.9	21.3
U.S.40	1.0	20.0	2.0	23.0	2.5	27.3	5.6	26.7	9.2	30.1
No.100	0.1	5.3	0.4	6.7	0.5	7.5	1.6	12.2	2.4	12.7
Pan.	0.3	10.4	0.4	6.9	0.7	18.4	2.0	16.6	2.3	16.4
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

in size than the dolomite, norite, and quartzite.

(b) Gradings which fall close to those represented in figure 2 will probably show relatively good resistance to break-down in practice.

(c) From the point of view of breakdown, denser gradings, necessitating less rolling, should be selected in preference to obtaining the ultimate grading by degradation under rolling and traffic.

(d) The final gradings are only slightly different from the dense gradings suggested by Fuller (49) and Hveem (78).

The Effect of the Shape of Stone.

The effect of shape on the crushing of stone has been emphasised by Cimato (27.b) and by the Swedish Road Institute (159.a). Shelburne (144), however, neglected the effect. The work by Walker (178) indicates that flat and elongated particles in small amount do not affect the strength of concrete deleteriously. Research carried out by Gilkey (173.a) disproves this idea.

Markwick (105) defines "shape" as the extent to which a particle may be said to be flaky or elongated. Heywood (65) explains certain definitions pertaining to stone shapes.

Reasoning from first principles shows that a cubical stone has a larger moment of inertia and consequently possesses a greater beam strength than a flaky stone of similar length falling in the same sieve denomination.

Table III and figure 3 show the results of successive crushing on 200 gm. quantities of norite having different shapes, from which it is apparent that

(i) Elongated norite is superior in resistance to breakdown, which is easily explained by the following fact: two cubical stones placed end to end longitudinally would, if the contact faces were perfectly smooth, represent an elongated stone in the same sieve denomination. Two flaky stones placed upon each other would, in the same way, represent the shape of a cubical stone. An elongated stone, though, is

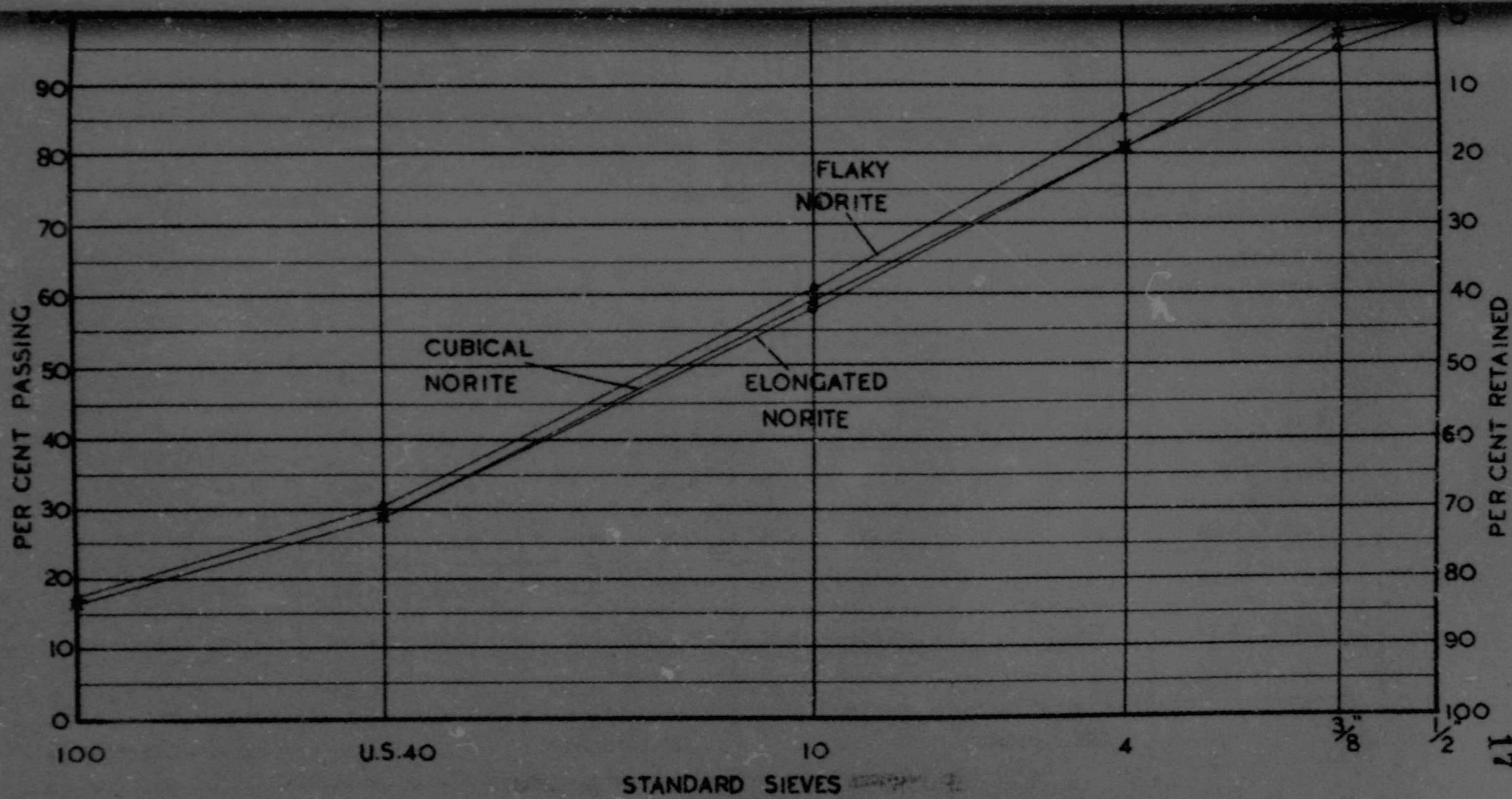

FIGURE 3. Effect of Shape of Stone on Final Grading after 16 Cycles of Degradation.

TABLE III GRADING ANALYSES OF DIFFERENT SHAPES OF NORITE IN THE CRUSHING TEST.

NOTE: For sake of brevity only the 1st and 16th cycles are given.

	ORIGINAL SHAPE OF AGGREGATE											
	CUBICAL				ELONGATED				FLAKY			
	1st Cycle		16th Cycle		1st Cycle		16th Cycle		1st Cycle		16th Cycle	
SIEVE	% By	Cum. %	% By	Cum. %	% By	Cum. %	% By	Cum.%	% By	Cum. %	% By	Cum. %
SIZE	Wt.	Ret.	Wt.	Ret.	Wt.	Ret.	Wt.	Ret.	Wt.	Ret.	Wt.	Ret.
3/8"	37.6	37.6	2.4	2.4	40.3	40.3	5.1	5.1	12.0	12.0	0.0	0.0
No. 4	34.6	72.2	17.1	19.5	33.6	73.9	14.3	19.4	46.7	58.7	14.5	14.5
No.10	13.9	86.1	21.3	40.8	13.6	87.5	22.1	41.5	24.0	82.7	25.3	39.8
U.S.40	9.2	95.3	30.1	70.9	8.6	96.1	29.6	71.1	12.1	94.8	29.3	69.1
No. 100	2.4	97.7	12.7	83.6	2.0	98.1	12.0	83.1	2.8	97.6	13.7	82.8
Pan.	2.3	388.9	16.4	100.0	1.9	395.9	16.9	100.0	2.4	345.8	17.2	100.0
	100.0		100.0		100.0		100.0		100.0		100.0	
	"Ratio"=0.778				"Ratio"=0.792				"Ratio"=0.692			

superior to a cubical one only if its length does not approach that of a lath, in which case it would be less resistant to break-down than a cubical stone of similar sieve denomination.

(ii) The amounts of fine material are remarkably constant, particularly after one cycle of crushing, proving that the differences in proportions occur not so much in the fine material formed from attrition as in the larger fragments created by fracture.

Conclusions:-

(a) Cubical stone is more resistant to comminution than flaky material of the same size and should be used in preference to the latter.

(b) Although elongated stone is often more resistant to fracture than cubical stone, the latter should preferably be used in practice, since it allows for better packing and stability.

The Effect of Grading on the Resistance to Crushing.

Figure 4 represents the crushing ratios of the gradings used previously in the successive crushing tests of cubical stone. The "D" values which are plotted as abscissae are found from the denominator of the crushing ratio formula, i.e.

"D" Value = The sum of the cumulative percentages retained on each of the sieves before crushing.

Conclusions:-

(a) For uniformly-sized stone, -½in. + 3/8 in. in size, with a "D" value of 800, the change in D value is relatively large for all the aggregates. This indicates that open gradings possess a relatively low resistance to breakdown.

(b) "D" values are ultimately reached, in the region of 300, where the changes in "D" value become small, i.e. little crushing takes place. Gradings in this region represent dense gradings in which the areas of contact of the constituent particles are large, giving rise to adequate distribution of superimposed forces.

(c) The slopes of the lines, and particularly their

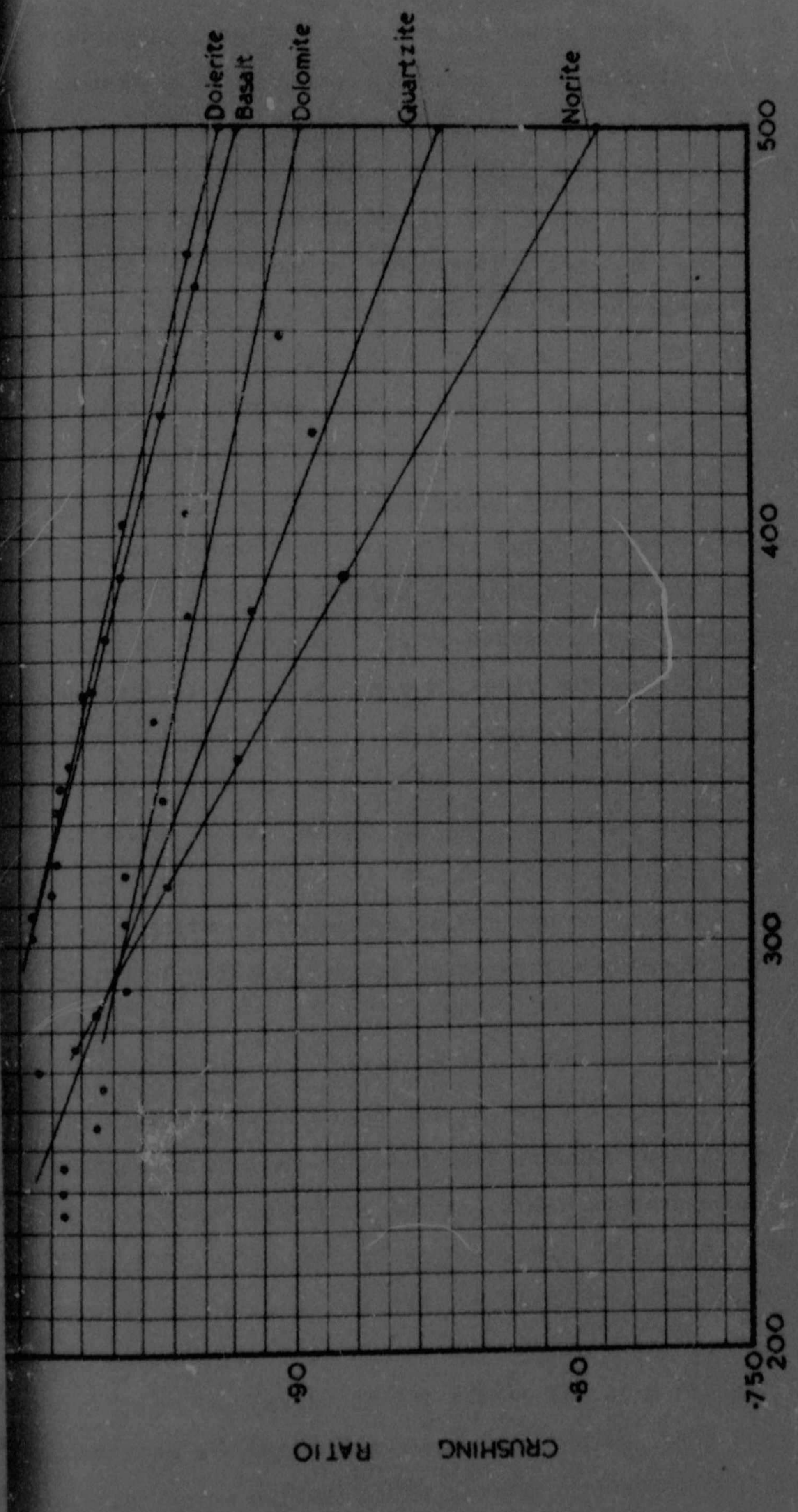

FIGURE 4. Effect of "D" Value on Crushing Resistance.

positions, give an indication of the susceptibility of the aggregates to crushing. Norite, for instance, is much more sensitive to crushing than basalt. (The dolomite line could perhaps have been drawn more steeply if more weight had been given to the points on the left.)

(d) The dolerite and basalt lines lie relatively close to each other, indicating that they possess crushing susceptibilities of the same order of magnitude. The other three aggregates, however, differ fairly considerably in their resistances to crushing.

The Effect of a Variable Crushing Force.

The argument as to whether light or heavy rollers should be used for the compaction of surface-treatment aggregates has long been pursued. Firm, dense surfaces can more easily be obtained by using heavy rollers, but are only achieved by incurring more crushing of the aggregate. Many road carpets are densified only after long passage of traffic which fractures the protruding stones and forces the binder through their interstices.

A series of experiments was run to show how the degradation of uniformly-sized stone varies with variable crushing force.

Quantities of sorted -½ in. + 3/8 in. cubical stones of the five aggregates used before, were weighed into 200 gm. batches in mixing bowls and were crushed (according to the crushing test described before) under pressures of 330, 660, 1750, 2700, 3500, 5200, and 7000 lb. per sq. in. The crushed material was sieved, weighed, and the crushing ratios calculated. Figure 5 represents the results.

(i) The shapes of the curves are significant. For small loads the slopes of the curves are gentle, then they become steeper and eventually flatten again. Beyond 6000 lb. per sq. in. the gradings are already so dense that an increase in load effects but a small increase in crushing. Table IV gives

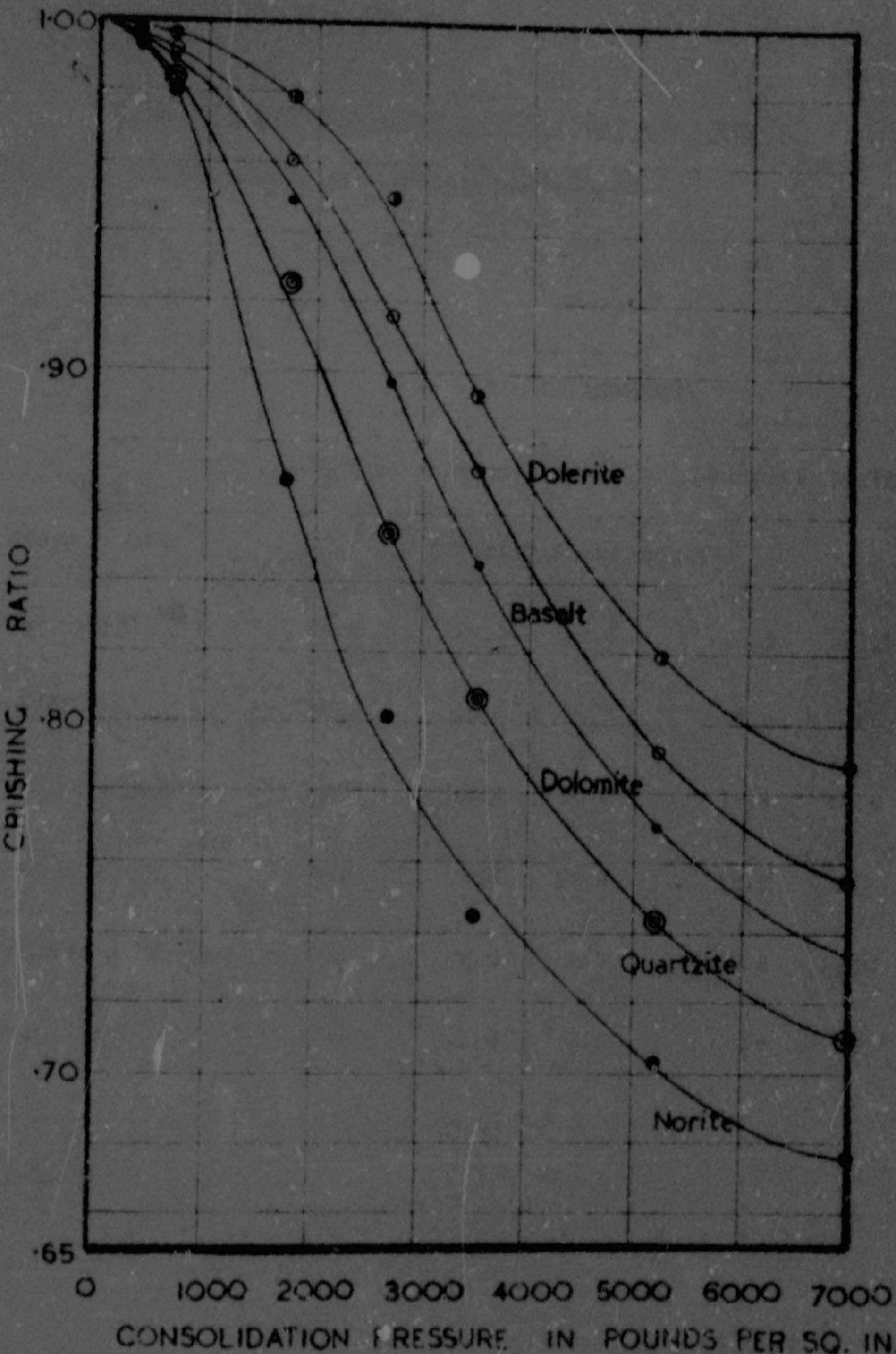

FIGURE 5. Variation of Break-down with Load.

TABLE IV GRADINGS OF -½" + 3/8" AGGREGATE AFTER BEING CRUSHED AT 7,000 LB. PER SQ.IN.

	TYPE OF AGGREGATE				
	Dolerite	Basalt	Dolomite	Quartzite	Norite
Sieve Fractions	Percentages by weight				
-½" + 3/8"	39.2	27.6	24.6	28.1	24.5
-3/8" + No. 4	33.0	40.5	41.3	32.0	31.0
-No. 4 + No.10	16.7	18.4	18.6	18.5	18.2
-No.10 + U.S.40	7.2	9.7	10.3	13.0	16.4
-U.S.40 + No.100	1.4	2.0	2.7	3.8	4.8
- No. 100	2.5	1.8	2.5	4.6	5.1

the gradings represented by the final points on the curves.

(ii) The five types of aggregate may be arranged as dolerite, basalt, dolomite, quartzite, and norite, in order of increasing crushing susceptibilities.

THE CRUSHING CHARACTERISTICS OF MIXTURES, OF ANGULAR AND FLAKY PARTICLES.

It is necessary to know to what extent the crushing resistance of a batch of aggregate is affected by the presence of flakes.

To ascertain this, batches of $-\frac{1}{2}$ in. + 3/8 in. aggregate, weighing 200 gm. and containing 0, 10, 20 .... 100 per cent flakes and 100, 90, 80 ..... 0 per cent cubical particles, respectively, were crushed in the writer's test at 2500 lb. per sq. in. and the crushed material sieved and weighed.

Figure 6 and table V show the results of this test.

Conclusions:-

(a) The positions of the curves are indicative of the crushing susceptibilities of the aggregates. Norite is the most sensitive, then quartzite, dolomite, and basalt and dolerite, respectively.

(b) The relative steepness of the curves shows that flakes greatly affect the structural strength of a batch of stone.

(c) From the point of view of resistance to degradation, 100 per cent cubical (angular) norite, for instance, is superior in quality to 100 per cent basalt or dolerite of the same sieve denomination, although the latter rocks are far superior in strength to the norite. This is conclusive evidence that the use of the correct type of aggregate may be negated by the use of flaky instead of cubical particles.

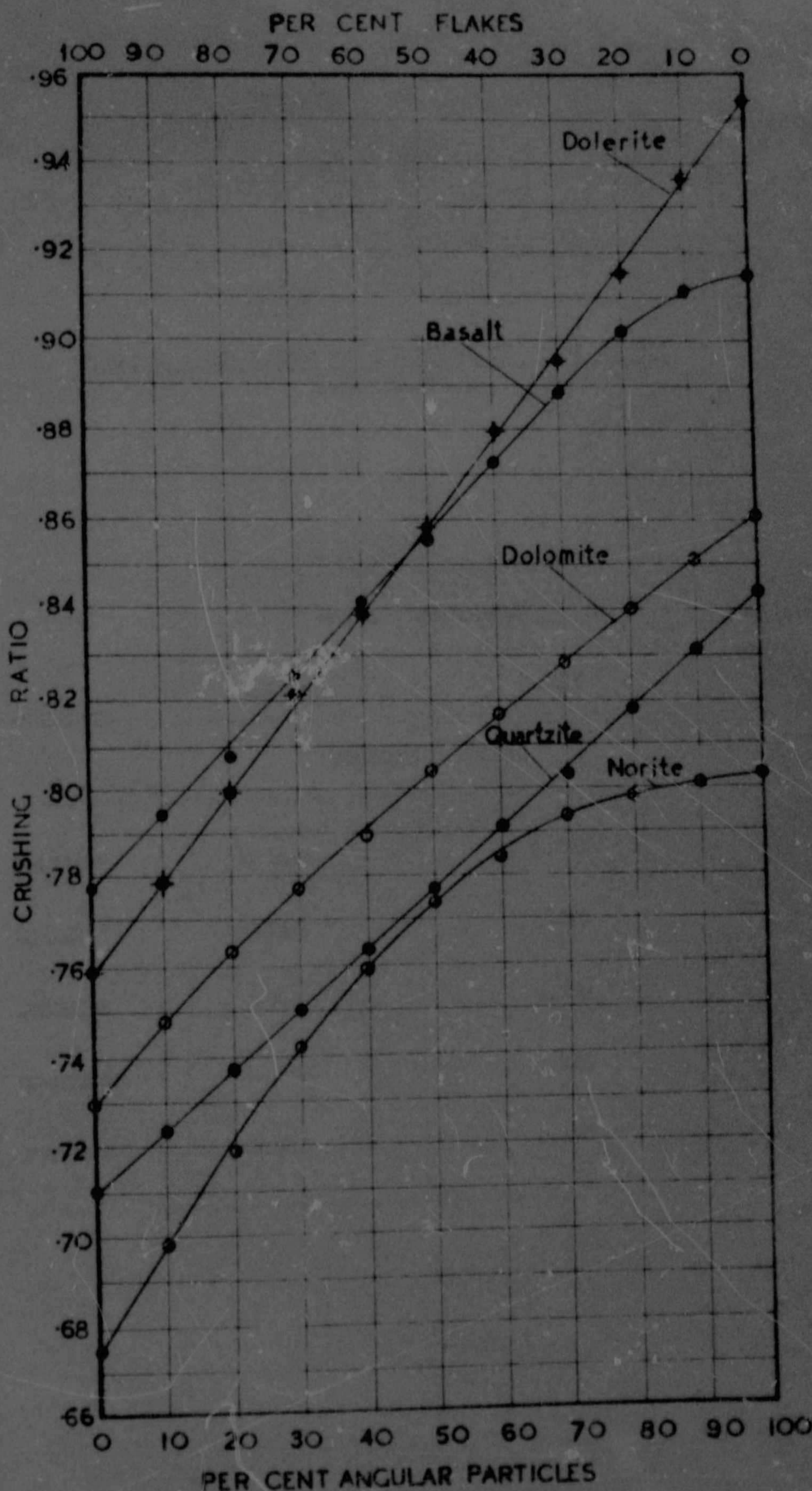

FIGURE 6. Comminution Curves of Mixtures with various proportions of Angular & Flaky Particles.

TABLE V THE EFFECT OF THE SHAPE OF STONE ON THE CRUSHING RATIO.

TYPE OF AGGREGATE	SHAPE OF STONE	
	ANGULAR	FLAKY
	CRUSHING RATIO.	
DOLERITE	0.954	0.759
BASALT	0.915	0.778
DOLOMITE	0.861	0.730
QUARTZITE	0.844	0.710
NORITE	0.803	0.675

CHAPTER IV.

THE COMMINUTION CHARACTERISTICS OF MINERAL AGGREGATES IN BITUMINOUS MIXTURES.

Accurate design of the aggregate sizes in a binder-aggregate system according to meticulously-prepared grading curves is often frustrated by the breakdown of the aggregate during the compaction of the mixture. Whilst it is impossible to establish a relationship between the grading of an aggregate before and after compaction which will be of universal application, the nature of the comminution process may be predicted if the effects of the salient factors involved be studied.

Review of the Literature.

A study of the Literature reveals that it includes but scant quantitative data on this subject. Macnaughton (103) points out that in service the particles in a mixture are rearranged and pressed closer together, with consequent grinding-off of corners, increase in fine material, decrease in voids, and possible development of instability owing to excess of binder. The writer considers that the proportion of binder should be so adjusted that the voids existing in a mixture during construction are filled only after a relatively long period, although special conditions may require a higher proportion of binder.

The present researches necessitate an investigation of the question whether road binders act as lubricants, i.e. facilitate compression. Kohler (88.a) believes that road tars do not exert a real lubricating action in the sense of reducing the friction, and that compression actually takes place more slowly than in the dry mineral mass. It appears that Kohler performed his experiments at 25°C. and for this temperature his statement may be valid. It is believed, however, that lubrication occurs at more elevated temperatures. In this connection Goldbeck (58) reports that pavements compress more in hot than in cold weather.

The statement,

"......... a bituminous coating (RC - 3) afforded
.... protection against degradation of aggregates,"

has been made by Shelburne (147) without reference to temperature conditions which obviously affect the issue. It is doubtful whether the asphalt cut-back used by Shelburne in his field experiments was sufficiently viscous to exert a protective influence on the aggregates which he compacted. unless an increase occurred in the viscosity of the binder during the premix process.

Bartholomaei (16.b) also states that with a binder present the particle disintegration is less than with uncoated aggregates, but he fails to make specific mention of the effect of the viscosity of the binder on the compression process.

With due respect to the views of the workers mentioned above, but with no definite information on the subject, the writer began the investigation of the problem stated below.

Does a bituminous binder provide a cushioning action in a compressible mineral mass?

To answer this question, work was done

(1) at constant temperature, with

(a) the size, and (b) the type of stone as variables, and

(2) at variable temperatures, to investigate the change in mechanical analysis of mineral aggregates at all the temperatures likely to exist on the road.

(1) THE COMMINUTION CHARACTERISTICS OF BITUMINOUS MIXTURES AT CONSTANT TEMPERATURE.

Choice of a Grading.

An open mixture, consisting of uniformly-sized particles, seemed most suitable since

(a) the comminution in open mixtures compared with that in dense mixtures is more extensive, and

(b) the tests on open mixtures are truly comparative from the point of view of uniformity: the presence of fines would interfere with the homogeneity of the mixtures.

<u>Choice of a Test Temperature.</u>

The temperature used was 55°C., because

(i) it was above the softening point temperature of the bituminous binder used and would therefore probably give rise to lubrication if lubrication was possible, and

(ii) the viscosity of the binder employed was of the same order of fluidity at 55°C as that of bituminous cut-backs under service conditions.

<u>Size of Stone as Variable.</u>

Experiments were carried out on the fracture of -½ in. + 3/8 in., -3/8 in. + No. 4, and -No. 4 + No. 10 fractions. In order to reduce the variables to a minimum, dolomite was selected for these tests.

Firstly, cubical chips, -½ in. + 3/8 in. in size, were used. A straight-run bitumen of 200 decimillimetres penetration was employed as a binder. The bitumen-aggregate mixtures were prepared by weighing 200 gms. of the aggregate into a mixing bowl with 0.25 per cent bitumen by weight. (Allowance was made for the binder remaining in the dish and for that adhering to the spoon and stirrer at the end of the test by adding extra bitumen of a predetermined amount.) The mixture was heated on a hot plate to a consistency sufficiently low for each stone just to be enveloped in bitumen on stirring. The coated stones were transferred in a dessert spoon to the mould which had been heated in an oven at 55°C. for an hour. The coated stones were lightly tamped into the mould by means of the spoon and the mould and its contents were allowed to stand on cork in an oven, regulated to 55°C. for an hour. Then the mixture was compressed at 2500 lb. per sq. in. Duplicate tests were performed.

The test procedure was repeated with 0.5, 1.0, 1.5, 2.0, 2.5, and 3.2 per cent binder by weight and with

-3/8 in. + No. 4 and -No. 4 + No. 10 stones using percentages binder shown in figure 7.

Extraction of Bitumen:-

A series of extractors somewhat similar to the apparatus used by Zube (191) was employed, their design being based on the description given by Smallwood (153). Large-scale research, however, seemed arduous with these extractors, and since the extraction process formed only a secondary part, of this section of the work, the writer decided to make use of a rapid extraction method of his own.

A number of 8-oz. bottles with water-tight screw tops was procured, any number of which could be used simultaneously. A compressed specimen taken from a mould was gently transferred to a bottle and the bottle was filled with benzol. The mixture was left stationery for 12 hours, and shaken at intervals of 2 hours. At the end of this period the clean chippings were poured onto a Tyler No.100 sieve and washed with clean benzol until no traces of bitumen were left. The dry aggregate was sieved and weighed after evaporation of the benzol. The -No. 100 material was assumed equal to the discrepancy between the initial and the final weights of the aggregate. The test results are given in figure 7.

(i) The curves of the crushing ratios plotted against the percentage binder are cusp-shaped.

(ii) An optimum percentage of binder exists at which a maximum amount of crushing takes place.

Conclusions.

(a) The downward trend of the curves disproves the cushioning action at normal binder contents, suggested by some investigators. The amount of particle disintegration actually increases with increase of binder, owing to the lubricating action taking place. Lubrication is accompanied by an increase in density and by a change in the mechanical analysis of the aggregate.

(b) A point is reached at which maximum degradation takes place, viz. at 2.0, 4.0, and 6.8 per cent binder

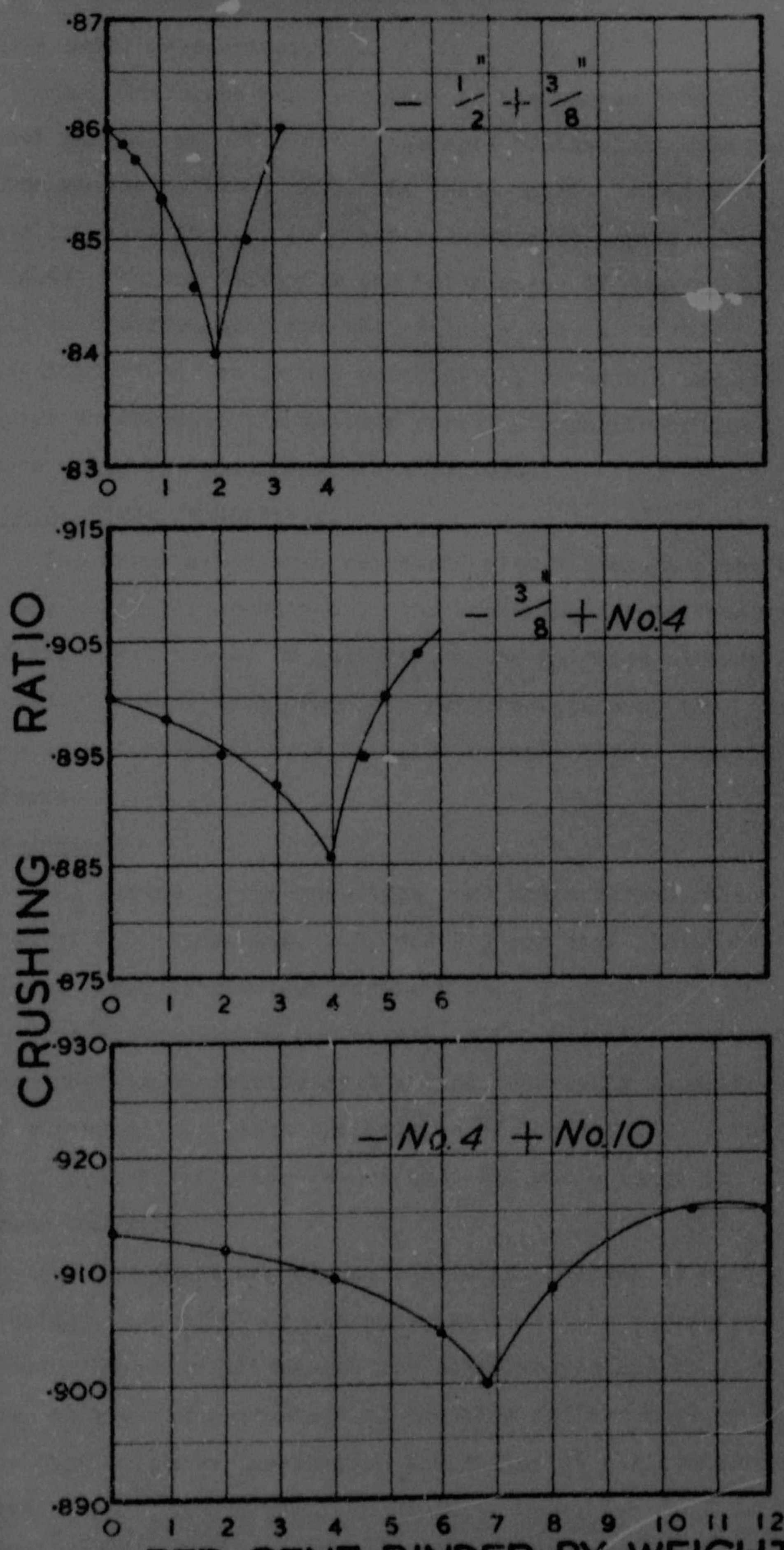

FIGURE 7. Effect of the Size of Aggregate in a Bituminous Mixture on its Break-down Characteristics.

(by weight) respectively.

(c) The right hand portions of the curves eventually reach heights equal to the intercepts of the left hand portions on the vertical axis. At these points "cushioning" sets in, viz. at 3.2, 5.0, and 9.3 per cent binder (by weight), respectively, for the three sizes of aggregate. It will be observed that for the -½ in. + 3/8 in. stone the "cushioning" effect is not perceptible, since 3.2 per cent binder constitutes the maximum carrying capacity of the stone under the test conditions employed.

Type of Stone as Variable.

The experiments were repeated using different types of -½ in. + 3/8 in. aggregates, viz. employing norite, quartzite, dolerite, and basalt in addition to the dolomite already tested. Figure 8 is a graphical representation of the results and table VI is a detailed example of the results for dolerite.

Conclusions:-

(a) Curves of the cusp type were again formed, with cusps at 2.0, 1.75, 2.0, 2.5, and 2.0 per cent binder by weight, respectively (see figure 8).

(b) With dolerite and basalt, which are fine-textured rocks possessing relatively low binder-carrying capacities, the curves do not reach the heights of the vertical intercepts, i.e. lubrication occurs over the whole range of binder contents.

(c) The positions of the curves are indicative of the crushing susceptibility characteristics of the aggregates tested. Dolerite and basalt lie relatively close to each other as regards resistance to crushing and are more resistant than dolomite, quartzite, and norite at all binder contents.

(2) THE EFFECTS OF TEMPERATURE AND THE TYPE OF BINDER ON THE COMMINUTION OF BITUMINOUS-COATED AGGREGATES.

The viscosity of a bituminous material depends upon its temperature, the degree of variation being defined by

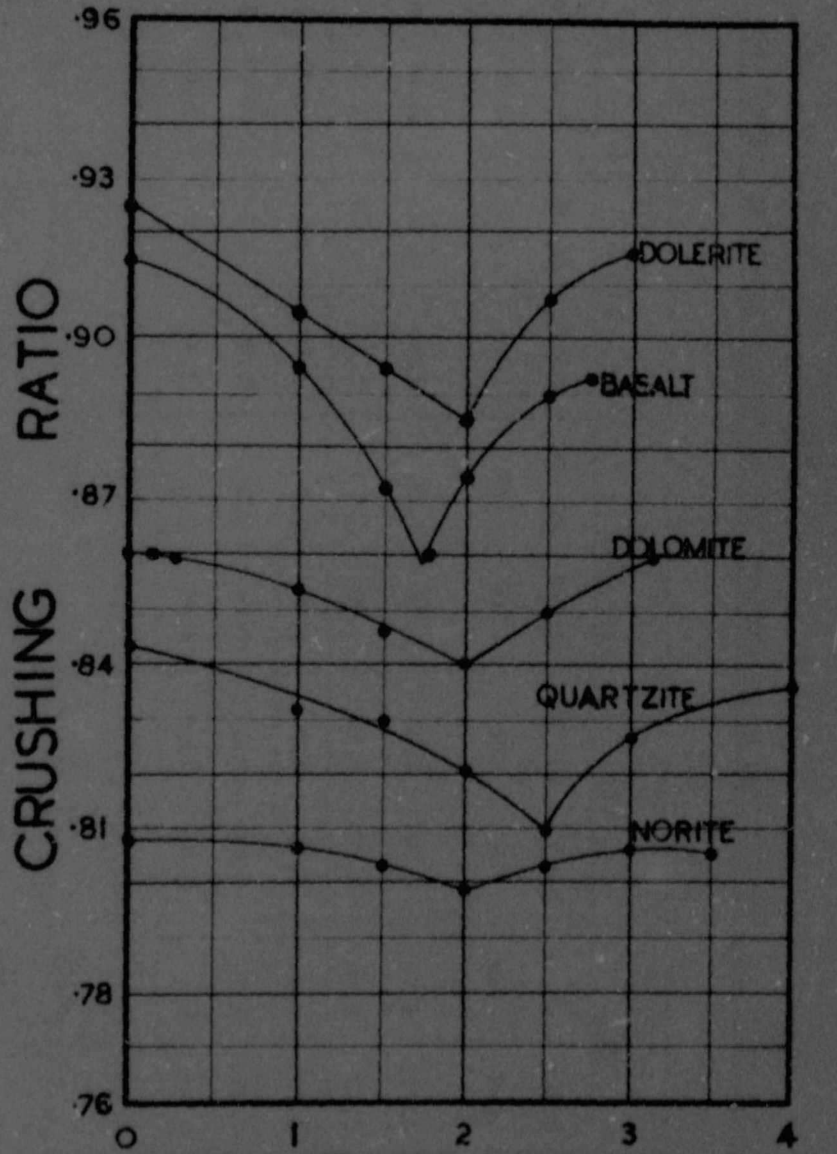

FIGURE 8. The Comminution of a Bituminous Mixture with the Type of Stone as Variable.