TABLE VI THE EFFECT OF BINDER CONTENT ON THE COMMINUTION OF DOLERITE IN A DOLERITE-BINDER MIXTURE.

PER CENT BINDER BY WEIGHT	NIL		1.0		1.5		2.0		2.5		3.0	
SIEVES	% By Wt.	Cum.% Ret.	% By Wt.	Cum.% Ret.	% By Wt.	Cum.% Ret.	% By Wt.	Cum.% Ret.	% By Wt.	Cum.% Ret.	% By Wt.	Cum.% Ret.
3/8"	74.8	74.8	66.1	66.1	65.6	65.6	62.5	62.5	67.1	67.1	71.2	71.2
No. 4	16.8	91.6	25.4	91.5	23.3	88.9	25.4	87.9	24.5	91.6	20.2	91.4
No.10	6.0	97.6	5.6	97.1	7.1	96.0	7.4	95.3	5.7	97.3	5.6	97.0
U.S.40	1.6	99.2	1.8	98.9	2.2	98.2	2.7	98.0	1.7	99.0	1.9	98.9
No. 100	0.2	99.4	0.2	99.1	0.3	98.4	0.2	98.3	0.4	99.2	0.4	99.3
PAN.	0.6	462.6	0.9	452.7	1.6	447.1	1.7	442.0	0.8	454.2	0.7	457.8
	1000		100.0		100.0		100.0		100.0		100.0	
CRUSHING RATIO =	$\frac{462.6}{500.0}$ = 0.925		$\frac{452.7}{500.0}$ = 0.905		$\frac{447.1}{500.0}$ =0.894		$\frac{442.0}{500.0}$ = 0.884		$\frac{454.2}{500.0}$ =0.908		$\frac{457.8}{500.0}$ = 0.916	
PERCENT VOIDS	24.5		23.1		21.5		21.0		19.6		17.8	

its temperature susceptibility. Bituminous binders are fluid when hot; hence the benefit of the workability of bituminous mixtures at high temperature.

The writer is of opinion that the degradation of agregates is influenced to quite a considerable degree by the viscosity, given the type of binder, and probably by the type of binder, given the viscosity. Bartholomaei (16.b) does not concur with this view, and states that the type of binder used does not appear to affect the degree of particle disintegration. Knight's results (85) of extractions of compressed mixtures containing different types of binder, are in accordance with the writer's theory.

By compacting bituminous premix specimens for laboratory testing, Wilson (185) also found that the aggregate breaks down in the mixture during compaction. Endersby (40) considers that the problem of predicting the behaviour of an asphalt-aggregate mixture from tests on dry mineral aggregate should be approached with caution. The introduction of bitumen results in a large increase in the Mohr constant and some decrease in the angle of friction.

Experimental Procedure:-

The writer designed a series of tests to illustrate the behaviour of the aggregates in bituminous mixtures when compressed over a wide range of temperatures.

The aggregate employed was -3/8 in. + No. 4 cubical dolomite. The binders selected were 100 and 200 penetration bitumens and a tar with approximately the same viscosity at 20°C. as the 200 penetration bitumen. The weight of aggregate used was 200 gms. and the binder content 2½ per cent (by weight). To effect compression, a pressure of 2000 lb. per sq. in. was applied to the mixtures, which were confined in the 2 in. dia. mould described before.

The temperature range employed was -10°C. to 70°C. The mixtures were prepared on a hot plate by heating 200 gms. stone with 7.2 gms. binder (2.2 gms. was the predetermined weight of binder which remained on the spoon, stirrer, and mixing bowl) to a temperature which reduced the viscosity of the binder just sufficiently to allow of uniform mixing. The mixtures were transferred to the 2 in.dia. moulds and the moulds and their contents were left at the required temperature for an hour before testing. Duplicate tests were performed for each temperature. A refrigerator was used for the low temperature tests (-10°C and 0°C.). The 22°C.temperature was that of a water bath. The 40°, 55°, and 70°C. temperatures were obtained by using a thermostatically-controlled oven. At temperatures above 70°C. the results were erratic due to the heterogeneous mixtures resulting from the flow of the binder.

The moulds containing the specimens were transferred to the testing machine as rapidly as possible to ensure a minimum heat loss. After compression, the aggregates were extracted and analysed mechanically. (See table VII and figure 9 for the results).

Conclusions:-

(a) The curves indicate an increase in crushing with an increase in temperature owing to the increased lubrication provided by the more fluid binders.

(b) The slopes of the curves are indicative of the sensitivity of the aggregate to degradation, a property which is affected by the temperature of the binder employed. In general, the tar curve is steeper than the bitumen curves and the 200 penetration bitumen curve is, in general, steeper than the 100 penetration curve.

(c) At low temperatures (below 10°C.), the tar possesses little resilience and hardly any relative movement of the stones takes place. An anvil action takes place, i.e. fracture is limited to the stones on the surface which are held firmly in position by the brittle tar.

(d) At low temperatures the 200 penetration bitumen becomes more non-resilient than the 100 penetration bitumen, probably due to the higher content of light oils in the former.

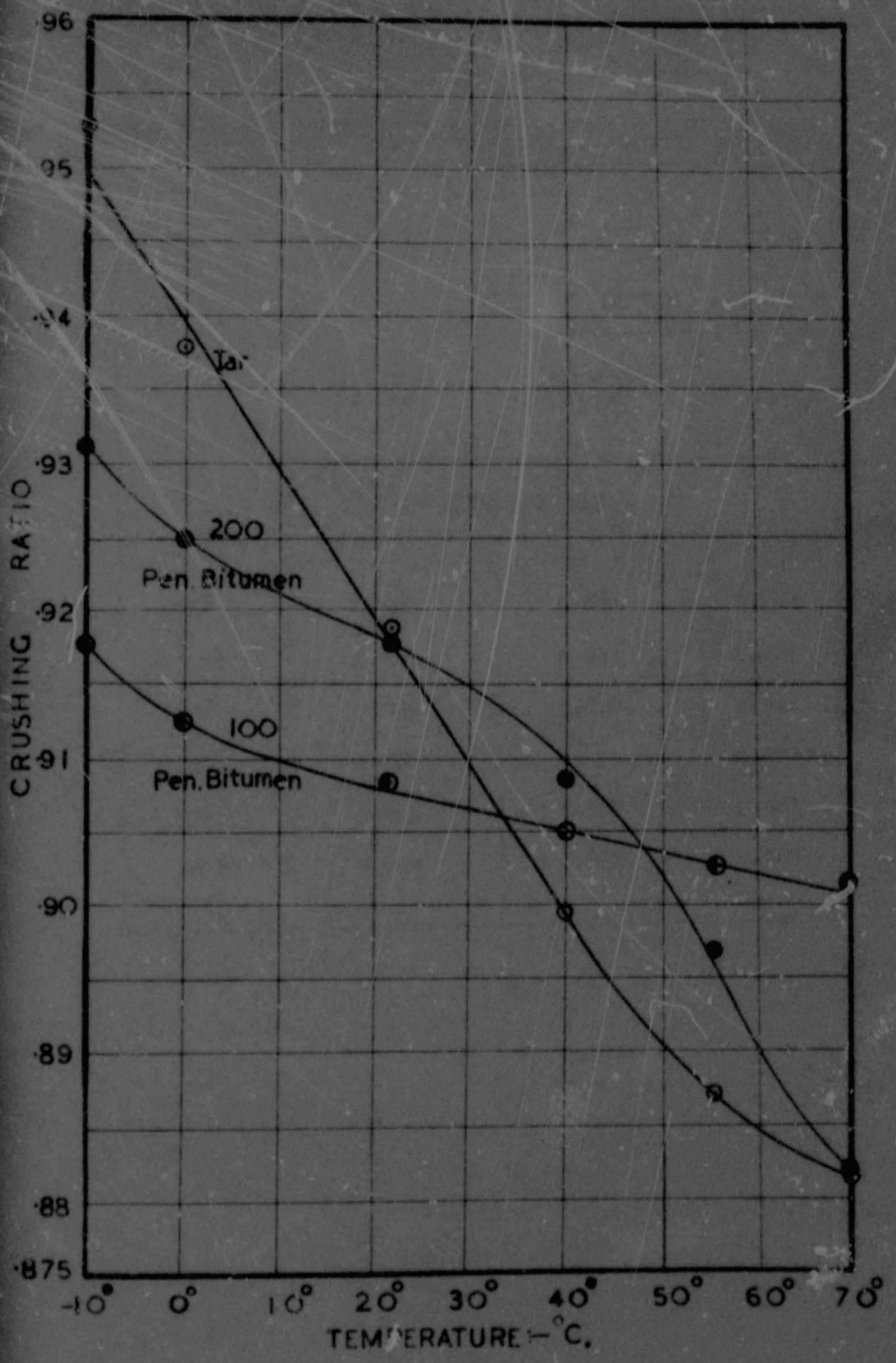

FIGURE 9. Variation of Comminution with Temperature in a Bituminous Mixture.

TABLE VII THE EFFECT OF THE TEMPERATURE OF A BITUMINOUS MIXTURE ON THE COMMINUTION OF THE AGGREGATE.

	TYPE OF BINDER		
	100 Pen. Bitumen	200 Pen. Bitumen	Tar.
TEMP.	CRUSHING RATIO		
-10°C	0.918	0.931	0.953
0°C	0.912	0.925	0.938
22°C	0.908	0.918	0.919
40°C	0.905	0.909	0.899
55°C	0.903	0.897	0.887
70°C	0.902	0.882	0.882

(e) At 22°C. the 200 penetration bitumen gave rise to the same degree of breakdown as the tar, probably since their consistencies were then approximately similar.

(f) At temperatures above 50°C. the binders can be classified as (i) tar, (ii) 200 penetration, and (iii) 100 penetration bitumen, in the order of decreasing lubricating effect, which effect can probably be related to their viscosities and bond strengths (66).

CHAPTER V.

THE INTERPRETATION OF LABORATORY ROUTINE COMMINUTION TESTS.

A Survey of the Literature.

The elucidation of the factors involved in the comminution of aggregates has been attempted by many investigators. The literature dealing with the laboratory testing of road aggregates discloses, however, that most of the work done on the subject occurs as independent research on specific tests, and has still to be correlated. There are, however, two informative treatises which are of value in these studies, namely, the books compiled by Knight (82) and Stiny (161). (See also 81 for another useful publication by Knight).

A Review of the Crushing Tests on Road Aggregates.

In B.S.S. 882 - 1940 (24 a.) a crushing test is described which was probably developed from the German crushing test (quoted by Stiny (161a.)). In the opinion of the writer these tests are rather tedious and lack the advantages of simplicity and rapid operation which are characteristic of the writer's crushing test.

The Italian Roads Research Institute at Milan (27.b) tests road chippings for resistance to brittleness by using an 880 lb. roller and -3/8 in. + No. 4 stones. A better test is employed by the Swedish Road Institute at Stockholm (159.a) which makes use of a 31 lb. steel weight falling through 9.8 in. onto 500 gms. chippings placed on a steel anvil of 4 in. dia. One of the advantages of the test is that the strength of various sizes of chippings is evaluated, by using uniformly-sized stones from 0.16 in. to about 0.63 in.

Knight (see 92) is responsible for working out instructions of the Treton test which was probably evolved from the Swedish tup test. A 33 lb. hammer is dropped through

$17\,^3/_4$ in. onto - $\frac{3}{4}$ in. + 5/8 in. stones, and 10 blows (instead of 20) are employed, since the increased height of drop imposes more severe conditions. The writer considers the Treton test to be one of the most important crushing tests from the point of view of the practical engineer,

(a) for determining the relative resistances to fracture of various highway aggregates in pavement design, and,

(b) for gauging the uniformity of supply of aggregates during construction.

<u>The Attrition of Road Aggregates</u>.

The writer has made a study of attrition, i.e. the type of comminution causing abrasion of a stone and not necessarily fracture. This type of wear is typical of large stones in direct contact with traffic. Thus Knight (82.a) reports that only a small amount of wear in the form of "bull-nosing" took place in a granite sett which had been subjected to main road traffic on a gradient of 1 in 20 for 60 years. The Swedish Road Institute (159) published results of measurements on sett paving showing a linear relationship between the average wear per year and the traffic intensity, from which it appears that a load of 1000 vehicles per day corresponds to an average abrasion of 0.09 m.m. per year. These setts also tended to wear more at the edges than at the centre, corroborating Knight's findings.

Bullows (27) showed with different types of rock that if crushed stone is subjected to attrition, the attrition is reduced to a minimum once the fragments have become rounded. Shelbourne's results of road roller tests (144) illustrate that 1.3 times as much degradation occurred in crushed as in uncrushed gravels from the same source. The writer's conclusion is that, for a given aggregate, fracture is only somewhat affected by the surface irregularities of a stone while attrition is almost completely governed by them.

An unpublished investigation by Calloway (reported by

Gaudin (52)) discloses the fact that the tumbling of sand grains on a river bed produces rounding and wear, and that the wear due to tumbling decreases rapidly with decrease in grain size, other things being equal. In a test described later, the writer has shown that the attrition in the Deval test decreases with the size of stone tested.

Bagnold (16.a) has published results of grading curves of samples of sand taken from desert dunes. When plotted on a differential diagram, it was revealed that the mechanical analysis of the sand grains formed in nature by weathering process and during transport by wind and water, resembles a normal probability curve.

Probably the first attempt to apply the wear of aggregates by attrition to scientific testing was made by French engineers (Ann. des Ponts et Chaussées, 1879 and Bull. du Ministre des Travaux Publics, 1881), who developed the Deval abrasion test (11), which is now a standard laboratory routine test for aggregates.

Criticism of the Deval Test.

The writer believes that the Deval abrasion value is determined by the surface irregularities of an aggregate and does not take the "internal (or fibre) strength (7)" into account. It therefore fails to predict the behaviour of an aggregate in chipping size. The dry attrition value is also erratic since the dust formed during attrition acts as a cushion between the stones and on the sides of the barrel. This dust is allowed to escape through slits in the Austrian Standard test (110.a) in which a horizontal barrel of triangular cross section is used. Walker and Stewart (177) have published the erroneous statement (criticised by Knight (37)) that the Deval attrition test is quite reliable when used alone. The writer finds it impossible to reconcile this statement with the results of the Deval test combined with those of crushing strength, the Page impact test, the Dorry abrasion test, and the Treton test (175.a). Goldbeck (53) concludes that no relationship exists between the Deval abrasion test and the breakdown of stone under the roller. Miller and Sarjant (107.a) have found that four porphyries from the National Physical Laboratory list (66.a) show a gradual increase of impact and crushing strength, but an increasing attrition in the direction opposite to the general improvement of physical properties.

As a result of work done on the Los Angeles rattler (12), the Deval test has fallen largely out of favour. The former is not a pure abrasion test, since the charge of cast-iron spheres introduced with the aggregate sample gives rise to fracture by impact.

It appears that definite correlation has been found between the loss in the Los Angeles test and (a) the strength of concrete (Litehiser (97)), and (b) the service records of materials used in surface treatment construction (Woolf and Runner (188.a)). The Los Angeles test also shows up any weakness in stone intended for paving mixtures. When a low grade aggregate is tested, a high loss occurs, and a coarser aggregate than would ordinarily be used, should be employed (as suggested by Fahnestock (43)), to prevent undue accumulation of fines in the pavement.

Experimental work.

The writer chose the Treton and the Deval tests for detailed investigation and made a comparison between the Treton loss and the B.S.S. 882-1940 crushing value.

THE TRETON TEST.

The Effect of the Size of Stone.

Cubically shaped norite of sizes -2 in. + 1½ in., -1½ in. + 1 in., -1 in. + ¾ in. -¾ in. + ½ in. -½ in. + 3/8 in. -3/8 in. + No. 4., and -No. 4 + No. 10 (Tyler denomination) was prepared and in each test sufficient stone was used to cover the Treton anvil in one layer. The average weights of stone required for the various sizes were 332, 243, 176, 150, 110, 60, and 35 gms. respectively. Figure 10 shows the Treton loss after 10 blows plotted against the aggregate size, assuming as an approximation that the average size of stone lies midway between the sizes of the sieve apertures defining it.

Conclusions:-

(a) There is approximately a straight line relationship between the size of stone in impact and its Treton loss.

(b) Large stones possess a larger resistance to impact. This fact explains a desirable trend in surface treatment design, toward the use of as large a stone as possible when weak and brittle aggregate is employed. It also explains the relatively high resistance to impact of stone setts.

The Effect of the Weight of Stone.

Cubical - ¾ in. + ½ in. norite was tested by means of the Treton apperatus in batches containing increasing numbers of stone, viz. 1, 2, 3, 4.........etc. and weighing 9.0, 15.5, 24.5, 42, 53, 62, 79, 110, 171, 200, 400, and 600 gms., respectively. The results have been represented graphically in figure 11.

Conclusions:-

(a) A straight line relationship exists for the comminution of single-sized aggregate (up to about 80 gms.), provided that the stones are not in mutual contact before being tested.

(b) The flexed part of the graph refers to tests with adjacent stones in contact. Here the straight line law ceases to hold.

(c) As soon as the stones occur in two or more layers another straight line relationship is created.

The Effect of the Number of Blows:-

Cubcial quartzite, norite, dolerite, basalt, and dolomite chippings, -½ in. + 3/8 in. in size, were employed,

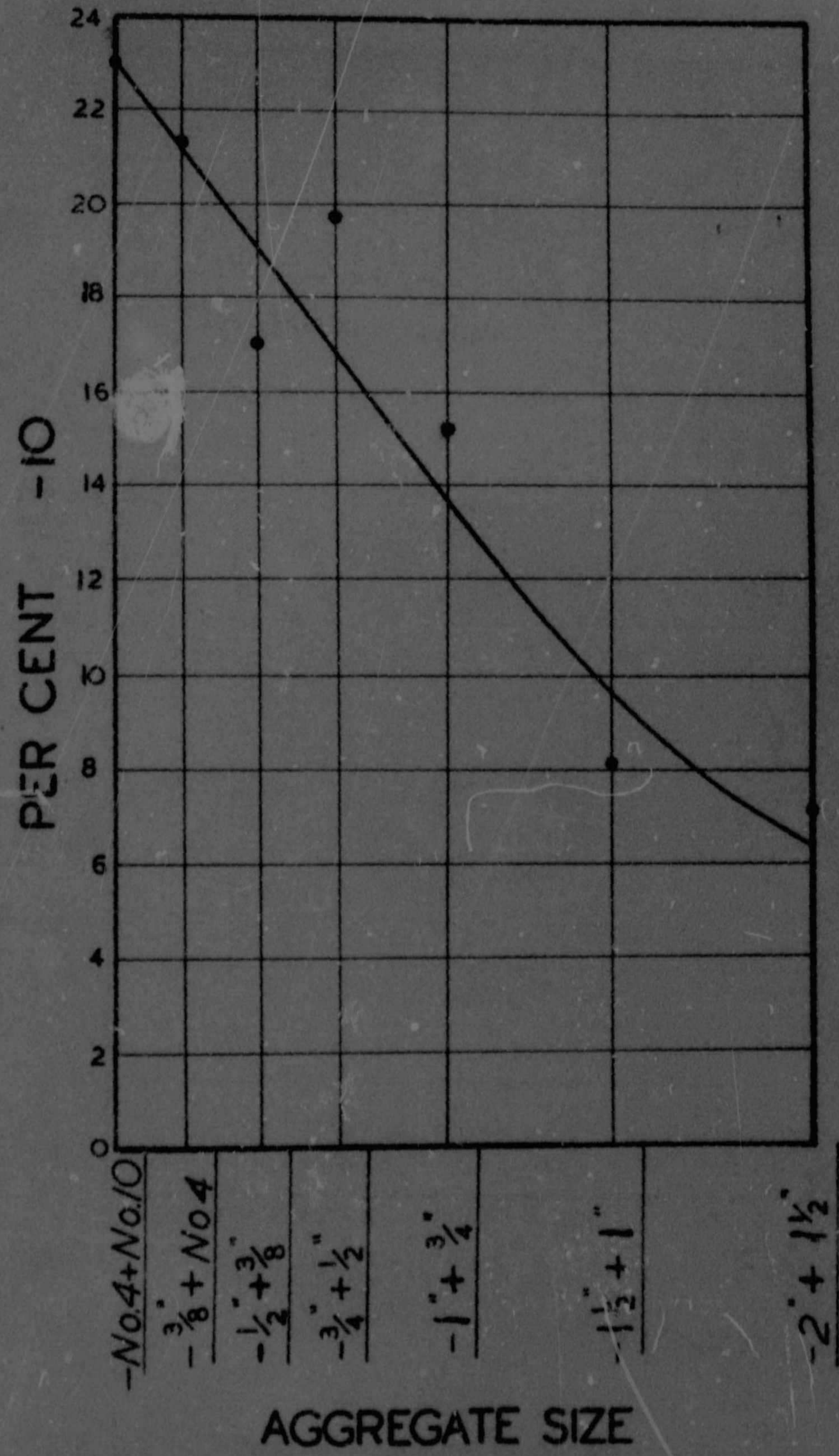

FIGURE 10. Effect of Size on Treton Loss.

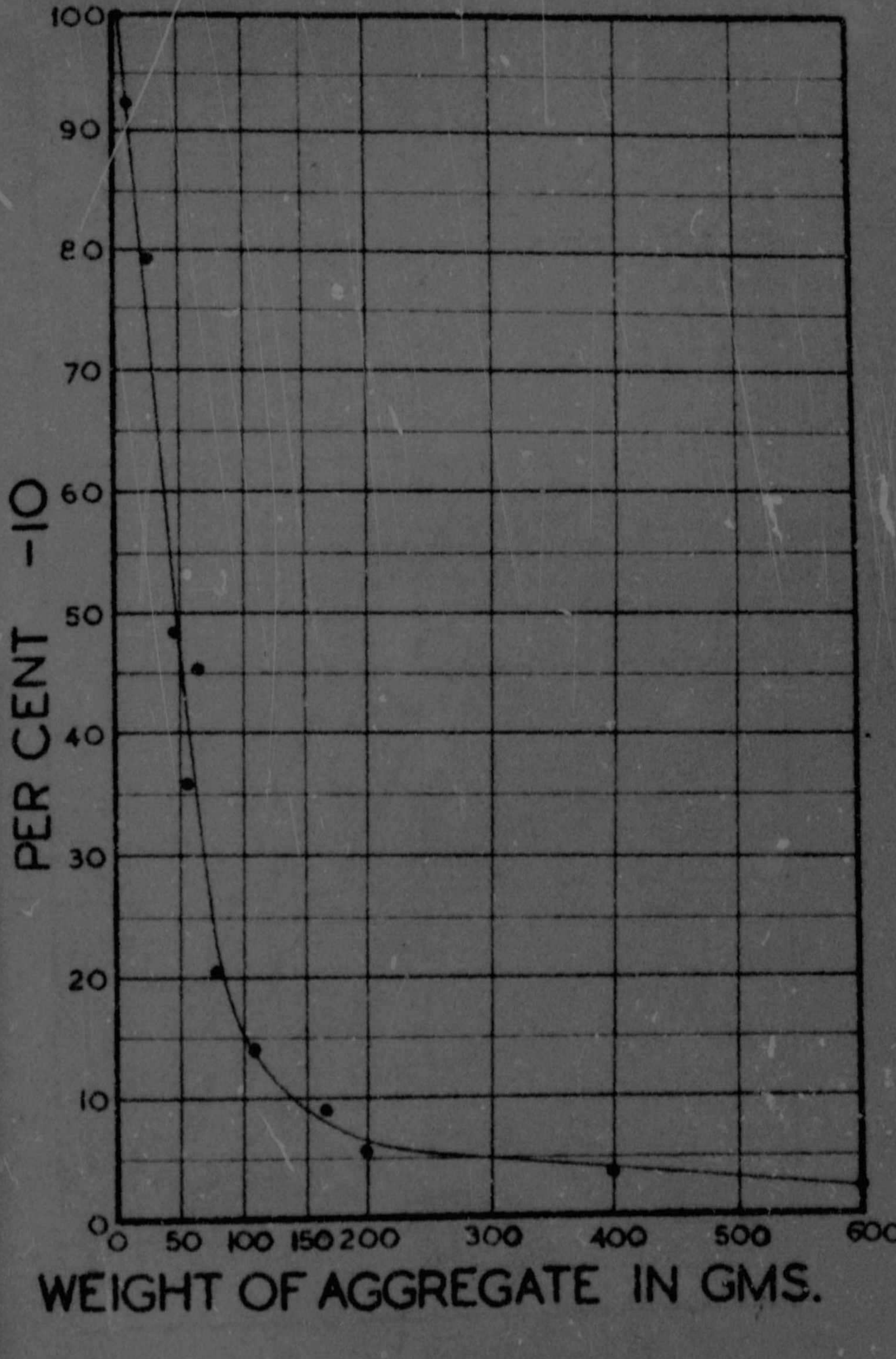

FIGURE II. Effect of Weight on Treton Loss.

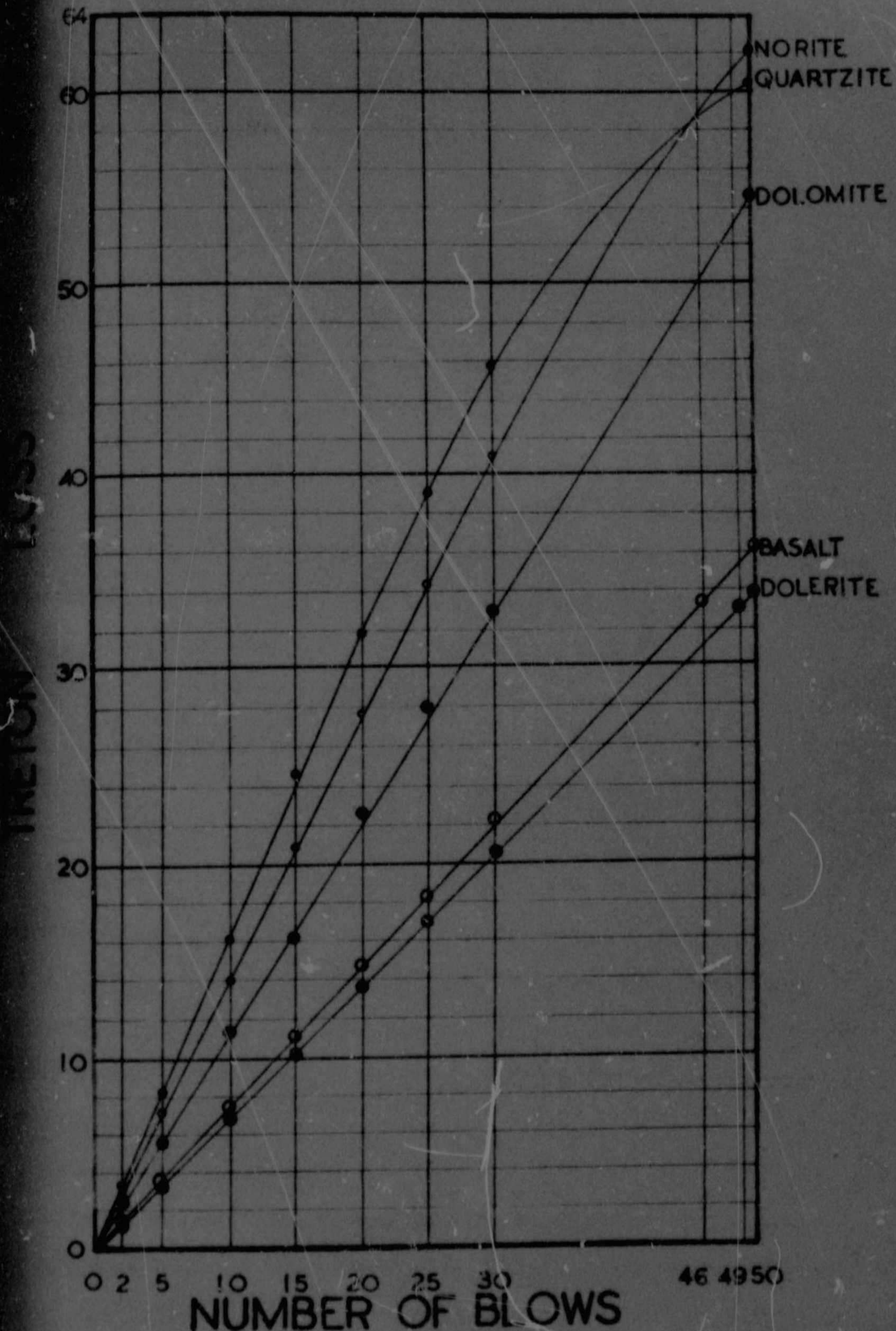

FIGURE 12. Effect of No. of Blows on Treton Loss.

using 94, 108, 107, 101, and 102 gms. according to their specific gravities 2.65, 3.02, 3.00, 2.83, and 2.87, respectively. Impact tests were performed, using the Treton apparatus and increasing numbers of blows up to 50 in number, as shown in figure 12.

Conclusions:-

(a) The degradation loss, in general, increases proportionally with the number of blows. For purposes of comparison it is advisable to use such an amount of blows as will give results lying sufficiently far apart, especially for aggregates of approximately similar resistance to impact. (E.g. the dolerite and the basalt in the writer's experiments.)

(b) The crushing susceptibilities of the five aggregates are indicated by the slopes of their crushing lines. (E.g. dolerite, norite, and quartzite, respectively.)

THE DEVAL TEST.

The Effect of the Size of Stone.

Cubical norite, falling in the sieve denominations -2 in. + $1\frac{1}{2}$ in., -$1\frac{1}{2}$ in. + 1 in., -1 in. + $\frac{3}{4}$ in., -$\frac{3}{4}$ in. + $\frac{1}{2}$ in., and -$\frac{1}{2}$ in. + 3/8 in., was used in this test. Eleven pounds of material was subjected to 10,000 revolutions of attrition in the Devel rattler. The results have been plotted in figure 13, and again it was assumed that the size of a stone is defined as half the sum of the sieve apertures in its denomination.

Conclusions:-

(a) The Deval attrition value is affected by the size of aggregate being tested. Other things being equal, the wear due to attrition (or "tumbling") decreases rapidly with the decrease in size of the aggregate. This conclusion agrees with that reported by Gaudin - see section on attrition, page 42.

(b) The writer accords with B.S.S. 812-1938(24) in regard to the remark that the ratios between the Deval

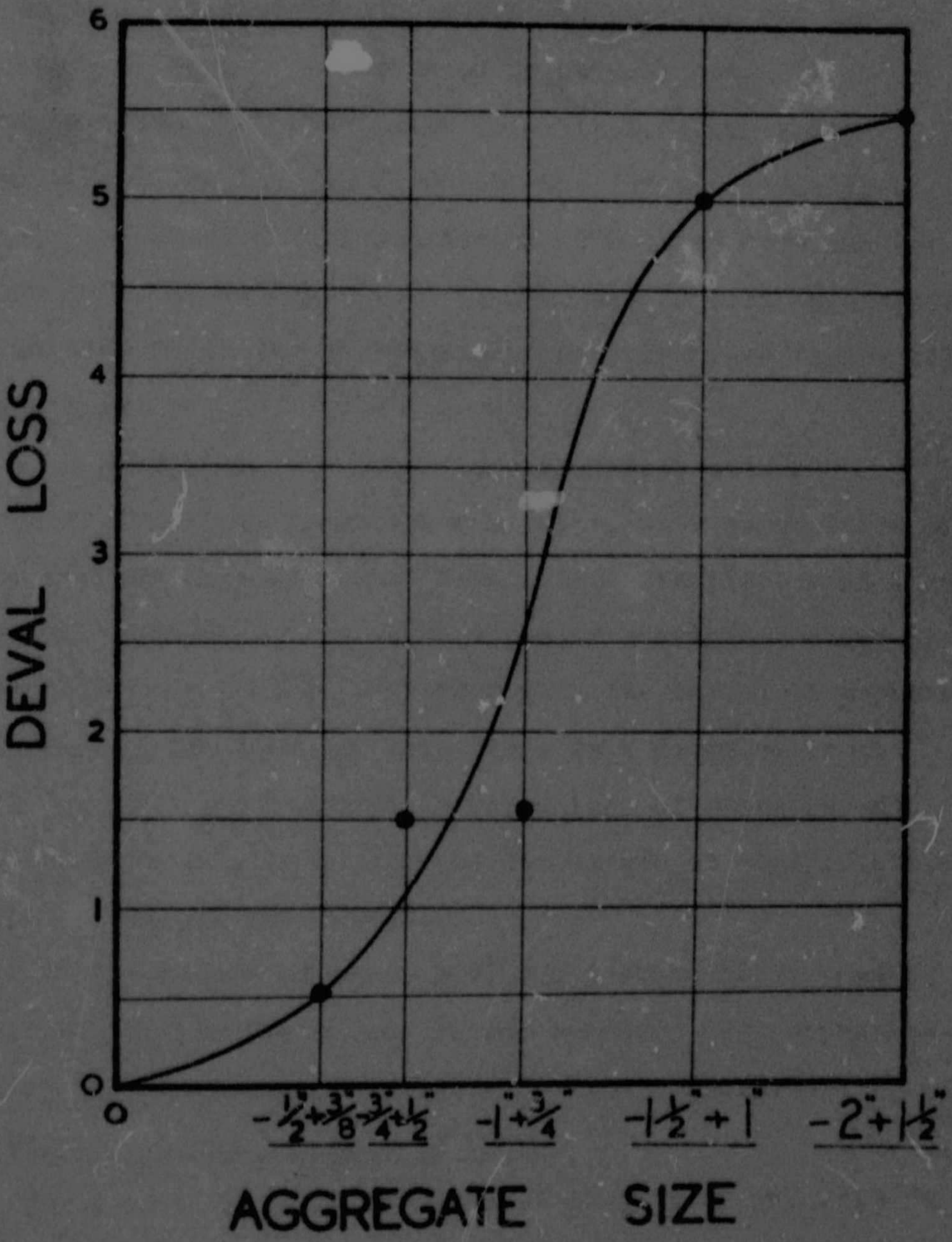

FIGURE 13. Effect of Size on Deval Loss.

values for various sizes are dependent on the relative stone shape and perhaps other factors, but does not believe that the statement in the following sentence is necessarily true:

"The attrition value for 1 in. and ½ in. stone as obtained directly from the test, if multiplied by 1.5 and 2.5 respectively, will give resulting values which are roughly equivalent to that obtained for 2 in. stone."

The Effect of the Weight of Stone.

Cubical - 2in. + 1½ in. norite was employed and the variation in weight was effected by using 1 stone (0.38 lb.), 5 stones (1.09 lb.), 10 stones (2.31 lb.), 4.41, 7.93, 11.00, 16.00, 25.00, and 39.00 lb. The latter sample just filled one barrel of the apparatus. The tests were run for 10,000 revolutions and the Deval loss was in each case plotted against the logariths of the weight of stone (see figure 14).

Conclusions:-

(a) Initially, the Deval loss increases with the weight of stone, up to an optimum point, when an addition of stone results in a decreased Deval loss. The right hand line represents conditions in which there is sufficient stone present for the stones in contact with the barrel to protect those resting on them, so that there is a decrease in the Deval loss with an increase in the weight of stone tested. When the barrel is full, and the stones are at rest relative to the barrel, no loss occurs.

(b) The weight of stone giving a maximum Deval loss is 9 lb. The 11 lb. value used in the standard test therefore appears to be relatively suitable for the purpose.

The Effect of Time on the Deval Loss.

For this test 11 lb. batches of cubical -2 in. + 1½ in. norite were rotated in the Deval rattler for 1000, 2000, 4,000, 8200, 10000, and 40000 revolutions, i.e. for 37.5, 75, 150, 252, 375, and 1500 minutes, respectively. Figure 15 represents the logaritam of the number of revolutions plotted against the Deval loss.

Conclusions:-

For values between 1000 and 40000 revolutions, the wear

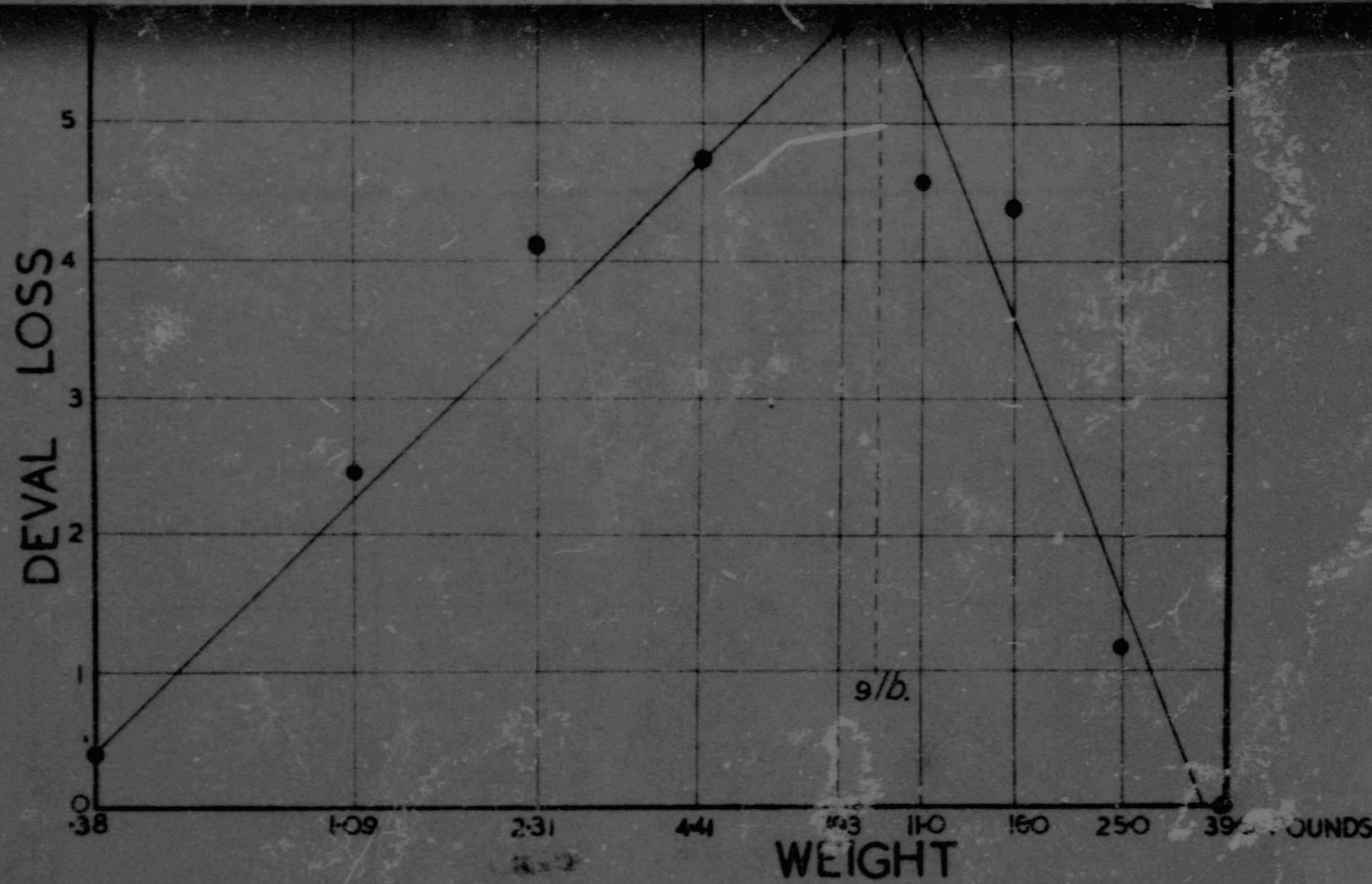

FIGURE 14. Effect of Weight on Deval Loss.

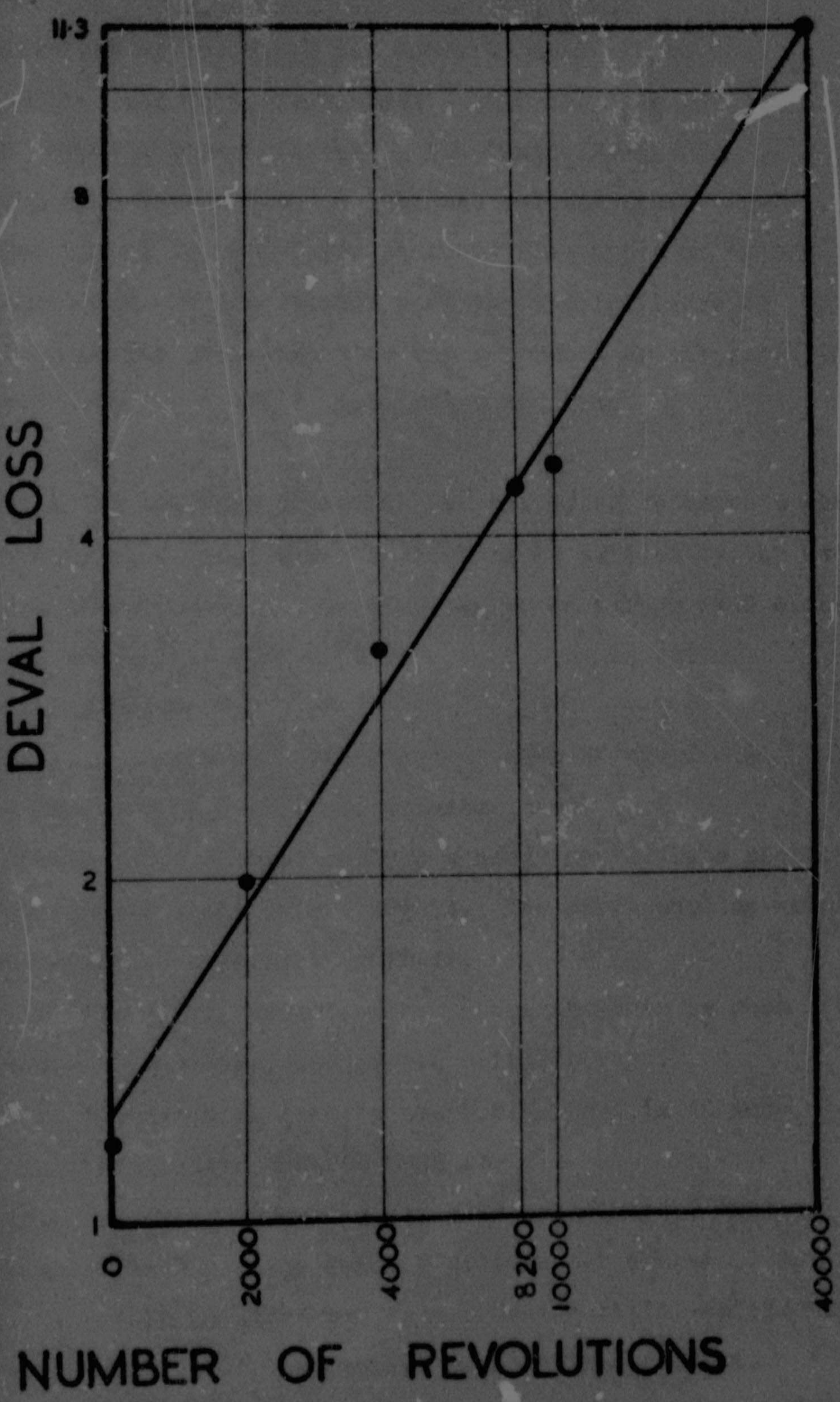

FIGURE 15. Effect of Time on Deval Loss.

the Deval rattler is related to the logarithms of the number revolutions by a straight line relationship.

THE B.S.S. 882 - 1940 CRUSHING VALUE (MODIFIED) COMPARED WITH THE TRETON VALUE.

Cubical -½ in. + 3/8 in. aggregates were used and the ues obtained in the B.S.S.882 - 1940 crushing test comed with the loss obtained in the Treton test. (The latter is the true Treton value, since the value normally reported that for -⅞ in. + 5/8 in. stones.) Five types of aggregates e employed and the results were plotted in figure 16. The .S. modified crushing value was expressed as the percentage terial passing a No. 7 sieve after crushing.

nclusions:

(a) The position of a point on the curve represents the sistance of an aggregate to crushing as defined by the two sts employed. Basalt and dolerite, whose values fall close each other, are much more resistant than dolomite, artzite, and norite.

(b) At this stage, the disadvantages of the B.S.S. 2 - 1940 crushing test may be enumerated:

(i) The B.S.S. test employs a heavy mould, base plate, d plunger of total weight 73¼ lb. The corresponding weight the writer's apparatus is 15 lb.

(ii) The B.S.S. test requires about 16 times as much gregate of the same size as the writer's test.

(iii) The crushing load in the B.S.S. test is 40 tons, at in the author's test is 7885 lb.

(iv) The B.S.S. crushing value is calculated from the rcentage fines passing a No. 7 sieve after crushing. The iter's result is expressed as a crushing ratio, which takes e whole grading of the crushed product into account.

The simplicity, rapidity of operation, and the accuracy f the test designed by the writer, is therefore evident.

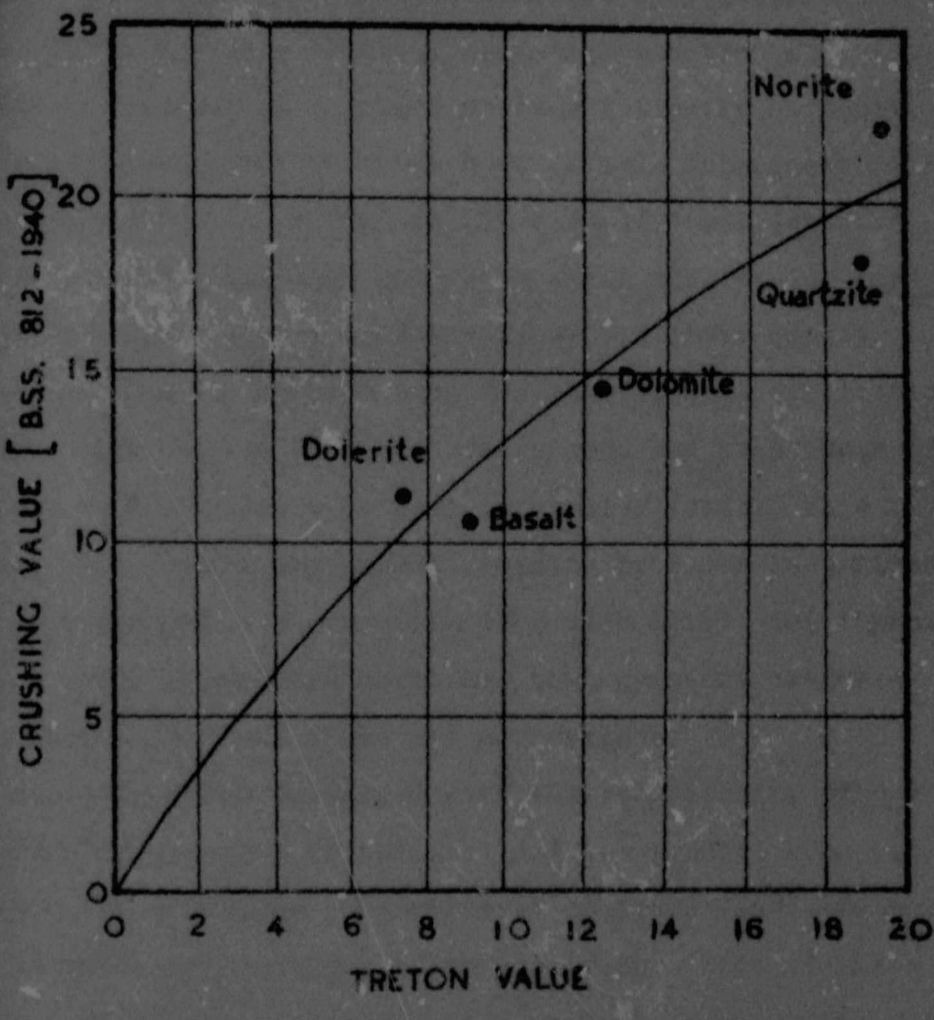

FIGURE 16. Comparison between Treton Value and B.S.S. 812 1940 Crushing Value.