

TABLE XI. EFFECT OF A COATING OF BINDER ON THE
CRUSHING OF REEF QUARTZITE.

Analyses of aggregates after 4 roller trips.

DETAILS OF BINDER	STANDARD SIEVES	% By Wt. Ret.	Cum. % Ret.	Crushing Ratio
NONE	3/8"	84.5	84.5	$\frac{477.6}{500.0}$ = .955
	No. 4	11.4	95.9	
	No. 10	2.4	98.3	
	U.S. 40	1.0	99.3	
	No. 100	0.3	99.6	
	- 100	0.4	477.6	
		100.0		
1.5% 200 PEN. BITUMEN	3/8"	86.6	86.6	$\frac{481.1}{500.0}$ = .962
	No. 4	10.2	96.8	
	No. 10	1.8	98.6	
	U.S. 40	0.8	99.4	
	No. 100	0.3	99.7	
	- 100	0.3	481.1	
		100.0		
1.5% R.C.2 OUTBACK BITUMEN	3/8"	81.0	81.0	$\frac{471.4}{500.0}$ = .943
	No. 4	13.0	94.0	
	No. 10	3.6	97.6	
	U.S. 40	1.6	99.2	
	No. 100	0.4	99.6	
	- 100	0.4	471.4	
		100.0		

rolling operations, and should have increased the crushing of the aggregates.

Summary:-

(i) When tested in the field, the aggregates lay in the same order, from the standpoint of resistance to degradation, as when tested in the laboratory by means of the crushing test.

(ii) The way in which the addition of bituminous binder affects the compaction characteristics of dry aggregates depends on the properties of the binder. This conclusion accords with the lubrication hypothesis advanced in a previous chapter.

(iii) Correlation was found to exist between the results of the crushing test and field results determined by means of a 10 ton roller on a water-bound macadam foundation.

CHAPTER VIII.

THE EFFECTS OF THE COMMINUTION OF STONE ON THE SERVICE BEHAVIOUR OF A ROAD.

The degradation of road aggregates by rollers and traffic during the consolidation process is unavoidable, so that the mechanical analysis of the stone ingredient in a road bed is usually in a continual state of change towards an ever increasing reduction in size.

The Destructive Effect of Iron-tyred Vehicles.

It is well-known that an iron-tyred vehicle does an immeasurably greater amount of damage to roads than a similar vehicle equipped with pneumatic tyres (79.a). The damage is noticeable to a marked extent on roads which have received some form of bituminous treatment. A heavily laden vehicle with steel tyres exerts a tremendous pressure on the road which is distributed over a small area. The undulating white tracks (composed of rock dust), which are formed by the passage of horse-drawn carts and ox wagons, are still a common sight on the bituminous pavings of the High Velds of South Africa.

The Distribution of the Breakdown of aggregates in a Road Structure.

According to the current theories of load distribution in a pavement, the distributed load from superimposed forces on the surface decreases progressively with an increase in depth, until it ultimately disappears. The wearing surface, or riding carpet, then, is the portion of the highway structure which suffers most severely from the forces of degradation. Hence soft, friable stone is generally used only for lower courses and not for wearing courses, while medium quality stone is used for water-bound macadam pavements carrying medium traffic. Hard, tough stone finds the greatest

four in the majority of surfacings, either in the form of broken stone or chippings for wearing courses, or for surface dressing.

Densification Effect.

The disintegration of aggregates consequent on compaction often gives rise to a dense, impervious bituminous surface. Parker (122) has claimed that in the construction of bituminous pavements with slag of a soft nature, a certain amount of crushing is desirable for filling the voids and binding the pavement courses together.

Herrmann (64.a) believes that the minimum void content of a mixture is best obtained by the use of a high proportion of coarse-grained material. The mix employed should contain particles of all sizes, or excessive alterations in particle size will arise during compaction and wear. The distinction between compaction and compression is emphasised. Compaction consists in the filling of voids by the fine particles produced from the breakdown of larger particles under traffic stresses, as in the stabilising of macadam. Compression, on the other hand, consists in the pressing together of existing particles, as with bituminous concrete.

Corrugations, Ravelling, and Pot-holing.

High quality surfaces must be both dense and stable, i.e. resistant to displacement and to liability to corrugate.

Long wave corrugations, about 30 in. in wave length, have been noticed by the writer on roads possessing well-compacted subgrades of adequate bearing value, and were presumably caused by the degradation of the large quantities of flaky aggregates present in the structure. Initially, small patches of road surface were densified by the degradation products of the flaky stones under the kneading action of traffic. These areas then resulted in a bouncing action of the wheels of fast-moving vehicles which transmitted the initial depressions with a regularity common in roads composed of low quality aggregates.

The comminution of aggregates contributes to ravelling,

a surface defect in a road which is caused by portions of the mixture becoming uncoated and giving rise to a deficiency in binder. During rolling, any soft stones are crushed like lumps of clay, while better quality material seems to break by means of a shearing action along vertical or almost vertical planes (61). A poor quality aggregate soon becomes susceptible to ravelling, since the uncoated stones produced in the comminution process do not possess cohesion to resist the scouring action and the suction caused by pneumatic-tired vehicles driven at high speed. Excessive ravelling, in turn, gives rise to the creation of pot-holes, at which stage the road may be regarded as having failed.

Fillerization Phenomena.

The internal movement of the aggregate component of a bituminous mixture results unfavourably in reducing the size and perhaps the stability due to the large particles (41), but results favourably in producing a closer grading and an increase in stability due to the stiffening of the binder ingredient of the mixture by the addition of rock filler. In the analysis of samples taken from old roads the writer has observed that the bituminous binder undergoes a hardening process subsequent to the laying of the mixture. The phenomenon was especially noticeable in these portions of mixtures which lay close to the riding surface of the road and was impregnated with the fines formed from the comminution of the aggregates. Various authors, including Abraham (2), Emori (35), Pfrenkle (127), Schlöpfer (139), Taylor (165), and Wilhelm (183) have described the stiffening action of rock fines on bituminous binders. The general conclusion is that the addition of a filler, within limits stabilises the binder employed and that excessive filler renders the end product brittle.

The Effect of the Comminution of Aggregates on the Adhesion of Bituminous Binders to Stone Fractions.

Riedel and Weber (quoted from Moll (108.a)) observed that many surfacings constructed according to specification tender to destruction soon after completion. Their only

conclusion (133.a) was that the adhesion of binder to stone had not fulfilled expectations. Moisture was found to be the main cause of the trouble, by reason of its penetrating between binder and stone and displacing the binder, i.e. the particular stone was wetted by water more readily than by the binder and the stone may be called hydrophilic.

Hubbard (71) has developed a water storage test for investigating the adhesion of asphalts to aggregates in the presence of water. Oberbach (121.a), criticises the Riedel and Weber theory of hydrophilic and hydrophobic stones and the boiling test (a stone is considered hydrophobic if boiling the coated stone for a short time with water causes no appreciable separation of the binder from the stone). Oberbach suggests that the coated stones should be immersed in water at normal temperature. Mellison and Schmidt (103.a) state that the nature of the storage water has little influence on the results obtained, but Sulda, Jekel, and Haller (162) believe that when adhesion is poor, the effect of varying the pH of the aqueous medium is marked.

Ramchandani (130.a), whose conclusions have been criticised by Knight (84), has assessed the relative binder-carrying capacities of various aggregates. Knight (84), Hubbard (71), Herrmann (64.c), Hallberg (60.a), and Lee (94), agree that in studying the mutual relation of stone and binder the surface texture of the stone is more important than its chemical composition. Results given in a paper by Lee and Carter (95.a) indicate that differences in the ease of coating various types of aggregate cannot be explained only in terms of surface texture. This conclusion is substantiated by Winterkorn (187) who believes that the resistance to stripping of bitumen-coated aggregates is dependent upon the surface-physical and the chemical character of the rock.

As to the effect of the size of stone on adhesion, Geissler (54.a) maintains that the sizes of stone tested in the standard German test for adhesion (DIN. 1995) are those which are of greatest importance. Moll (108.a), however,

concludes that, in general, the adhesion qualities of ballast correspond to those of chippings from the same rock, i.e. adhesion is independent of the size of aggregate.

With regard to the effect of the type of binder, certain workers (162) contend that tar and bitumen have a similar adhesivity to a given stone. Lee (94), on the other hand, is of opinion that tars have better wetting properties than residual bitumens of similar viscosity.

Improved adhesion may be effected in various ways. Tvers (42.a) suggests efficient drying of the aggregate, Ariano (16) recommends preliminary treatment with tar oil, Geissler and Kleinert (55.a) have employed creosote oils, while Cardia (27.a), Geissler (54.a), and Lee and Carter (95) believe that the use of a small amount of filler is advantageous. In this connection, the writer considers that the breakdown of aggregates in a road mixture increases the resistance to stripping of the binder films owing to the stiffening of the binder by the injection of the rock dust formed. Klinkmann (80.a) and Hallberg (60.a) also conclude that the viscosity of the binder has a pronounced effect on the resistance to water of the binder-mineral mixture.

Conclusions:-

The writer has shown by means of the Riedel and Weber test (133.a) that crushed bituminous mixtures strip much more readily than uncrushed mixtures. On this basis, therefore, a revised procedure is suggested for the testing of adhesion.

It is proposed that, in addition to the tests normally carried out, stripping tests also be performed on mixtures which have been subjected to a standard degree of compaction which is comparable to that experienced in service. Since the extent to which crushing is effected by a standard compactive force depends mainly on the structural strength of the aggregates in question and since the normal stripping values are determined by the inherent surface characteristics of the aggregate, the results of the two types of tests will not

necessarily be in agreement. The writer is of opinion, though, that due consideration should be given to the results of the stripping tests on crushed mixtures, because it is certain that these are of practical importance.

A certain amount of filler penetrates into the binder subsequent to the comminution of aggregates in a road, resulting in a stiffening of the bituminous binder and an increase in its resistance to displacement from the stone. This effect, although advantageous, is often overshadowed by the following deleterious effects.

(1) If conditions are unfavourable, the dust created during comminution, instead of being absorbed by the binder, may surround the aggregate and impair the adhesion by insulating the aggregate from the binder. The capillary passages which are formed in the dust layer enveloping the aggregate will in turn facilitate the ingress of water and the stripping of the binder.

(2) The fracture of a coated stone creates discontinuities in the binder film. These result in the disruptive leverage effects of water and of the tangential forces exerted by traffic, and give rise to the destruction of the surfacing.

It may be mentioned briefly that the stripping phenomenon here discussed, affects the behaviour of a road in various ways, including the following:

(a) Stripping is conducive to ravelling owing to the creation of bare aggregate surfaces.

(b) The removal of the binder from the aggregate promotes instability in riding carpets which rely for their resistance to displacement on the mechanical interlock of the aggregates as well as on the bond of the binder.

(c) The displacement of binder films in road mixtures results in uncoated areas which are rendered susceptible to the scouring action of fast-moving vehicles. The writer has repeatedly made the observation that the binder-coated areas of a road are more resistant to abrasion than the dry or "hungry" portions.

(d) In road mixtures which depend on the continuity of the binder to make them waterproof, repeated rupture of the binder films eventually renders the mixtures permeable to water.

The Effect of the Comminution of Aggregates on the Surface Texture and the Skidding Resistance of a Road.

Bird and Scott (19) and Moyer (110) have investigated the problem of the skidding resistance of a road with practical tests by means of a motor cycle and a side-car skidding apparatus. Bird and Scott conclude that the condition of surface dressings is satisfactory, as regards roughness, provided that the binder holds the chippings without covering them. In this connection the writer considers that the removal of excess binder from the upper portions of the chippings brought about by stripping or attrition, may improve the surface roughness of the road.

Moyer (110) believes that an important factor in surfaces having high coefficients of friction is the presence of gritty particles which give the surface a "sand paper" texture. The writer believes that loose surface grit formed from comminution may lead to slipperiness.

Moyer (110) concludes that the glazing or polishing effect of traffic on certain surfaces is responsible for the decrease in the coefficients of friction observed for these surfaces tested wet. It is well-known that on the Witwatersrand many surfacings, in which flat faces have been worn on the poor quality aggregates (gold fields quartzite (189)), present a mosaic appearance, and display this "polishing" effect.

Wilson (186) has employed a "texture" printing method of recording slipperiness, but confesses that it is difficult to carry out. From a study of texture prints he finds that a surface becomes

- (i) progressively rougher, due to disintegration, or
- (ii) progressively smoother due to the sinking of the aggregates below the riding surface.

PART II.

THE STABILITY CHARACTERISTICS OF BITUMINOUS MIXTURES.

CHAPTER IX.

THE STANDARDISATION OF A TEST PROCEDURE FOR DETERMINING THE STABILITY OF BITUMINOUS MIXTURES.

After studying the existing mechanical tests on bituminous road mixtures (see appendix I) the Hubbard-Field and the unconfined compression tests were selected to determine the stability characteristics of bituminous paving mixtures.

Since the results of any mechanical test depend upon

- (1) the type of specimen employed, its dimensions, and the way in which it is prepared, and
- (2) the procedure followed in the test;

it is necessary to consider the effect of these variables.

(a) THE EFFECT OF THE HEIGHT-DIAMETER RATIO.

In both the Hubbard-Field and the unconfined compression test two-inch diameter specimens were employed, except where otherwise stated. These were compacted to approximately one inch in height in both tests.

Hubbard and Field (75.a) suggest 1 in. high briquettes in the 2 in. dia. stability apparatus designed by them, while Vokac (172) uses specimens of similar dimensions in the unconfined compression test.

Vokac (169) finds that cylinders of the same density and diameter to height ratio have approximately the same unit compressive strength, but Pfeiffer (126) considers that a diameter to height ratio of 0.5 or less is essential for the "true compressive strength" to be obtained.

Vokac uses the same rate of compression for both sizes of cylinder (1.13 in. and 2 in. dia.) but Skidmore (151) finds

that the shear strength is independent of the size of specimen if the rate of load application is made proportional to the diameter of the cylinder. In carrying out shear tests, Lee and Markwick (96) have found that when the same stress is applied to specimens of different sizes, the rate of strain is independent of the length of the specimen when the width and thickness are kept constant, and independent of the thickness when the length and width are kept constant.

Endersby (36) maintains that in Mohr circle tests the height-diameter ratio should be kept at least above 2 if the "true characteristics" of the material are to be evaluated, confirming the findings of Pfeiffer (126).

Knight (81) has published results showing how the number of blows in the Page impact test depends on the height of specimen employed.

Experimental Work.

(1) Unconfined compression test. The writer investigated the effect of the height of the test specimen as follows: Test cylinders of various heights were prepared in a 2 in. dia. steel mould using a consolidation pressure of 2500 lb. per sq. in. For this purpose increasing quantities of sub-angular river sand, -No. 10 + No. 35 (Tyler) in size, were combined with 5 per cent (by weight) 200 penetration bitumen in increasing quantities from about 50 to 150 gms. Compression took place at 0.05 in. per min. after the test pieces had been immersed in a water bath at 22°C. for two hours, in testing the cylinders were enveloped in water at the same temperature.

Figure 20 and table XIII illustrate the test results.

Conclusions:-

If the diameter of a specimen is kept constant, an increase in its height causes

- (1) a decrease in compressive strength (lbs per sq. in.),
- (2) a decrease in the rate of decrease in compressive strength.

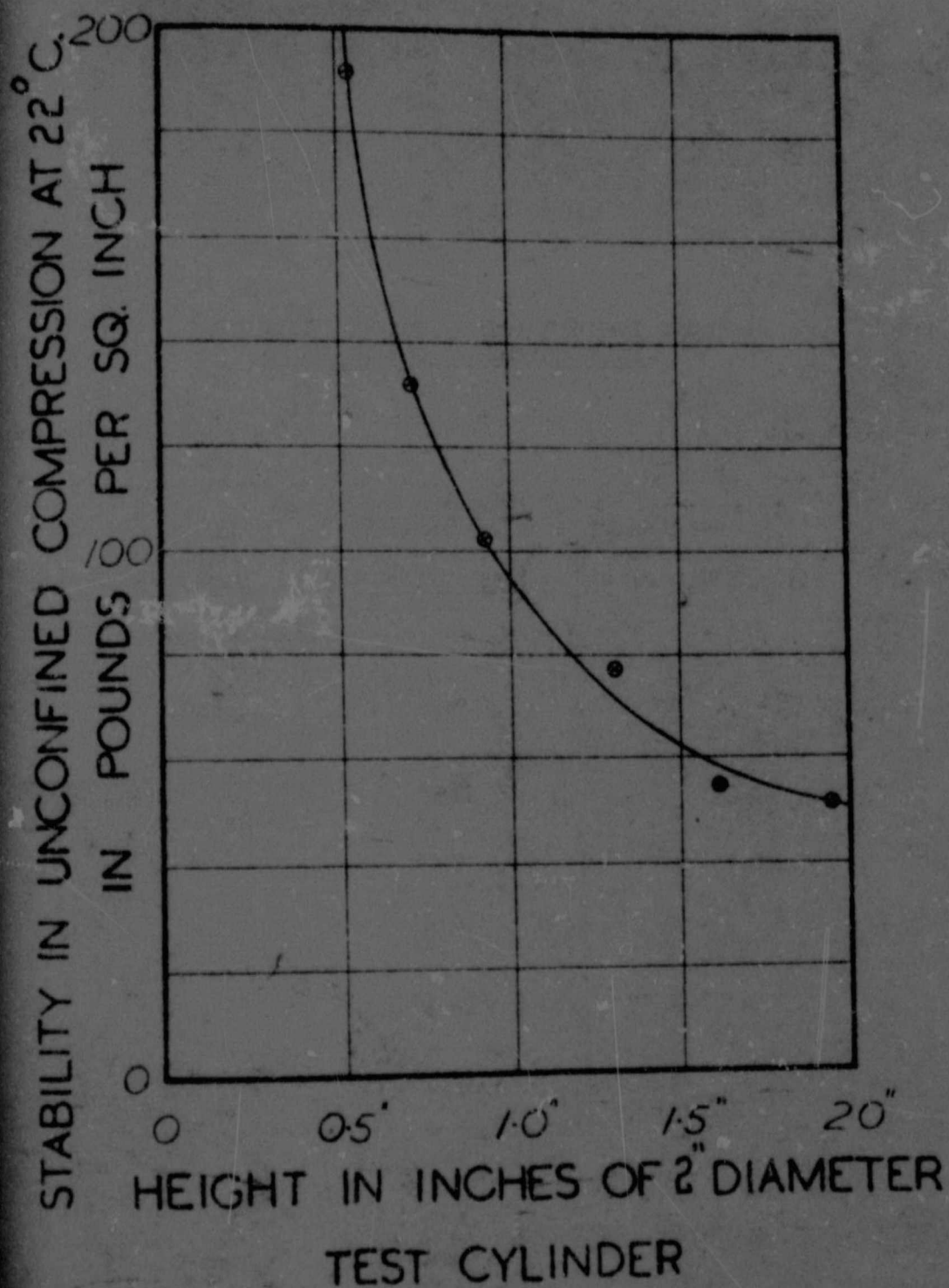


FIGURE 20. Effect of Height of Specimen on Unconfined Compression

TABLE XIII EFFECT OF HEIGHT OF TEST SPECIMEN
ON UNCONFINED COMPRESSION VALUE.

Height of Specimen in Inches	Height Diameter Ratio	Unconfined Compression in Lb. @ 22°C.
	= $\frac{\text{Height in Inches}}{2 \text{ Inches.}}$	
0.53	0.27	192
0.71	0.35	132
0.92	0.46	101
1.30	0.65	78
1.61	0.82	55
1.95	0.97	52

(11) Hubbard-Field stability test. The test was repeated by using the same mixture in 2 in. dia. Hubbard-Field moulds (75.a). These were compressed at 2500 lb. per sq.in., the test procedure being similar. In both this and the previous test, the density of the compressed mixtures remained approximately constant for the different specimens. Duplicate series of specimens were prepared, the first series being tested with the shear ring of the apparatus removed and the second in the normal manner.

The results have been plotted in figure 21.

Conclusions:-

(1) The Hubbard-Field stability value increases with an increase in the height of the test specimen, the rate of increase becoming less as the height of specimen is increased.

(2) The friction value is proportional to the height of the specimen, the friction line representing the friction on the sides of the mould opposing extrusion of the specimen when the shear ring is removed.

(3) The shear ring in position causes an extra effect, a shear value = total Hubbard-Field stability value minus the friction value.

(b) THE EFFECT OF COMPACTION.

The usual methods for consolidating bituminous mixtures in laboratory tests are tamping, direct compression, vibration, rolling, or a combination of these processes. Owing to the granular nature of these materials the ultimate mean density obtained depends on compaction conditions.

The density of specimens moulded from both ends is usually less than for specimens moulded against a plate: for the latter cylinders there is a density gradient from top to bottom. The latter method of compaction was employed in the laboratory due to its correlation with conditions existing in practice due to the passage of rollers and traffic. Howe and Hughes (67.8) obtained a reverse distribution in practice, i.e. a density in the lower half of the carpet which was 75 per cent greater than that of the top half. They

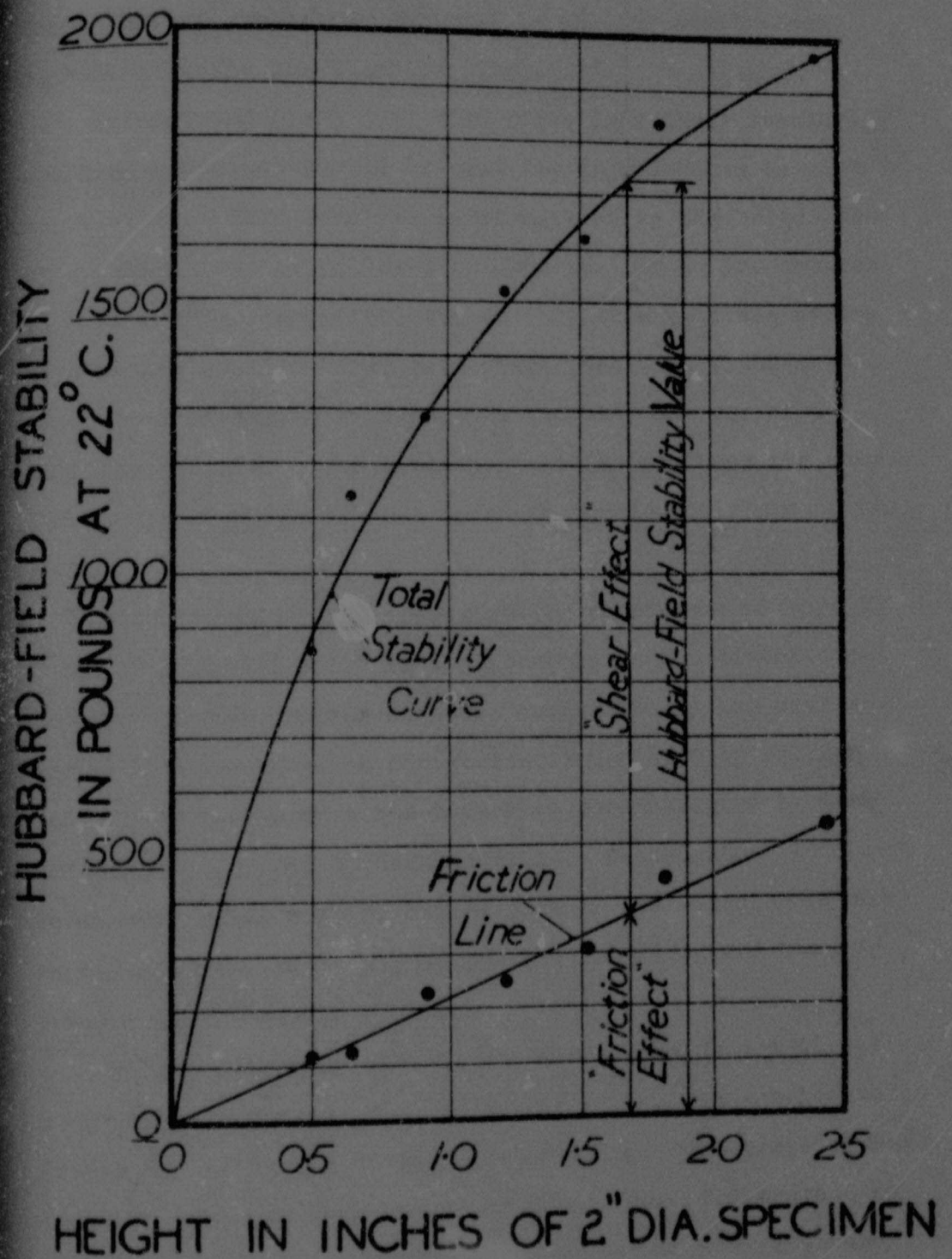


FIGURE 21. Analysis of Hubbard-Field Stability.

believe this to be due to the lower half of the carpet being warmer during rolling (99.).

Since the structural strength of a bituminous mixture generally increases with its density (as will be shown later), the method of compaction employed in all the widely-used mechanical tests has been specified.

Hubbard and Field (74) (75) state that their standard moulding technique should be used for reproducible results to be obtained. This consists in consolidating the briquettes by standard tamping followed by 3000 lb. per sq.in. compression at 250°F. West (181) states that this produces cylinders with a smaller voids percentage than that found in the road after intensive rolling. He suggests the use of a laboratory roller machine which he claims produces the same percentage of voids as that found in the same mixture on the road.

It is thought that a road roller compacts a mixture by a kneading action which is not possible in the direct compression or the tamping method. Pauls (123.a) has devised a sector machine in which compaction is achieved by rolling. Laboratory roller machines have also been designed by Adam and Murdoch (4) and by Neumann (111). Macnaughton (103) has shown that power tamping avoids some of the crushing of the aggregate produced by direct pressure moulding and has devised a power tamping machine.

Unless otherwise stated, the writer has used a direct compression pressure of 2500 lb. per sq.in. In service tests (described in Part I of this dissertation) this pressure was found to give the same amount of break-down of aggregate as 15 to 20 passes of a 10-ton Diesel roller on a water-bound macadam base.

(c) THE EFFECT OF AGEING.

All substances undergo a change on being exposed to air, moisture, and sunlight. Bituminous substances are not immune from such action. Abraham (1) states that the changes brought

about in bituminous substances upon exposure to the elements involve one or more of the following reactions:-

(i) Evaporation, i.e. "a loss of volatile constituents on exposure to air and the sun's heat."

(ii) Oxidation. "This takes place on exposure to air and progresses more rapidly at high than at low temperatures."

(iii) Carbonization. "This represents the formation of 'free carbon' in a bituminous material, and is induced by an extensive elimination of hydrogen."

(iv) Polymerization. "This is due to a condensation of the molecules and manifests itself by a hardening or setting of the substance, which has also been termed 'trixotropy' or 'spontaneous hardening'."

(v) Effects of moisture. "All bituminous substances are more or less affected upon exposure to moisture, which manifests itself in two ways, namely by the actual absorption of water and by the gradual leaching out of soluble constituents. These actions become intensified when the substance has oxidised, since oxygenated substances have a greater affinity for water than the hydro-carbons themselves."

The writer has found that storage largely increases the strength of bituminous mixtures, especially when tars or cut-back bitumens are used.

In order to eliminate the factor of ageing and its effects the writer decided to make extensive use of straight-run bitumens in his researches. These bitumens were found suitable for comparative tests and the chief advantage of their use was that the specimens were "cured" directly after compaction by immersion in a water bath at 22°C. for two hours.

(d) THE EFFECT OF THE TEST TEMPERATURE.

In Part I of this dissertation it was illustrated that the fluidity of some binders is more susceptible to temperature changes than others. It is comparatively easy to determine the degree of such effects in stability tests.

In the field of testing, unless a series of tests is run at different temperatures on each material (39) which would be expensive in a routine programme, there remains the problem of selecting the most representative testing temperature.

Flister (47.8) tested mastic over the range of 30°C. to -20°C and found that the material had a maximum tensile

strength at 0°C. Lonsdale (99) gives the results of compression and shear tests obtained by Vokac and Skidmore, respectively, which indicate that the compressive and shear strengths are approximately halved for every 20°C. rise in temperature between 0°C and 60°C.

The German standard temperature for testing is 22°C., but Neumann (111) also uses 50°C. Vokac (172) expresses the belief that the open compression value at 25°C. is very useful.

After making a study of the effects of temperature, the writer has adopted the temperature of 22°C. (corresponding to the German standard temperature) for comparative tests. It has been found that slight variations from 22°C. do not greatly affect the data.

Neumann (110.a) has recorded a maximum road temperature (presumably in a surface course) of 60°C. so that the Hubbard-Field test temperature of 60°C. has some basis in practice, viz. being the highest summer temperature normally to be expected. The question arises, does more deformation take place when conditions are worst (i.e., in the relatively short period of hot weather), than in the longer period of moderate temperatures? The answer to the problem seems to be that the test temperature should be adjusted to the climate in which the material is used.

(e) THE EFFECT OF THE RATE OF TESTING.

The writer has used 0.05 in. per min. Other investigators, such as Hubbard, Hveem, and Vokac, have found in quasi-static tests that a certain correlation exists between their tests and observed field results, although irregularities of pavement and oscillations of springs (36) add the factor of impact to that of a brief duration of pressure.

Conclusions:-

The two tests, the Hubbard-Field and the unconfined stability tests, as developed by the writer, have been useful for comparative purposes as will be seen later. It will be noticed that cubical aggregate as coarse as $\frac{1}{2}$ in. + $\frac{3}{8}$ in.

in size has been used in the 2 in. dia. Hubbard-Field apparatus, despite the statement of the designers (75.a) who state (without published proof), that the 2 in. dia. test specimen and mould,

"make it impossible to test....fine graded asphaltic concrete, in which.... the percentage of aggregate retained on the 10-mesh sieve exceeds 35 per cent of the total."

The writer, on the contrary, has found that the 2 in. dia. Hubbard-Field apparatus may be used extensively for fine graded asphaltic concrete. Excellent correlation has been obtained with the unconfined compression test performed on the same material.

CHAPTER X.

FACTORS AFFECTING THE BINDER REQUIREMENTS AND STABILITY OF BITUMINOUS MIXTURES.

In practice, many factors are encountered which affect the behaviour of a bituminous road surface, including the properties of the various ingredients, the method of construction, temperature conditions, and the type of foundation employed. Laboratory tests have shown that some of these factors have considerable effect on the structural strength and the optimum amount of binder required in a bituminous mixture.

1. The Degree of Consolidation.

It has been found that in most mechanical tests the stability of a test piece generally increases with increase in density. Hubbard and Field (75.a) stress the importance of obtaining maximum compaction during the construction of pavements which are to be subjected to severe traffic conditions immediately after laying. They believe that their stability test, applied to core samples taken from a pavement, gives reliable information as to whether or not the pavement has been thoroughly and uniformly rolled.

(a) Binder Content as Variable. The writer used 100 gms. of cubical $-3/8$ in. + No. 4 dolomite and, using a 200 pen. bitumen and a 2 in. dia. mould, made three series of test specimens, employing an amount of binder equal to 0, 0.5, 1.0 2.0 per cent by weight of the stone. The consolidation loads used in the three series of tests were 3000, 7550, and 20000 lb., respectively. The approximate height of the compacted specimens was one inch. The specimens were immersed in water for two hours and tested in unconfined compression. Figure 22 and table XIV show the results of these tests.

Conclusions. It is concluded that:-

(i) the stability of the mixtures increases with the con-

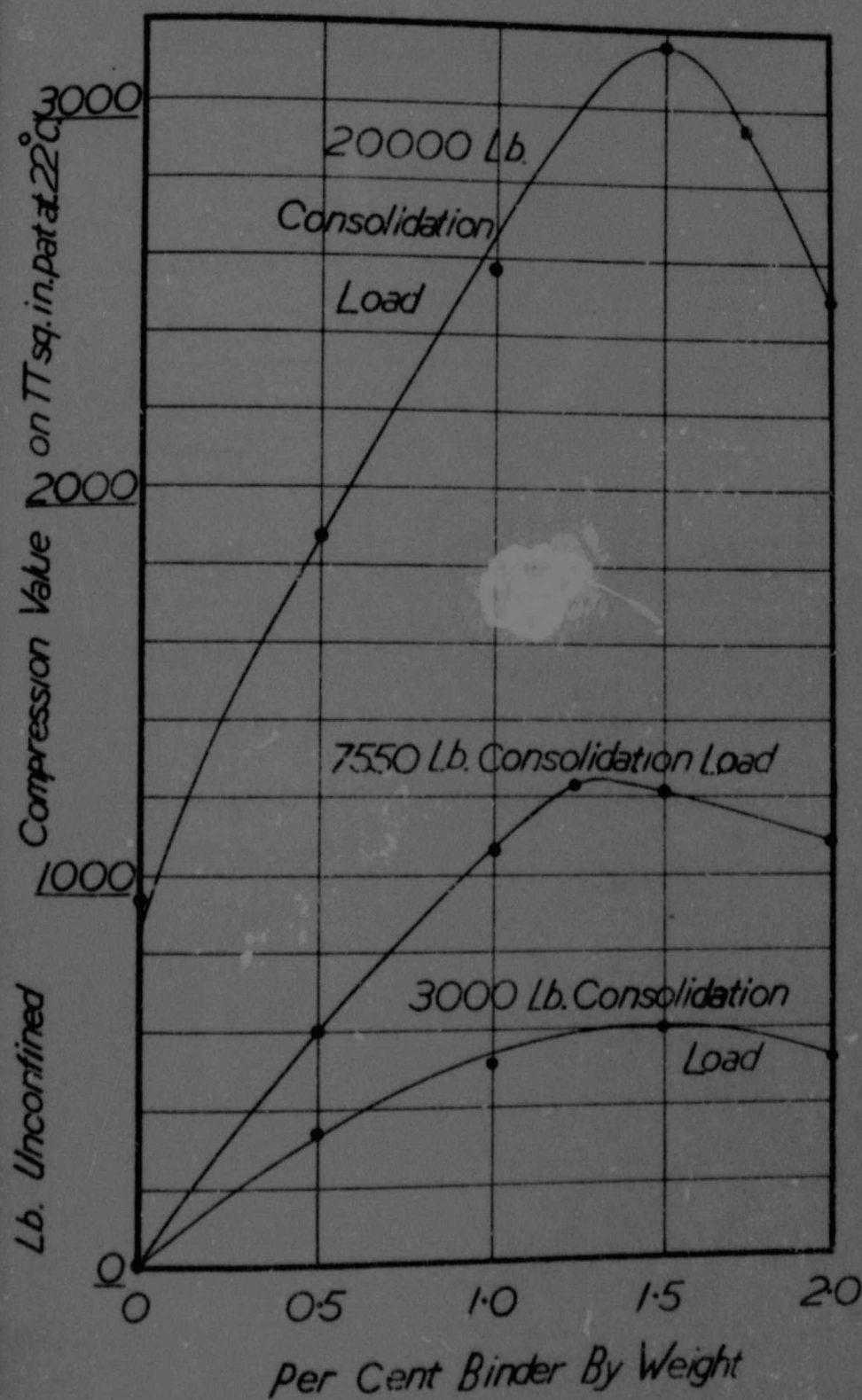


FIGURE 22. *Effect of Consolidation on Stability.*

TABLE XIV EFFECT OF CONSOLIDATION ON STABILITY.

CONSOLIDATION LOAD	MAXIMUM STABILITY IN LB.	OPTIMUM % BINDER BY WT.
3,000 lb.	600	1.5
7,550 lb.	1,240	1.3
20,000 lb.	3160	1.5

Author Croeser H M W

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