

~~AN INVESTIGATION INTO THE~~
SEGREGATION OF PARTICLES
IN GRANULAR MASSES

A THESIS SUBMITTED TO THE
UNIVERSITY OF LONDON
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY.

BY

MAHMOOD AHMAD QAZI

M.Sc, (TECH).

DEPARTMENT OF CHEMICAL ENGINEERING,
IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY,
LONDON - S. W. 7.

DECEMBER - 1965.

ACKNOWLEDGEMENT

The author wishes to express his sincere thanks and deepest gratitude to Emeritus Professor D.M. Newitt, M.C., D.Sc., F.R.S., for the supervision, encouragement and the constant invaluable advice given to him in the course of the present investigation.

Thanks are also due to Mr. J.S. Oakley and the members of the workshop for their help in the construction of the apparatus used in this work.

The author is indebted to The Attock Oil Company Ltd., Rawalpindi; Ghulam Mohayyuddin Foundation, Chittagong and the Pakistan Council of Scientific and Industrial Research, Karachi for the financial assistance which enabled him to undertake this work.

A B S T R A C T

AN INVESTIGATION INTO THE SEGREGATION OF PARTICLES IN GRANULAR MASSES

The thesis deals mainly with a study of the mechanism by which segregation may be made to occur in a granular mass composed of particles of the same composition but of two size ranges or a mass consisting of particles of the same size range but of two differing densities. The object was to ascertain whether by a suitable design of separator a continuous separation could be effected.

The materials used were (a) sand of varying size ranges and (b) mixtures of Coal and Magnetite. The flow characteristics of these materials were examined and, in particular, measurements of the Angle of Repose of the single materials and of mixtures were carried out.

A quantitative study was made of the segregation occurring when conical heap of material was formed by flow from a hopper.

A series of separators were designed in which one section consisted of a cone and the other a cylinder or cones of various angles. The separators were provided with a continuous feed arrangement and could be rotated about their longer axis at various speeds.

The Angle of Repose of the feed material and the shape of the vessel were found to be important factors in effecting complete separation. The mechanism of separation, however, was found to be complex and whilst complete separation could usually be obtained, the optimum conditions had to be found by experiment.

The effects of feed rate, rate of revolution and residence time were determined.

.....

ERRATA

PAGE	LINE	READ	FOR
Contents	Chapter 6	HEADS	HEADS
72	Fig 12 A	$Mg \sin \beta$	$Mg \cos \beta$ (tangential)
89	5 of Paragraph	greater	less
131	8	multiplied	divided
135	11	h_1	h
	last	delete	16
136	9	h_2	h
	last	delete	16
138	8	h_1	h
139	7	h_2	h
241	7	$(\mathcal{I}_R - \mathcal{I}_0)$	$(\mathcal{I}_0 - \mathcal{I}_R)$
242	2	$(\quad)$	$(\quad)$
	9	$\mathcal{W}_R (\mathcal{I}_R - \mathcal{I}_0)$	$\mathcal{W}_R (\mathcal{I}_0 - \mathcal{I}_R)$
	16	$(\mathcal{I}_R - \mathcal{I}_0)$	$(\mathcal{I}_0 - \mathcal{I}_R)$
243	1	Analysis	Analyses
	4, 11	$(\mathcal{I}_R - \mathcal{I}_0)$	$(\mathcal{I}_0 - \mathcal{I}_R)$
232	17	$\left[(-1.0)^2 + (0)^2 - - - (-1.0 + 0 + - -)^2 / 12 \right] / 12 - 1$	
233	1	$0.742 / \sqrt{12}$	$0.742 / 12$
265	13	delete	π
	14	πr_1^2	r_1^2
	15	πr_2^2	r_2^2
267	last	$\left[e_m / 2 \cdot r_m^2 - 1/2 r_m^2 \sin e_m / 2 \right] h$	
269	Def 13	April 1957	1953
271	Def 37	J.C. Richards	BCRA Bull. 147 April, 1955
	Def 40	Donald MB & Roseman. B.	

CONTENTS

CHAPTER 1

INTRODUCTION	1
--------------	---

CHAPTER 2

GLOSSARY OF TERMS	4
NOMENCLATURE	12

SECTION I - LITERATURE SURVEY

CHAPTER 3

ANGLE OF REPOSE	14
-----------------	----

CHAPTER 4

SEGREGATION OF PARTICLES	42
--------------------------	----

SECTION II - EXPERIMENTAL

CHAPTER 5

ANGLE OF REPOSE	71
-----------------	----

CHAPTER 6

SEGREGATION IN HEADS	102
----------------------	-----

CHAPTER 7

SEGREGATION IN ROTARY VESSELS	149
-------------------------------	-----

CHAPTER 8

SUMMARY AND CONCLUSIONS	255
-------------------------	-----

APPENDIX

I, II AND TABLES	258
------------------	-----

BIBLIOGRAPHY

269

CHAPTER 1.INTRODUCTION

The properties of a particulate mass are in some respects akin to those of liquids and in others to those of homogenous solids in ^{the} plastic state. Thus in pneumatic conveying and in 'fluidised' beds, the particle - fluid system obeys many of the laws of fluid flow. When tightly packed as in hoppers or tablets the mass may undergo plastic deformation, cleavage and fracture. It has, however, some additional unique properties, which depend upon particle size, shape, density and frictional resistance. If, for example a particulate mass comprised of particles of two different sizes or of uniform size but different densities is allowed to form a heap on a horizontal surface, the heap will be of conical shape and the angle at the base of the cone will have a limiting value known as the angle of repose. But in addition it is found that during the formation of the cone, partial segregation of the particles according to size or density takes place. The phenomenon is well known and is responsible for certain

practical difficulties which arise when handling particulate materials. Thus segregation may interfere with the free flow of material from hoppers or the movement of ^{the}burden in furnaces. It may lead to undesirable chemical changes in mixed fertilizers and may contribute to caking or agglomeration in storage. But controlled segregation might also be made use of as a means of separating mixed particles in place of the conventional methods of sieving or elutriation. It is this possibility which has been investigated in the present work, the object being to devise a continuous process for separating particles according to size or density from a mixture by making use of ~~the~~ momentum differences.

A preliminary consideration of the problem suggested that for effective separation, the mass would have to be kept in continuous movement in a vessel so shaped that the inclined surface of the contents could be maintained at or near the dynamic angle of repose. Before setting out to design such a vessel, however, it was thought necessary to standardise a method for measuring the angle of repose, determine the effect of particle size and density on the angle and ascertain the

3.

extent of segregation in a cone of material formed by flow from a hopper which was so designed as to minimise the extent of segregation of the discharge. Much of this information is available in the literature, but there are, in certain cases, contradictory results or errors of method, which are difficult to reconcile.

It was also considered desirable at the outset to give clear definitions of some of the terms found in the literature, and not infrequently misused. These will be found in Chapter 2 together with a list of symbols employed in this thesis.

CHAPTER 2.(a) GLOSSARY OF TERMS1. AGGLOMERATE:

Assemblage of particles rigidly joined together as by partial fusion (sintering) or by growing together.

2. AGGREGATE:

Assemblage of particles which are loosely coherent.

3. ANGLE OF FRICTION (θ):

The angle where a material just begins to slide over an inclined surface. It is defined by the equation -

$$\tan \theta = F/N$$

where F = frictional force

& N = Load

θ is the angle of friction.

4. ANGLE OF INTERNAL FRICTION (β):

The angle assumed by the interface when a layer of granules just slides, under the influence of gravity, over a stationary layer of the same material.

5. ANGLE OF REPOSE (α):

The maximum angle assumed by the boundaries of an uncontained granular material in static equilibrium with ^{the} surrounding fluid medium (usually air).

6. ANGLE OF RUPTURE (δ):

A somewhat indeterminate angle which usually differs only slightly from the angle of internal friction. It may be defined as the angle assumed by the interface when a layer of granules moves in bulk over a stationary layer of the same material.

7. ANGLE OF SLIDE:

Represents frictional forces between granules of a solid material and an inclined surface. For all practical purposes the surface must be specified.

8. ANGLE OF WALL FRICTION (γ):

A measure of frictional resistance of the wall of a container to the motion of a granular mass in contact with it.

9. ANGULAR:

Sharp edged or having roughly poly-hedral shape.

10. BRIDGING:

Formation of arches of keyed or jammed particles across the direction of flow.

11. BULK DENSITY (ρ_B):

The weight per unit volume of a quantity of solid particles measured under stated conditions. Usually expressed as lbs/ft^3 or gms/cc .

12. CLASSIFICATION:

Grading of particles in accordance with size, shape or density.

13. COEFFICIENT OF FRICTION (μ):

The ratio between perpendicular pressure and tangential pressure existing between surfaces in contact. Denoted by μ coefficient of friction is $\frac{P_n}{P_t}$.

14. COHESION:

The tendency of materials of like composition to hold (stick) together due to intermolecular forces of attraction.

16. DENSITY (ρ):

The weight per unit volume of the particle (material) expressed as lbs/ft³ or gms/cc.

17. DYNAMIC ANGLE OF REPOSE (α_d):

The angle with the horizontal which the surface of a cone of material forms while the particles are still in motion.

18. ELECTROSTATIC CHARGE:

Unbalanced distribution of electrons on the surface of particles that influences their attraction or repulsion from other particles or a container surface.

19. EQUIVALENT FREE FALLING DIAMETER:

Diameter of a sphere which has the same density and same free falling velocity in a given fluid as the particle.

20. EQUIVALENT SURFACE DIAMETER:

Diameter of a sphere which has the same effective surface as the particle when determined under stated conditions.

21. EQUIVALENT VOLUME DIAMETER:

Diameter of a sphere which has the same effective volume as the particle, when determined under stated conditions.

22. FLOWABILITY:

Properties of a powder which determine its ability to flow under stated conditions.

23. FREE FALLING VELOCITY:

Velocity of fall of a particle through a still fluid at which the effective weight of the particle is balanced by the drag exerted by the fluid on the particle.

24. FRIABILITY:

Tendency of the particles of a powder to break down in size during storage and blending under the influence of small mechanical forces.

25. GRANULE:

An agglomerate of particles that itself behaves like a particle.

27. LUBRICANT:

Material added in solid or liquid form to assist the movement of particles during flow or compaction.

28. PARTICLE MEAN SIZE:

Dimensions of a hypothetical particle such that if a powder were wholly composed of such particles, it would have the same value as the actual powder in respect of some stated property. It is also called 'average particle size'.

29. PERCOLATION:

The mechanism by which fine particles pass (filter) through the voids of the bigger particles.

30. PERFECT MIXING:

Arranging particles in a mixture such that the individual particles of any one species are distributed with uniform spacing among all other particles.

31. PERMEABILITY:

Facility with which a porous mass e.g. a powder bed permits ^{the} passage of ^a fluid.

32. POROSITY:

Ratio of volume of open pores or voids to the total volume of the material.

33. PROJECTED DIAMETER:

Diameter of a circle which has the same area as the projected profile of the particle in its most stable condition.

34. ROUGHNESS:

ϵ of a surface is considered to be the average depth of interstices between the particles making up the surface. Roughness index (ϵ) is proportional to the average diameter of the particles making up the surface.

35. SEGREGATION:

Separation of constituents during handling transportation, blending or processing of a mixture or separation of particles of the same density according to size.

36. SHAPE FACTOR:

can be defined as a measure of the sphericity of a particle, based either on particle surface or volume measurements.

37. SIZE DISTRIBUTION:-

Distribution of size fractions in a powder.
 Separation of particles of different sizes by sieving or other methods.

38. SIZE FRACTION:

Portion of a powder composed of particles between two given size limits. It may be expressed in terms of weight, volume, surface or numerical frequency.

39. SLIDING COEFFICIENT OF FRICTION:

is the tangent of the angle at which a surface must be inclined in order to continue the sliding of material on it.

40. SPECIFIC SURFACE:

Surface area of the particle in a unit mass of powder determined under stated conditions. It is generally expressed as sq. cm/gm upto a value of 10,000 and sq. m/gm for higher values.

41. STANDARD DEVIATION:

Statistical measure of how much the concentration of one component in a sample varies from the true concentration that characterises the entire mixture.

42. STATIC ANGLE OF REPOSE:

is the angle with the horizontal which the surface of a cone of material makes in its most stable configuration.

43. STATIC COEFFICIENT OF FRICTION:

The tangent of the angle at which a surface must be inclined in order that the particles resting on it ^{may} start sliding down the plane.

(b) NOMENCLATURE

<u>SYMBOLS</u>	<u>MEANINGS</u>	<u>DIMENSIONS</u>
A	Area of cross-section	L^2
a, b, c	Constants	--
C	Force of cohesion	MLT^{-2}
D_{ave} , d	Average diameter of a particle	l
f	Heywoods Shape Factor	--
f_s	Surface shape coefficient	--
f_v	Volume shape coefficient	--
F	Frictional force	MLT^{-2}
$\mathcal{F}$	Percent of fines present in a sample	--
$\mathcal{F}_o$	Percent of fines in the original mixture	--
g	Accelaration due to gravity	LT^{-2}
$\mathcal{R}$	Percent of dense material present in a sample	--
$\mathcal{R}_o$	Percent of dense material in the original mixture	--
k & k'	Constants	--
m	Mass of a particle	M
M_e	Degree of mixing at steady state	--
n	Specific surface	L^{-1} , $L^2 M^{-1}$
N	Number of particles per sample	--
P	Perosity or fractional voids	--
P_n	Normal pressure	$ML^{-1}T^{-2}$
P_t	Tangential pressure	"

<u>SYMBOLS</u>	<u>MEANINGS</u>	<u>DIMENSIONS</u>
r	Radius of a circle	L
s	Standard Deviation	--
S	Boundary surface at any instant	L^{-1}
S_0	Maximum surface / Volume	L^{-1}
t	Time	T
v	Voidage	--
V	Velocity	LT^{-1}
X	Fraction of material unmixed at any time.	--
α	Angle of repose	Degrees
β	Angle of internal friction	"
γ	Angle of wall friction	"
δ	Angle of plane of rupture	"
θ	Angle of friction	"
ρ	Density of material/ ^{or} particle	ML^{-3}
ρ_b	Bulk density	"
ρ_t	True density	"
μ	Coefficient of friction	--
ϵ	Surface roughness	L
σ	Theoretical value of standard deviation	--
ϕ	Demixing potential	--
η	Efficiency factor for a machine	--
ϕ	Degree of segregation	--
Φ	Total volume of solids	L^3
φ	Degree to which the voidage of one component is saturated by the other.	--
1,2,3	Subscripts indicate number of a component.	

CHAPTER 3.LITERATURE SURVEY
THE ANGLE OF REPOSEINTRODUCTION:

Rankine (1) was the first to put forward in 1858 the concept of a coefficient of friction for particulate materials. He said that the resistance to displacement by sliding along a given plane in a loose granular mass is equal to the normal pressure exerted between the parts of the mass on either side of that plane multiplied by a specific constant called the coefficient of friction of the mass and is equal to the tangent of angle of repose.

$$\text{The angle of repose} = \tan^{-1} \mu = \tan^{-1} \frac{P_n}{P_t} \quad (1)$$

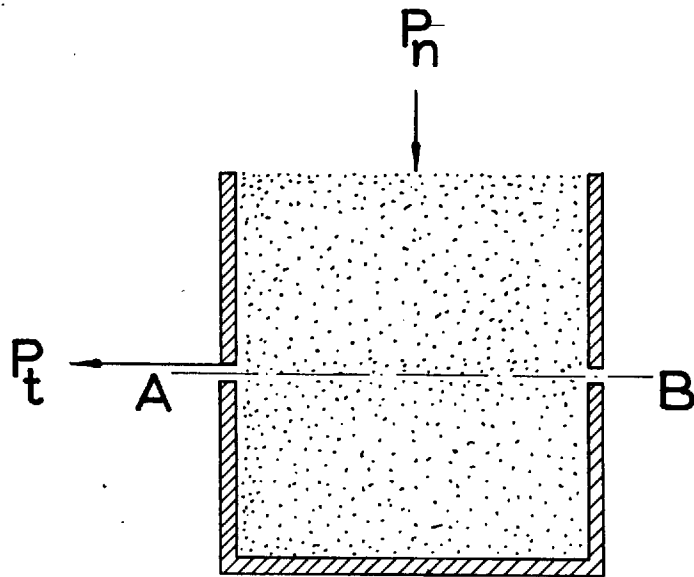
where P_n and P_t are normal and tangential pressures. Later in 1883, Darwin (2) carried out experiments using an apparatus in which he measured the force required to keep a hinged door in position against a mass ~~of sand~~ of sand; he found a big difference between the observed values of the angle of repose and the values calculated on the basis of Rankine theory. He stated that "the discrepancy is enormous

the and Rankine theory may safely be neglected". The discrepancy found by Darwin is due to the fact that he was comparing the angle of repose, determined by pouring the material into a heap, with the angle of friction calculated from Rankine's Theory, which is always higher.

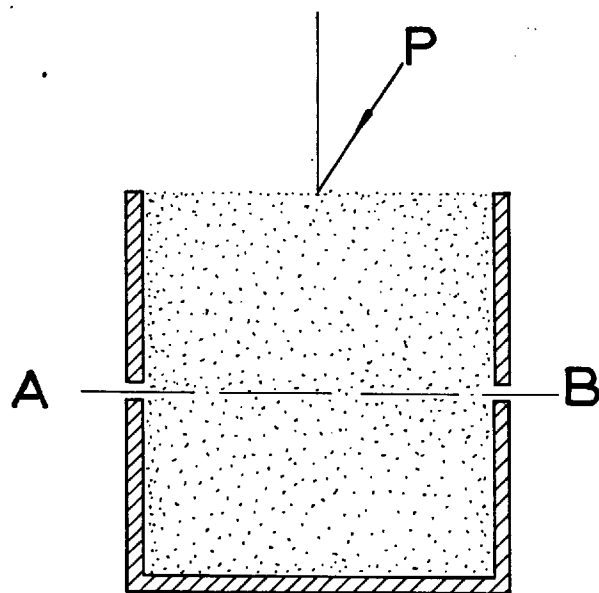
Later workers have accepted Rankine's Theory. Wilson (3) found results in full agreement with this theory. He also found that the coefficient of friction increases with moisture upto a maximum after which it begins to decline. Crosthwaite (4) was able to varify Wilson's observations on the effect of moisture on the coefficient of friction. He said that for sand and granular materials Rankine's theory holds provided the angle of friction and not the angle of repose is taken as the calculated value.

Ketchum (5) used an apparatus to measure the angle of friction which consisted of two identical boxes filled with the same material placed over one another as shown in figure(1). P_n is the normal pressure applied to the top box and P_t is the tangential pressure required to move the box along the plane A.B. The coefficient of friction is, therefore,

Fig(1)



(a)



(b)

17.

given by a ratio of the two forces according to:

$$\mu = \tan \theta = \frac{P_n}{P_t} \quad (2)$$

where θ = angle of friction.

He found that the angle of friction thus measured is nearly always larger than the angle of repose, i.e. the angle at which a material will stand if poured in a pile on a horizontal floor. He has also drawn attention to the results of Goodrich (6) and Hamieson (7) which are in agreement with his results and support his conclusions.

In 1954, Richter (8) measured the static and sliding coefficient of friction of chopped grass, corn, silage and hay etc. sliding on galvanised steel in order to obtain data for the design of chutes. Polished surfaces reduced the coefficient for dry materials, but had less effect on that of wet material, which may be due to adhesion associated with the high moisture content of these materials.

Later Holbrook and Fraser (9) showed that whereas the coefficient of friction of a granular mass composed of cubes is the same for all size cubes, in the case of irregular sizes of granules, ~~the large granules~~ have a smaller /
coefficient than the

smaller sizes. They attributed this to an increase in the surface to volume ratio as the particle size decreases. They quote experiments by Lanza (10) which have demonstrated that friction varies according to the area of rubbing surfaces.

It has been shown by Train (11) in a critical survey, that there are at least five methods for measuring the angle of repose of granular solids, namely:

1. Fixed funnel method,
2. Fixed diameter cone method,
3. Tilting box or slide method,
4. Revolving cylinder, and
5. A circular disc of fixed diameter immersed in a container of granular solids in which the granules are allowed to escape from the bottom, leaving a **cone** of solids on the disc.

He concludes that the surface slopes of a heap measured by the above methods may vary by as much as 3° ; For spheres, irrespective of the type of the material and size, the calculated slope was a function of the type of packing on the surface and varied from 19.3° to 45° , depending on the packing. In practice,

however, a surface consists of a random distribution of regular packings and the two boundary values are found to be 22.5 and 27.5° . Train considers that the angle of repose is the result of what he calls "interparticulate friction".

More recently Pratap (12) has compared the angle of repose given by the following methods:

1. Inclined tube with a slit,
 2. A box with a slit at the bottom, from which the material could be drained. The angle which the wedges of material left behind made with the horizontal was taken as the angle of repose, and
 3. Moving funnel method,
- in addition to methods 4 & 5 used by Train.

His conclusion is very similar to that of Train that "the angle of repose, when measured by different methods lies between two limits ~~and a parti-~~
~~cular value is~~ determined by the method used". He adds, however, that if various sources of error are eliminated, the angle of repose should be independent of the method used.

Zenz (13) considers that the dynamic angle of repose is more important than the static angle as it is found in all cases where the bulk of material is in motion; the static angle is a limiting case.

Fowler and Chowdzeisner (14) using the tilting box method and dry granular materials of varying shape and density derived an empirical equation of the form

$$\mu = \tan \theta = a.n^2 + b \sqrt{\frac{\epsilon}{D_{ave}}} - c.p + d \quad (3)$$

where a, b, c & d are constant

n = specific surface (cm^2/g)

p = density (g/cm^3)

D_{ave} = average diameter (in)

μ = coefficient of friction

θ = angle of friction

ϵ = surface roughness (cm)

The roughness of the surface is taken as the average depth of interstices between the particles composing the surface. The roughness index ϵ is, therefore, proportional to the average diameter of the particles making up the surface.

It will be noted from the equation that " ϵ/D_{ave} " may be considered as a relative roughness factor and where this is equal to unity i.e. mate-

rials are sliding over themselves, the angle of friction equals the angle of repose and is independent of the diameter of the granules. This is also apparent when $\frac{\epsilon}{D_{ave}} = 0$ i.e. the surface is smooth.

When the material is sliding over itself, i.e. $\frac{\epsilon}{D_{ave}}$ is unity, the values of shape factor and density when substituted in equation (3) will give the coefficient of friction and consequently the angle of repose of the corresponding material. The values have been compared with those obtained experimentally in table (I).

From the following table, it will be seen that the calculated values of the angle of repose for the first five materials-based-on equation (3) are higher than the experimental values, Ballotine giving rather high value. The last three materials i.e. coal, limestone and hematite give high/^{calculated} values of the angle of repose because the values of their shape factors fall outside the range (0.67-1.0) for which this equation has been specified.

Krishna (15) carried out similar experiments with sand and coal using both sharp cuts and various mixtures of fine and coarse fractions. The sharp

TABLE I

NO	MATERIAL	PARTICLE SIZE		DENSITY ρ	SHAPE FACTOR	ANGLE OF REPOSE α	
		MESH	INCHES			CALCULATED	OBSERVED
1	LEAD SHOTS	18/25	305.5×10^{-4}	11.34 g/cc	1.0	28.5°	28.0°
2	SEEDS	18/22	286×10^{-4}	2.65 g/cc	1.0	34.5°	31.0°
3	BALLOTINE	14/16	434.5×10^{-4}	2.97 g/cc	1.0	34.5°	25.5°
4	SAND	18/22	305.5×10^{-4}	2.64 g/cc	0.8	39.0°	36.0°
5	CORN	18/22	305.5×10^{-4}	1.41 g/cc	0.78	40.0°	36.0°
6	COAL	18/22	305.5×10^{-4}	1.30 g/cc	0.58	48.5°	36.0°
7	LIMESTONE	18/22	305.5×10^{-4}	2.69 g/cc	0.52	51.5°	36.0°
8	HEMATITE	18/22	305.5×10^{-4}	3.72 g/cc	0.62	45.0°	38.0°

cuts and blended mixtures consisted of 9/10 mesh, 14/20 mesh, 20/28 mesh and 28/35 mesh size materials.

He correlated his results in the form

$$\mu = \tan \theta = 0.284 \left(\frac{158 n}{d \rho v} \right)^{0.8} \quad (4)$$

where θ = angle of friction

n = specific surface of particles cm^2/gm

v = void fraction

d = particle diameter - inches

and ρ = density gm/cc .

Specific surface of a particle is related to its average diameter by the equation

$$n = f_s \cdot d^2$$

where f_s = surface shape coefficient.

Therefore equation (4) can be written in a modified form as

$$\mu = \tan \theta = 0.284 \cdot \left(\frac{158 f_s \cdot d}{\rho v} \right)^{0.8}$$

The values of the surface shape coefficient, average diameter of the particles, its density and voidage of the material were substituted in the above equation. From the value of the coefficient of friction thus obtained, the angle of repose was calculated as $\tan^{-1} \theta$ and these values have been compared with those obtained experimentally in table (II).

TABLE II

O.	MATERIAL	PARTICLE SIZE (INCHES)	DENSITY ρ	VOIDAGE v	SURFACE SHAPE FACTOR	ANGLE OF REPOSE α	
						CALCULATED	OBSERVED
	COAL	305.5×10^{-4}	1.3 g/cc	0.384	3.17	34.5	36.0
	LIMESTONE	305.5×10^{-4}	2.66 g/cc	0.462	3.01	23.5	36.0
	CORN	305.5×10^{-4}	1.41 g/cc	0.414	3.45	33.2	36.0
	BALLOTINE	434.5×10^{-4}	2.95 g/cc	0.364	3.14	26.1	25.5
5	SEEDS	305.5×10^{-4}	2.65 g/cc	0.394	3.14	21.5	28.0
	LEAD SHOTS	315.5×10^{-4}	11.34 g/cc	0.354	3.14	34.0	31.0

From the above table, it will be seen that calculated values of the angle of repose based on equation (4) for different materials are with one or two exceptions, close to the experimental values.

Pilpel (16) using approximately spherical particles of granulated MgO (sp: gravity 3.0) in the size range 90-800 microns obtained a relationship between particle sizes and the angle of repose, namely:

$$\alpha = a \cdot d^{-1} + b \quad (5)$$

where α = angle of repose in degrees

d = particle diameter in microns

and a and b are constants whose values for magnesia are 18×10^3 and 32.2 respectively.

This equation with different constants holds reasonably well for a number of other materials eg: dried lactose, granulated sulphathiazole (22) and pulverized coal.

From this equation it is clear that the angle of repose decreases with an increase in diameter of the particles in the cohesive range i.e. when the particle size is less than 100 microns. Particles in this range produce a substantial increase in the angle

of repose, due to enhancement of the attractive forces that normally operate between particles of the material concerned. There are five types of force which may be postulated as acting between the particles in a powder, namely:

1. Force of friction between the particles.
2. Force due to presence of absorbed gas and/or moisture on particle.
3. Mechanical forces, caused by interlocking of particles of irregular shape.
4. Electrostatic forces arising from friction between the particles themselves and the surface with which they come in contact.
5. Cohesive forces operating between neighbouring particles.

due to moisture on the particles

Of these, the surface tension forces are small and normally electrostatic forces are negligible. Frictional and cohesive forces are therefore, predominant in the size range less than 100 microns.

Beyond this size range, mechanical and frictional forces increase and eventually become predominant. Thus Qureshi (17) working in the range of 150-612 microns has shown that the static angle of repose diminished with a decrease in the particle size.

Brown (18) has given a summary of work by various authors in which the data of Rose and Tanaka (19) and Brown and Richards (20) suggest a drop in the angle of repose, as the particle size increases in the range where cohesion is predominant, and an increase in the range where interlocking forces are predominant; a minima occurs at 100 microns, where both interlocking and cohesive forces are equal.

It has been suggested by Dawes (21) that higher angles of repose are related to cohesion. He measured cohesion by arranging the material on a split plate of which one half was fixed and the other free to move on ball bearings. The whole is mounted on a table which is slowly tilted without vibration at a speed of approximately 15 degrees per minute. At a certain angle depending on the cohesive strength of the material, the movable half of the plate slides away from the fixed half and the mass breaks in two. By measuring the area of the broken face, and weighing the movable half, the force per unit area of cross-section required to break it can be calculated. The force opposing it i.e. cohesion, is then given by the equation

$$C = \frac{981 \times W \times \sin \theta_1}{A} \text{ . dynes /cm}^2 \quad (6)$$

where θ_1 = angle at which it breaks,

W = Weight of proportion breaking away (gms),

A = Area of cross-section (sq.cm), and

C = Force of cohesion.

It was found that the force of cohesion increases as the particle size decreases below 100 microns. The angle of repose correlated well with the measured force according to a linear relation.

Nelson (22) also found that in the case of sulphathiazole, the angle of repose which he called the 'coefficient of interparticulate friction' increases with decreasing average particle size in the size range below 100 microns.

It is usually considered that materials with an angle of repose less than 45° are free flowing whereas those with angles exceeding 45° flow only with difficulty.

EFFECT OF PRESENCE OF MOISTURE ON THE ANGLE OF REPOSE:

There are three ways in which moisture can be present in a granular material.

1. Chemically combined moisture, which is difficult to remove even on prolonged heating,
2. Moisture present in cavities and capillaries of granules, and
3. Moisture present as a layer on the surface of granules.

The angle of repose is affected by surface moisture due to an increased cohesion between the particles arising from surface tension forces.

Fowler and Wyatt (23) have given an empirical relation for the effect of moisture on the angle of repose as

$$\mu = \tan \theta = a n^2 + b \left(\frac{M}{D_{ave}} \right) + c \rho + d \quad (7)$$

This equation has a marked resemblance to the one proposed by Fowler and Chowdziesner (14) equation (3) for angles of friction for dry materials except that M/D_{ave} replaces $\sqrt{\epsilon/D_{ave}}$ where M is the percentage of moisture added.

The equation accounts for the results obtained for four granular solids in a satisfactory manner, but was found to be unsatisfactory for rape seed and millet. In the latter cases it is probable that the added moisture over the range used (0-5%) is completely absorbed by the solids leaving the surface dry.

It has been suggested that the variation of the angle of repose with moisture content is due to the surface layer of moisture that surrounds each granule and that surface tension forces become predominant and hold the aggregate of granules together. This explains why non-porous materials such as basalt, sand and polythene have angles of repose increasing with the moisture content.

Wolf and Hohenlieten (24) have found that the angle of repose depends both on the degree of compaction and the amount of moisture present. In their experiments, the angle of repose was taken to correspond with the angle of the cleavage plane obtained by dropping the side of a cubic box containing a bed of material. In almost all cases, they found that the angle of repose passes through a maximum at 12 percent moisture content. The angle of repose for loosely packed dry material increases from $40-55^{\circ}$ where the bed was compacted by vibration. The angle of repose for a fully compact coal increased considerably with moisture content reaching a value as high as 90° for 3.6 percent moisture.

Using a rotary cylinder they found that starting with dry material with a dynamic angle of repose of 32° , its value could be increased to 43° by slowly adding moisture upto 14 percent.

EFFECT OF PRESENCE OF FINES ON THE ANGLE OF REPOSE:

The influence of the presence of a proportion of fines on the angle of repose of a granular mass is of importance in many manufacturing processes, and the effect has been thoroughly investigated by various workers (16, 22, 25, 26).

Pilpel (16) has shown that as little as 5 percent by weight of fines increased the angle of repose of coarse magnesia by 5 degrees and retards its flow from hoppers. He concluded that for mixtures of coarse and fine particles, the angle of repose is inversely proportional to the weight fraction of fines present. He suggested that a large change in the relative values of frictional and cohesive forces could adequately account for the effect on the angle of repose for materials with sizes greater than 200 microns.

Nelson (22) has found that the addition of fines to coarse material markedly increases the

angle of repose. He found that an addition of 40 percent of fines to 30/40 mesh sulphathiazole particles caused the angle of repose of the coarse material to increase from its initial value of 44° to a final value of 60° . He defines fines as particles having a diameter less than 100 microns.

Bulsara and coworkers (25) found that sticky powders could be made to flow freely by the addition of flow conditioning agents, or by applying pressure differentials i.e. positive pressure, suction or vacuum; or by the addition of coarse materials. Various mixtures of coarse sand (20/30 mesh) were made with fly ash (19 microns) and microcel (3.2 microns) and allowed to flow from a bin. It was found that a decline in flow rate began when the concentration of fly ash and microcel in the mixtures was 20 and 13.6 respectively which corresponds to a concentration of fines giving a maximum bulk density. At greater concentrations, the fines become increasingly the continuous phase until at approximately three times the saturation concentration, the mixtures behave as though no coarse material ~~was~~ ^{was} present and free gravity discharge ceases.

Neumann(26) using the above sand adulteration method has found the relative stickiness of a number of powders in terms of the amount of 60/100 mesh sand required to render them free-flowing. Her results indicate a relationship between the angle of repose and the stickiness of materials. A summary of results is given below in table (III) and graphically presented in Fig. (2).

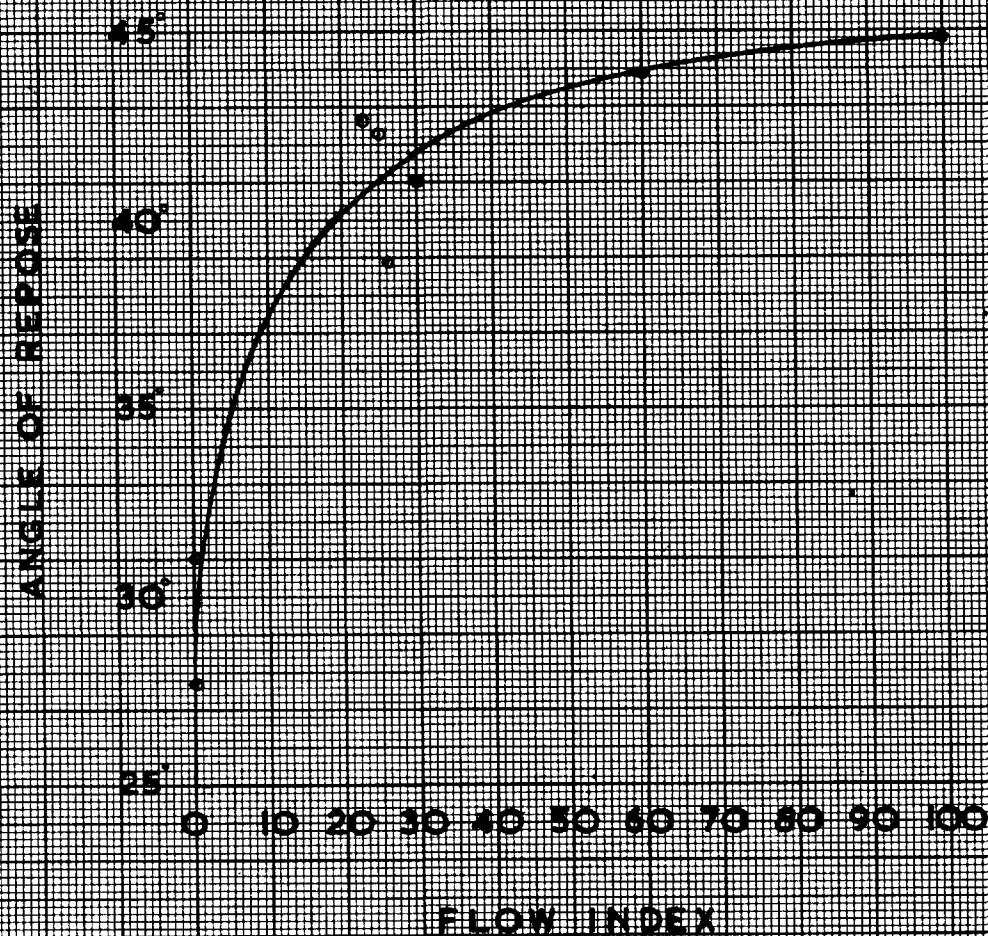
T A B L E (III)

MATERIAL	PARTICLE DIA MICRONS	PERCENT SAND REQUIRED TO RENDER FREE FLOWING	ANGLE OF REPOSE DEGREES
MICROSPHERES	25-50	ZERO PERCENT	27.7
CALCIUM FLUORIDE	30	ZERO "	31.0
SOD: CARBONATE	50/150	23 "	42.6
TITANIUM DIOXIDE	0.5	26 "	38.9
REFINED KAOLIN	2-10	1200 "	45.2
FULLER'S EARTH	0.1	25 "	42.3
ACTIVATED EARTH	5.25	60 "	43.9
CEMENT	5-15	100 "	44.8
FLOUR	25	30 "	41.0

Fig(2)

ANGLE OF REPOSE Vs STICKINESS

Stickiness expressed in terms of percent of 60/100 mesh size sand required to render the materials free-flowing is termed as flow index.



Kaolin and Cement required rather large amounts of sand to make them free flowing because of their strong cohesive properties and their natural tendency to absorb large quantities of moisture.

EFFECT OF PRESENCE OF SPECIAL ADDITIVES ON THE ANGLE OF REPOSE:

The free flowing properties of a granular material may be improved considerably by the addition of varying proportions of certain finely ground powders (of particle size less than 20 microns), generally referred to as 'flow conditioning' agents. The effect of these agents is complex because the nature of the additive, its concentration, particle size distribution and other variables are all involved.

The subject has been thoroughly investigated by various workers (27 - 31).

It has been found that there is an optimum level of conditioner for each system beyond which flow is not changed significantly. Their action is attributed to the individual or combined effect of the following:

1. They act as selective absorbants for gases, vapours or moisture otherwise absorbed on the surfaces of sticky materials;

2. By dispersing themselves throughout the voids and on particle surfaces of the granular mass, they promote flow probably by a lubricative effect;
3. Their action may, in some instances, be concerned with the removal of the electrostatic charges on the particles accumulated during processing or grinding;
4. It has been confirmed by microscopic examination (27,31) that these fine powders coat the surface of bigger particles, and hence prevent them from coming into direct contact. There are quite a number of these compounds in use but with the exception of graphite, these have not been studied in the present work.

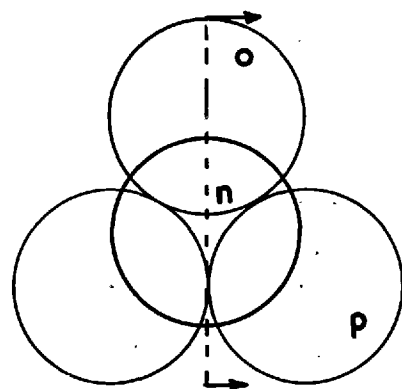
EFFECT OF PARTICLE SHAPE ON THE ANGLE OF REPOSE:

Pratap (12) examined the effect of particle shape on the angle of repose. Rape seed, ballotine and lead shots are approximately spherical and were found to possess lower coefficients of friction than non-spherical particles. From a plot of shape factor (which is a ratio of surface and volume shape coefficients) against the coefficient of friction based on the static angle of repose, he concluded that there is a linear increase in the angle of repose as the particle shape departs from sphericity.

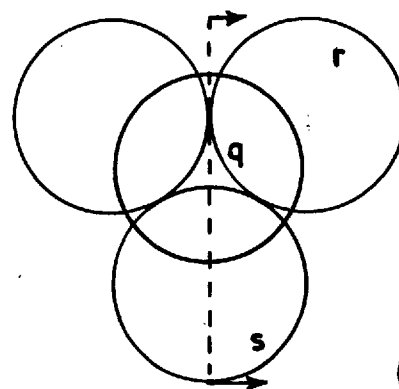
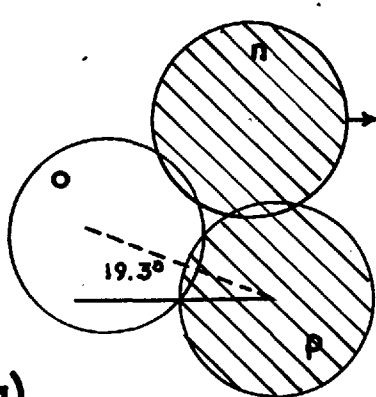
Train (11) has shown that limiting conditions exist for the angle of repose of spheres irrespective of their composition and size. The sliding of a single spherical particle down the slope of a randomly packed heap of spheres of the same size depends mainly on the type of packing. A sphere will stay in the hollow formed by a grid of three or four spheres on a slope providing its centre of gravity does not fall outside the lower boundary of the grid. The closest packing on a regular triangular grid permits rolling if the slope of the plane is 19.3° for one axis of symmetry and 35.1° for the alternative axis as shown by Fig. (3) a & b respectively.

In/^{the}case of regular square packing the necessary slopes to permit rolling are 35.3° and 45° Fig. (3) c & d respectively. These limiting conditions were confirmed experimentally. In practice, however, the surface of a heap of spheres will consist of a random selection of these grids and the slope will have an angle between 22.5° for the lower boundary and 27.5° for the upper boundary.

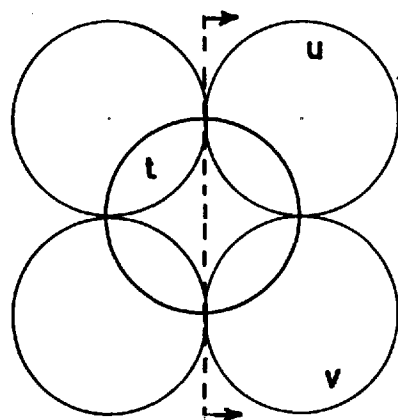
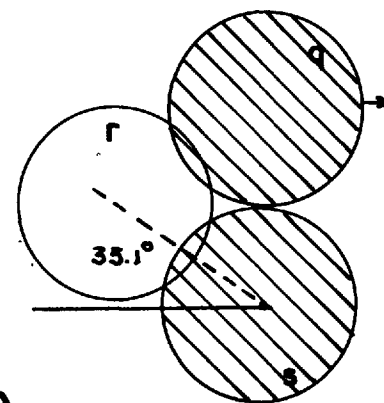
Fig(3)
(D.TRAIN)



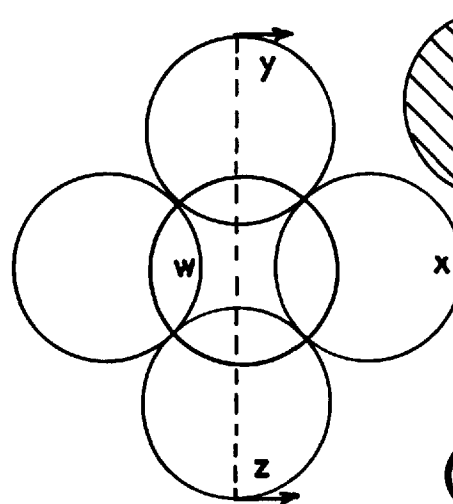
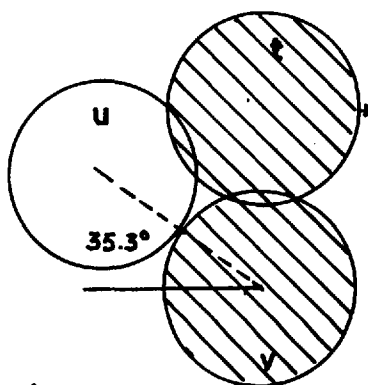
(a)



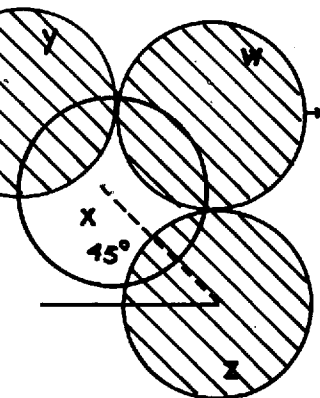
(b)



(c)



(d)



EFFECT OF DENSITY ON THE ANGLE OF REPOSE:

In various relations put forward for the angle of repose (equations (3), (4) & (7) density appears as one of the variables. If all the other variables are constant, the equations for the angle of repose in their simplified forms can be written as

From equation (3) and (7) $\mu = \tan \theta = \text{const} \times \rho$

From equation (4) $\mu = \tan \theta = \text{const} \times \left(\frac{1}{\rho}\right)^{0.8}$

It is seen from above that density appears in the numerator in (3) and (7) and in the denominator in (4).

To find out which of these relations is correct, four materials were chosen such that their particle size and shapes were approximately the same, but their density differed by a factor of three. The angle of repose of these selected materials was plotted against their densities, from which it is seen that the angle of repose varies directly as the densities. Fig. (4)

The data used in plotting of these graphs is given below in Table (IV).

Fig(4)

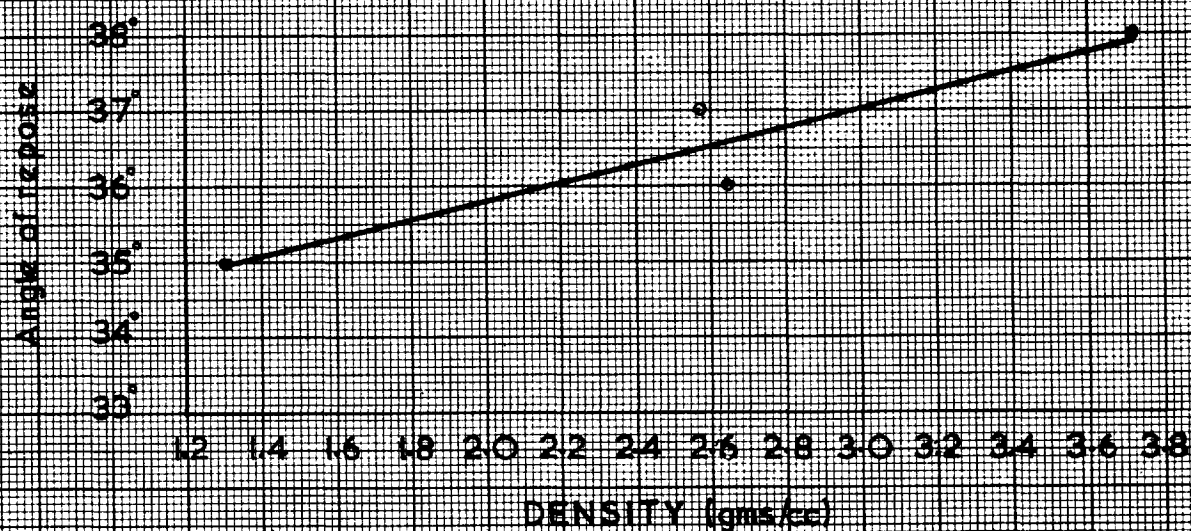
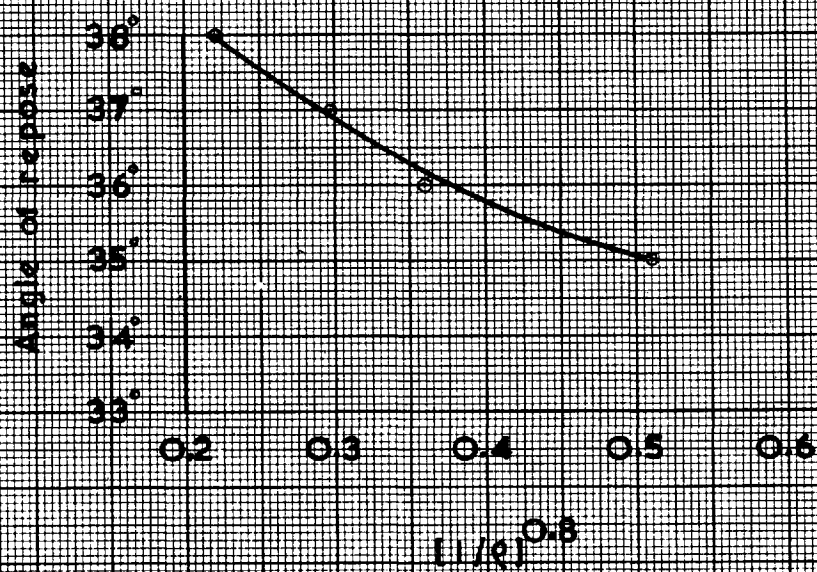
ANGLE OF REPOSE VS DENSITY ρ ANGLE OF REPOSE VS $(1/\rho)^{0.8}$ 

TABLE (IV)

No.	MATERIAL	PARTICLE SIZE	SHAPE FACTOR	DENSITY ρ	$(1/\rho)^{0.8}$	ANGLE OF REPOSE
1	COAL	18/22	10.38	1.3 g/cc	0.511	35.0°
2	SAND	"	8.24	2.64 "	0.359	36.0°
3	FELSPAR	"	9.82	2.57 "	0.2965	37.0°
4	HEMATITE	"	9.70	3.72 "	0.22	38.0°

From the above results, it is concluded that the angle of repose is proportional to the density of the material, as predicted by equations (3) and (7).

An investigation into the effect of particle size, addition of fines of the same material in varying proportions and the effect of addition of graphite in varying amounts of 2 different sizes on the angle of repose has been studied for various materials and ^adetailed account is given in Chapter 5.

CHAPTER 4
LITERATURE SURVEY
SEGREGATION OF PARTICLES

INTRODUCTION:

It has long been known that when a granular mass consisting of particles of different sizes or densities, uniformly mixed is subject to continuous movement, such as by vibration or tumbling in a rotating container, segregation occurs and an equilibrium state is reached at which composition varies through the mass but at any point is constant with time. Furthermore any movement in such a mass will tend to produce partial segregation, thus for example if such a mass is transferred from a container so as to form a loosely piled heap, then the composition of the heap will vary in a regular and predictable manner.

In this work although we are concerned mainly with the segregation produced by rotating granular masses in vessels of varying shapes and that produced by pouring the material through an aperture so as to form a loosely packed cone on a horizontal surface, a brief mention will be made of segregation by vibration.

The subject has been studied amongst others by (32, 33) who have shown, inter alia, that if a mixture of particles of different sizes is vibrated, the bigger particles can always be made to rise to the top of the bed, whatever their density.

SEGREGATION BY RANDOM MOVEMENT:

Quite a large number of papers have been published dealing with this subject ranging from segregation in bunkers and hoppers to unmixing in blending equipment. These have been reviewed by R.L. Brown (34) and more recently by J.C. Richards (35). It is proposed here to refer only to a selected few which have a direct bearing on the work reported in this thesis.

Holmes (36) carried out a series of experiments to determine the degree of segregation due to density difference using a closely sized (average particle size 6860 microns) mixture of coal (density 1.43) and fluorspar (density 3.1). The proportion of coal to fluorspar was approximately 7:1. The mixture was allowed to discharge from a conical hopper onto

a horizontal floor in the form of a conical heap, which was divided into sections as shown in figure (5 a) and analysed for composition.

In this type of experiments it is desirable to check if discharge from the conical hopper is constant in composition, since segregation may occur when charging the hopper with the mixture or subsequently during discharge. 3 samples of the discharge were taken at regular intervals of time and were found to consist of 14.9, 12.5 and 8.2 percent of fluor-spar, thus showing that some segregation had occurred prior to the formation of the discharged heap. The results of the analysis of samples taken from two experiments in which the height of fall of the material was 6 inches and 6 feet, respectively, are given in Table (V).

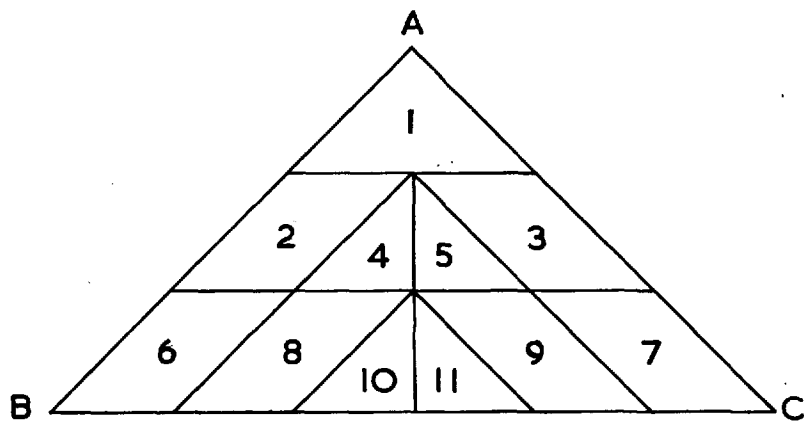
It will be seen from the table that whilst samples 1-5 and 10-11 show little evidence of segregation samples 6-9 show a marked separation. The curve in Fig. (5 b) indicates the regions of separation, the denser material forming a mushroom shaped core within the cone. It will further be noted that a more complete separation occurs in the series having a greater fall of the material.

TABLE (V)

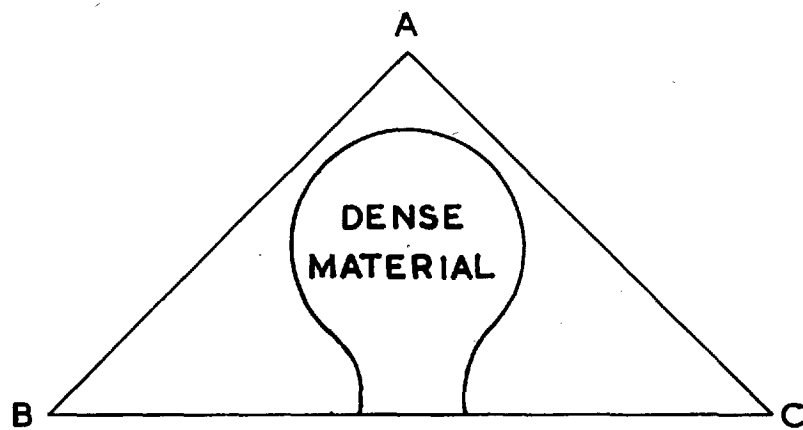
SAMPLE NUMBER (See Fig. (a))	PERCENTAGE OF FLUORSPAR	
	I (6" FALL)	II (6' FALL)
1	13.7	17.5
2	13.7	15.2
3	12.7	13.6
4	16.3	19.3
5	17.5	15.4
6	3.9	1.5
7	4.2	1.3
8	7.5	2.8
9	7.9	3.1
10	12.0	18.6
11	8.8	17.3

Fig (5)

(HOLMES)



(a)



(b)

Holmes explained these results by attributing the segregation in part to a tendency of the coal particles to rebound from the surface of the heap due to their greater resilience and in part to the tendency of the particles to penetrate into the cone. He also points out that the angle of repose of coal is less than that of fluorspar by virtue of which the coal particles move down the inclined surface of the heap more slowly than fluorspar. Experiments described later give the value of the angle of repose of the two materials as:

$$\text{coal} = 35.6^{\circ}$$

$$\text{Fluorspar} = 36.5^{\circ}$$

The conclusions resulting from his work are:

1. Segregation is greater when the material has a high initial velocity,
2. it increases with the size of the heap,
3. it is favoured by a suitable particle size distribution, and
4. in so far as moisture affects the angle of repose, it may also tend to inhibit segregation.

Now it is well known that when material containing particles of different sizes is poured into a heap, the larger particles run more easily down the

sloping surface of the heap due to their higher momentum, giving rise to a cone in which the central core contains more fines than the outer edges.

The most comprehensive investigation into particle behaviour are those due to R.L. Brown (37) who has examined inter alia, the way in which granules emerge from an aperture in a container. If $n dA$ is the number of granules passing per unit time out of an elementary area dA , of the aperture, then the way in which n varies across the aperture can be called the number profile. He concluded that "the number profile develops from the edge of the aperture and is independent of its size and shape".

If the emergent particle stream falls on a horizontal surface, the surface of the discharged granules can be inclined at slopes upto the angle of repose. He further draws attention to Reynolds' observations that for a granular mass to change its shape it must expand at least in local regions "In itself, a granular material can not support a tensile stress and in some respects it exhibits deformations akin to plastic deformation in solids".

Stairmand (32) mentions that one of the main ways in which segregation can be effected is by pouring the material into a heap. In a quantitative experiment, in which a granular fertilizer with 5% of added fines was poured into a heap, measurements showed that the centre core contained upto $3\frac{1}{2}$ times as much fines as the average; whilst the edges contained only $1/10$ th of the average.

Williams (33) poured a mixture of two sizes of spherical granules of mean diameter 2350 microns and 550 microns respectively, into a perspex box of dimensions 24" x 18" x 1". He found that a central core with an almost constant and very high fines content was surrounded by an outer region near the bottom edges of the heap with very low fines content. Counting the granules in a small area in different parts of the heap showed that the percentage of smaller particles varies between 1 and 75 percent, compared with 50 percent in the original mixture.

To find the effect of varying composition of the original mixture, the percentage of fines was varied between 20 and 80 percent, and maximum and minimum proportions observed in the heap in each case.

The results are given below

Percentage of fines	in original mixture	20	40	50	60	80
"	" " centre of heap	41	62	75	84	97
"	" at the edges	0	0	1	3	20

The same effect can be observed using materials of continuous grading. Thus in an experiment in which the fines amounted to 5 percent of the total mixture composed of particle sizes of continuous grading, it was found that again the fines concentrated in the centre of the resultant heap, when the mixture was poured onto a flat surface. Analysis of samples showed that the central part of the heap contained 18 percent of the fines and the outer part less than 1 percent compared with a mean value of 5 percent fines.

Comparing the results of Williams with those of Stairmand it will be found that they are in reasonable agreement.

1.	composition of original mixture	centre of heap	edges
1. Williams	5% fines	18.0 %	1.0%
2. Stairmand	5% "	17.5 %	0.5%

Further reference to the above investigations will be found in Chapter (6).

Colley (38) has discussed the segregation of particles in a heap and has stated that the use of a central distribution pipe Fig. (6) gives a smaller area of concentration of fines, and when material is drawn off from the centre the best blending is obtained.

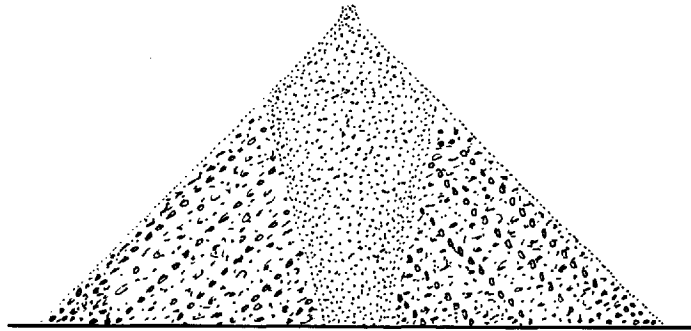
SEGREGATION IN ROTATING VESSELS:

When large and small particles of the same material are mixed in a rotating cylinder, there is a tendency for the mixture to segregate. This phenomenon is well illustrated by the Hardinge mill, which when charged with balls of varying diameters on rotation produces grading of the balls according to size , the smallest balls accumulating at the discharge end of the mill. The explanation of this is simple: when two balls of different weights are dropped together down a rough inclined surface which offers resistance to movement, the larger ball due to its greater weight and inertia keeps moving after the small ball has come to rest.

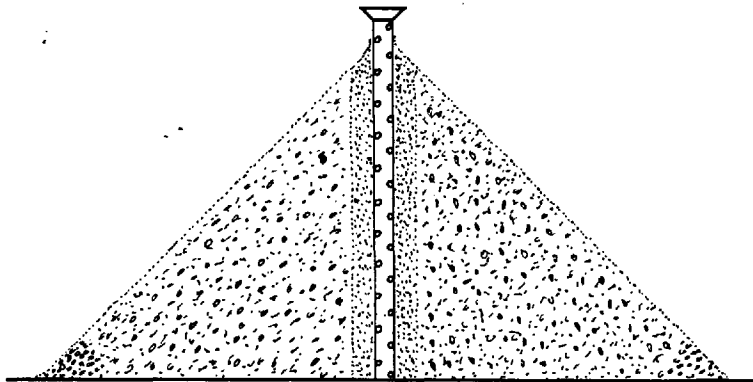
In the case of a rotating cylinder, Oyama (39) showed that the steady state, when solids of different sizes are mixed together, is associated with a definite type of segregation in the form of well

Fig(6)

(COLLEY)



(a)



(b)

defined bands normal to the axis of rotation. Even if a well mixed material is put into the cylinder, it will end up in the segregated state after sufficient rotation. When he mixed small (coloured black) and large (white) particles of limestone he found that there were alternatively arranged strips of black and white particles perpendicular to the axis of rotation of the cylinder. These strips, which were visible on the inclined surface of the bed, were reproducible for the same conditions and appeared to get sharper with time of rotation.

The strips also became clearer, (sharper in outline) with decreasing weight ratio of the two components (W_1/W_2) where d_1 , the diameter of coarse particles is 3500 microns and d_2 , the diameter of fine particles is 570 microns. He reported that they were easily produced at low speeds of the cylinder, even with a larger weight ratio and that the number of bands formed was a function of the speed of rotation. The origin of these strips has been attributed to local depressions of the bed of material in the neighbourhood of the two ends due to frictional effects.

These depressions have the effect of imparting a horizontal component ~~to~~ the velocity of particles as they cascade down the side of the cylinder in the region of the depressions. No explanation as to the propagation of these strips over the length of the mixer has been given.

A similar phenomenon was observed in the present work when coarse sand of particle size 18/22 mesh was mixed with fine sand of particle size 85/100 mesh (coloured black) and rotated in a horizontal cylinder of 3.5 inch diameter and five inch long made of 'pyrex' glass. The bands started appearing after 20-30 seconds and became more pronounced with time. A maximum number of 7 bands was observed for a 50 percent mixture at both low and high speeds, the minimum number being three. The number, thickness and position of the bands varied with time, most probably due to the fact that inside surface of the cylinder was not symmetrical. The bands appeared even at very low speeds and were very clear if the fines did not exceed 50 percent of the total mixture.

In an 8 inch long cylinder made of perspex (inside diameter 3.5 inches) a 50 percent mixture on rotation at low speeds (15 and 30 rpm) was found to give 9 bands after 10-15 minutes. At higher speeds (45 and 60 rpm) the bands took less time to appear, reached an equilibrium state in a shorter time (5 to 10 minutes) and gave fewer bands (4 - 6), the number of bands also depending on the composition of the mixture. Comparing these results with those obtained for a 5 inch long cylinder, it appears that the number of bands formed is some function of the length of the cylinder.

A similar band structure was also found to develop in a rotating conical vessel and further details of this phenomenon will be found in Chapter (7).

Visual observation of the formation of bands failed to disclose the presence of depressions near the end of the cylinder noted by Oyama (39). It was, however, observed that the material near the ends of the cylinder was carried to a greater height than the rest of the material and was given a curved trajectory. The distance through which the particles travelled depends upon the horizontal component of the

velocity imparted to the particles due to drag at the ends, the smaller particles being projected further than the coarse ones thus giving rise to a band of coarse materials followed by a band of fine particles.

The band formed near the end of the cylinder was found to be concave as shown in Fig. (7a).

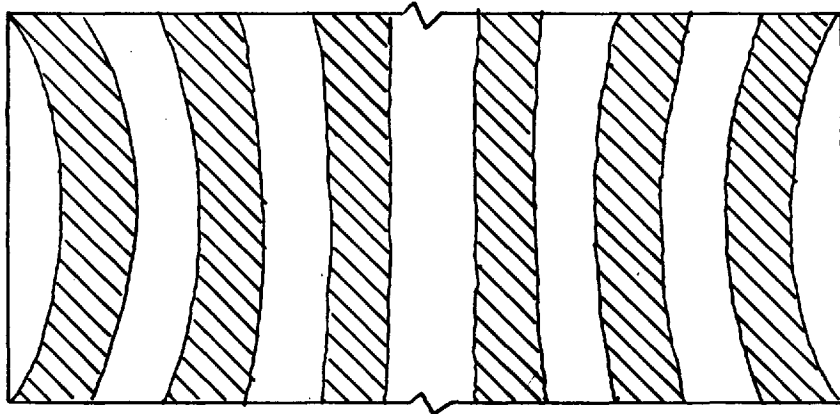
It was also noticed that the boundary of the band of fine particles had a curvature facing upwards while that of the coarse material had a curvature facing downwards. (See Fig. 7b).

An explanation of the formation of these bands has been given by Donald and Roseman (40) based on the velocity gradient set up due to the ends of the cylinder and is discussed later in this Chapter.

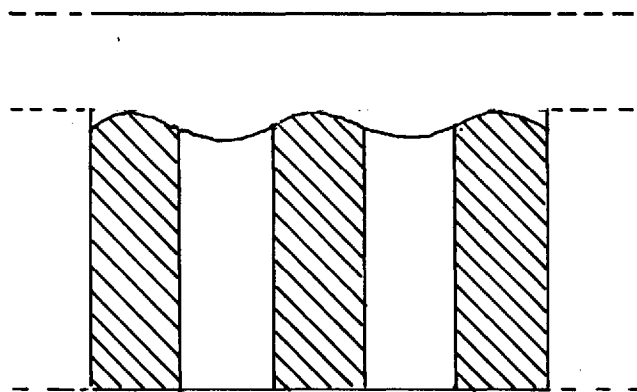
Coulson and ' Maitra (41), using a rotating cylinder with an inclined axis, have shown that if the fine particles are put into the bottom of the cylinder and the coarse ones on top, then on rotating no mixing occurs. If on the other hand, the position is reversed then the two layers change places, there being an intermediate stage at which an optimum degree of mixing occurs. They conducted a series of experiments with mixtures of varying particle size ratios. The curves for degree of mixing ($\log_e \frac{100}{x}$) versus

Fig(7)

BAND FORMATION IN A CYLINDER



(a)



(b)

time for each system were found to consist of two straight lines, the first rising and the second falling with time, corresponding to mixing and demixing processes respectively (Fig. 8). With this type of blender, the only stable condition is one of segregation with the coarse particles on top.

They expressed the segregation process by equation

$$S = S_0 (1 - e^{kt}) \quad (8)$$

where the value of k in all cases was found to be numerically equal to the value of k for mixing in the equation

$$S = S_0 (1 - e^{-kt}) \quad (9)$$

The value of k for segregation has been shown to increase linearly with particle size ratio. From their results it was concluded that segregation is a continuation of the mixing process.

To examine the effect of density, mixtures of coal with barium nitrate and lead nitrate, density ratio 1:2.5:3.5 respectively, were used, the particle size being 70 mesh. In the first series of experiments, coal was introduced on top of the denser material.

Fig(8)

DEGREE OF MIXING Vs TIME

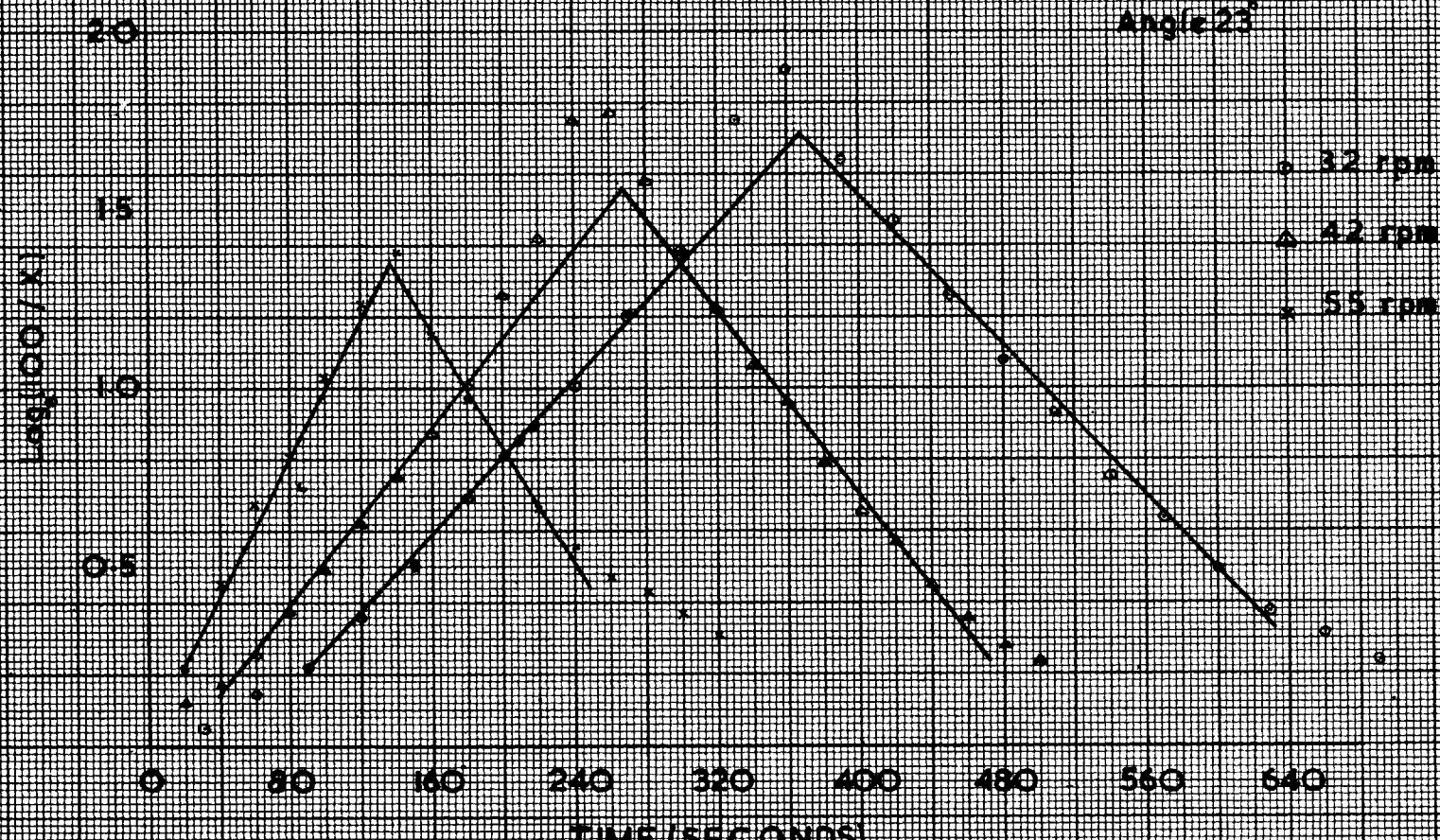
Initially : Cool at the bottom

Finally : Cool at the top

Salt : 75 mesh

Cool : 35 mesh

Angle 23°



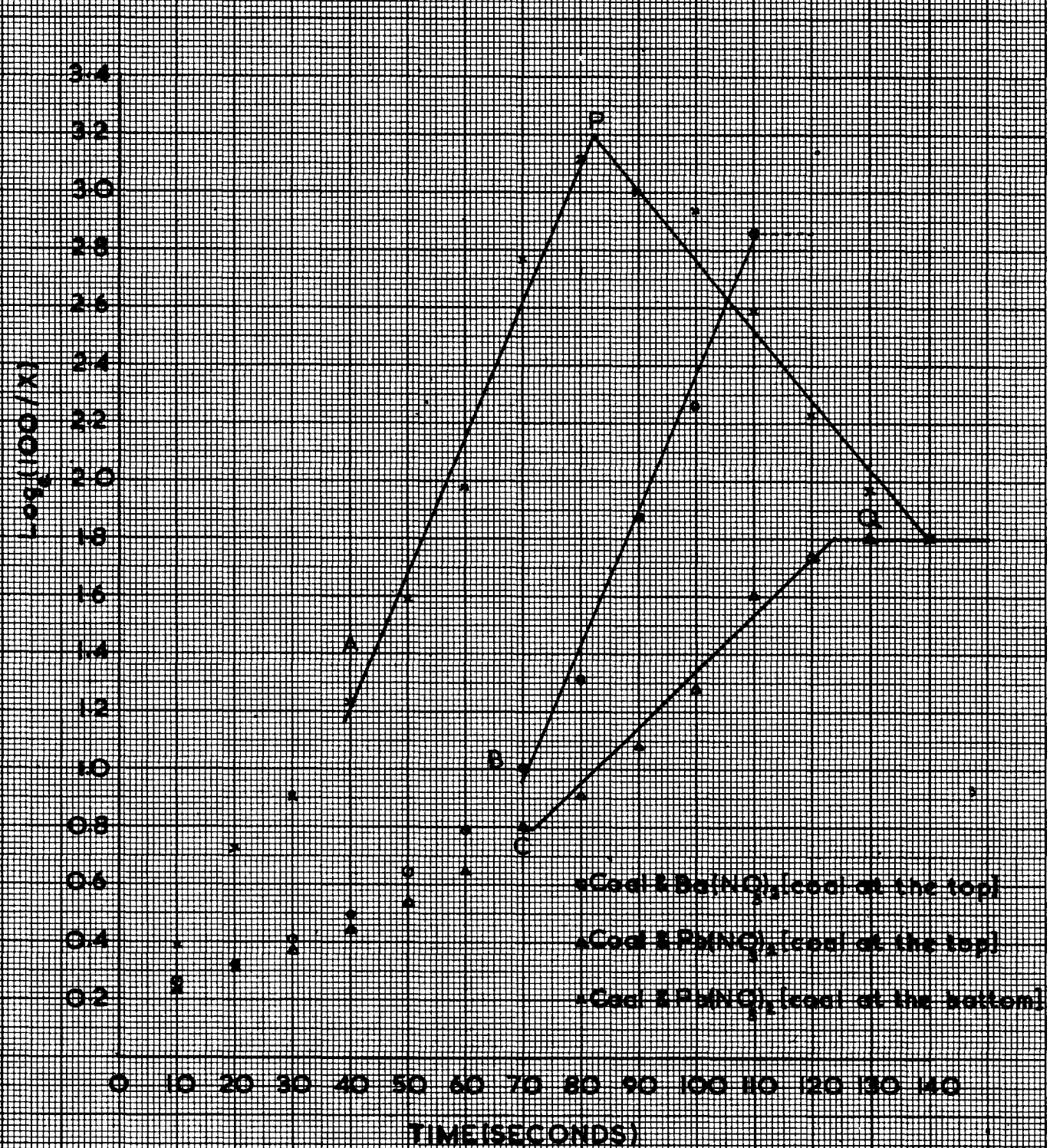
It was found that, whereas the barium nitrate and coal mixture reached a high degree of mixing, the lead nitrate and coal mixtures only attained a value of $\log_e \left(\frac{100}{x} \right)$ of about 1.8, representing a poor mixture. In the second series, the denser particles were introduced on top. In case ^{the} of lead nitrate and coal, the mixture attains a high degree of mixing (P in Fig. 9) after which it starts demixing and reaches a value of 1.8 for $\log_e \left(\frac{100}{x} \right)$ (Point Q). On further rotation there is no change.

Comparison of curves A, B and C shows that whilst A and B ^{have} approximately the same slope, curve C indicates a much slower rate of mixing. There is a longer period of slow mixing in the case of curve B than curve A, so that it can be concluded that mixing is achieved more rapidly if there is an appreciable difference in density between the materials, a ratio greater than 1:2.5.

Bonilla and Weidenbaum (42) studied the mixing of 40/50 mesh sand and salt (density 2.2 and 2.16 and ~~the~~ angles of repose 30.5° and 34.0° respectively) in a horizontal cylinder approximately 1/3 rd full and rotating about its axis. The rate equation

Fig(9)

DEGREE OF MIXING Vs TIME



proposed was found to hold in the early part of the mixing operation but not in the latter part. This deviation has been attributed to axial segregation which works against the mixing driving force of random motion. After long periods of mixing a higher sand concentration was present in the centre of the mixer than near the ends. This phenomenon was attributed to the difference in flow properties between the two kinds of particles and to the surface curvature which occurs at the ends causing one type of particle to have a larger horizontal component of motion towards the centre than the other. It seems reasonable to assume that similar segregation tendencies will be present in other tumbling mixing operations, where there are differences in flow properties and surface curvature near the ends.

Rose (43) developed an equation for mixing of granular materials in a rotating cylinder taking into account the effect of demixing. The equation is

$$\frac{dm}{dt} = a (1 - M) - b \phi \quad (10)$$

where ϕ = demixing potential, depending upon distribution of 2 components in the mixture,

$a = \text{const}^{\text{at}}$, depending upon the properties of mixer and the material,

$b = \text{constant}$, depending upon density, size distribution and shape of the particles,

and $M = \text{degree of mixing}$. (its value being zero for fully segregated and 1 for fully mixed material).

The final equations were

$$M = \left\{ 1 - \left[(1-b/a) e^{-at/2} + b/a \right]^2 \right\} \quad (11)$$

$$\text{and } M = \left\{ 1 - \left[b/a - (1+b/a) e^{-at/2} \right]^2 \right\} \quad (12)$$

Equation (11) corresponds to a starting condition with the dense component below ($\phi +ve$) while equation (12), corresponds to one where the dense component is above. In the latter case a maximum degree of mixing can be obtained after which segregation sets in. The curves drawn for the degree of mixing (M) versus time ($a.t$) show that on prolonged rotation, an equilibrium state of mixing will be attained.

Although equation (11) leads to a maximum value of $M = 1$ no real machine achieves perfect mixing.

Introducing a factor for intrinsic efficiency η , the equations become

$$M = \eta \left\{ 1 - \left[(1-b/a) e^{-at/2} + b/a \right]^2 \right\} \quad (13)$$

$$\text{and } M = \eta \left\{ 1 - \left[b/a - (1-b/a) e^{-at/2} \right]^2 \right\} \quad (14)$$

and at equilibrium

$$M = \eta (1-b/a)^2 \quad (15)$$

He used the published data of Coulson and Maitra (41), Weidenbaum and Bonilla (42) and some of his own experimental results to test the parameters involved under different conditions.

Donald and Roseman (40) have found that in a rotary cylinder all mixtures of particles of different sizes or density pass through an optimum state of mixing and then partially demix to an equilibrium state. The degree of segregation depends mainly on size and density differences and once these differences exceed a value of 1.2, segregation is found to occur. The decline in the mixing rate is due both to radial and axial^{de} mixing.

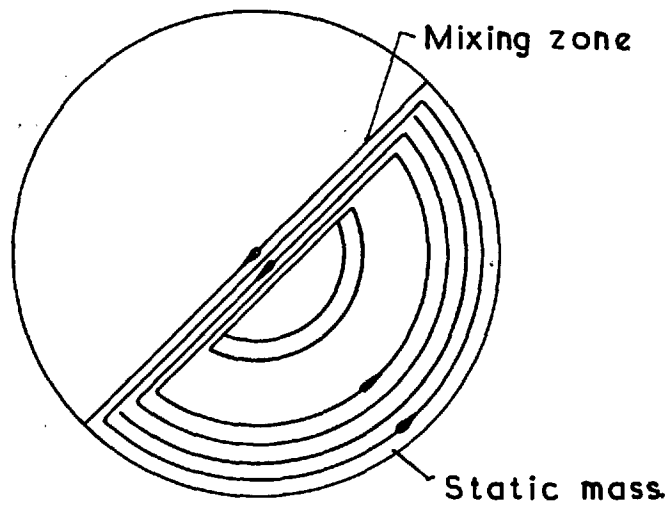
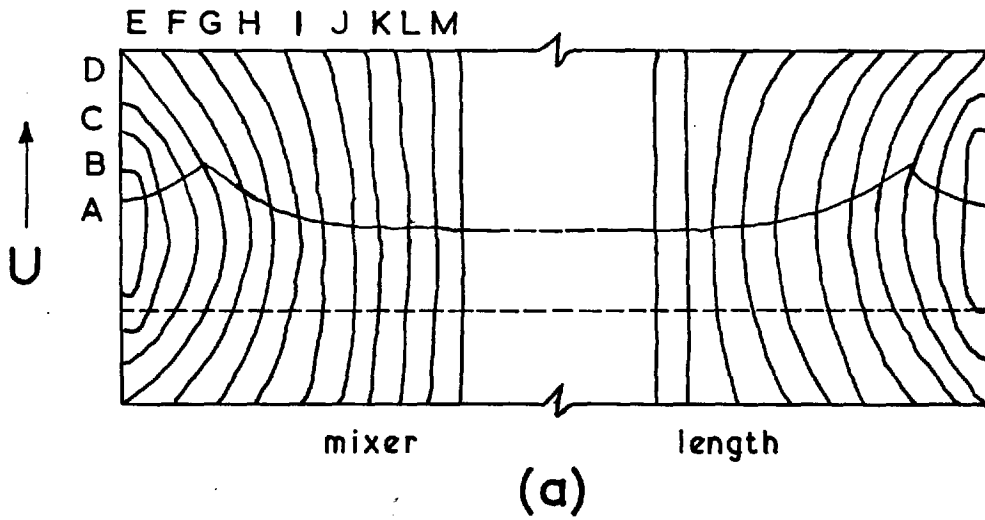
When in a mixture of different sizes or densities, a smaller (or heavier) particle is trapped in a void of the layer below, there is ^agreater tendency

for the ensuing collision, to produce a change in the path, since the smaller (or heavier) particles can slip through (or press apart) the supporting particles more easily than can ~~the~~ particles of similar size or density. As the mixer rotates, the smaller (or heavier) particles continually slip through the voids to the layer below until these particles reach the bottom layer. Once in this layer the smaller (or heavier) particles rotate in the circulating paths (Fig. (10b) since there are no voids below into which they ~~can~~ can fall. As more smaller (or heavier) particles pass down through the mixing zone layers, the voids of the bottom layer, and ^{the} central circulating paths are filled with fines and a stationary core of the smaller (or heavier) particles is formed along the length of the mixer. ^{segregation} This is aided by gravity and is much faster than the axial segregation.

The formation of alternate bands of small and large particles along the length of the mixer has been attributed to the axial velocity gradient set up due to the end effects of the mixer.

Fig (10)

(DONALD & ROSEMAN)



(b)

The axial velocity gradient is the greatest between the band of maximum velocity (D in Fig. 10a). and the two adjacent bands (C, E) and the fastest axial movement occurs at this point. The smaller or heavier particles in the two adjacent bands tend to move axially into the band of maximum velocity and as the particles cannot escape, the core in this band expands upwards. The core in the adjacent bands is replenished by the sideways movement of the smaller (or heavier) particles from the slower neighbouring bands (B and F) but as the velocity continually decreases from the maximum point, the rate of replenishment is less than the rate of denuding. Hence as the core first in D and then in E expands upwards, the core in neighbouring bands (A B C and F G) is diminished. At the same time the high flow angle (horizontal component of motion induced by the drag of ^{the} end walls) causes the larger (or lighter) particles to roll, due to gravity, from D E into A B C and F G.

The smaller (or heavier) particles accelerate down the slope faster than the larger or lighter particles, thus the higher the proportion of the smaller (or heavier) particles in a band, the greater

the average velocity of the band down the mixing zone.

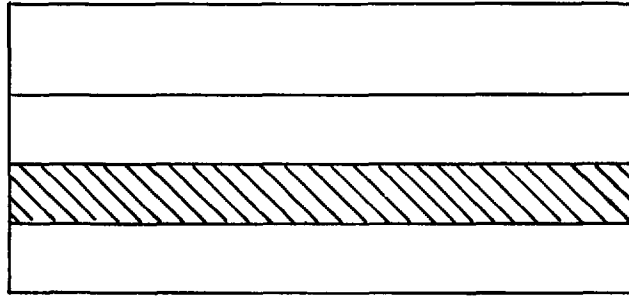
The diminished core/^{in the band} F G is sandwiched between 2 bands ~~given~~ (D E, H I) with a higher proportion of smaller (or heavier) particles and thus with a greater velocity, and all the remaining particles in the diminished core will be attracted axially in both directions. This 2-directional axial movement results in the formation of two bands of larger (or lighter) particles, (A B C, F G) alternate with a band of smaller (or heavier) particles (D E) and a region with high proportion of smaller (or heavier) particles (H I). This last named region has the greatest velocity of the remaining bands and in attracting the core from the neighbouring bands, produces additional bands over the length of the mixer.

Three final forms of a mixture obtained by rotating a mixture of particles of varying size and density can be

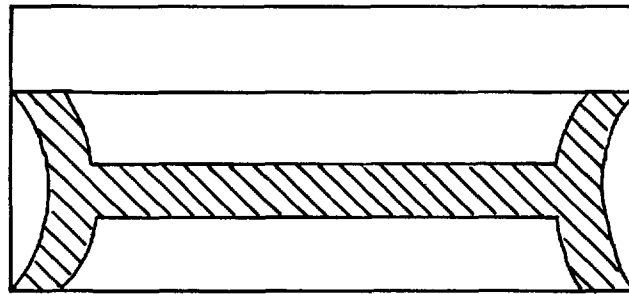
1. Diametrical mixture - smaller (or heavier) particles form a central core. Fig. (11) a
2. End longitudinal mixture - smaller (or heavier) particles form two end bands connected by a smaller core. Fig. (11) b

Fig(11)

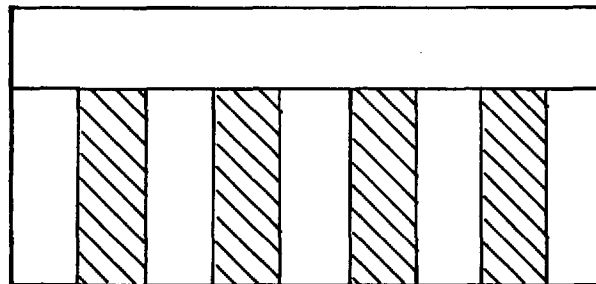
(DONALD & ROSEMAN)



(a)



(b)



(c)

3. Longitudinal mixture. Smaller (or heavier) particles form alternate bands with larger (or lighter) particles along the length of the mixer. Fig. (11) c

Donald & Roseman

^ ~~They~~ have said that the number of these bands depends on the length of the mixer and nature of the material.

CHAPTER 5THE ANGLE OF REPOSEINTRODUCTION:

If we consider a single particle B resting on an inclined plane P Q, the weight of the particle mg acting vertically downward can be resolved into two components namely $mg \cos \beta$ acting normal to the plane and $mg \sin \beta$ acting tangentially to the plane, where the angle β ^{is} ~~gives~~ the slope of the plane.

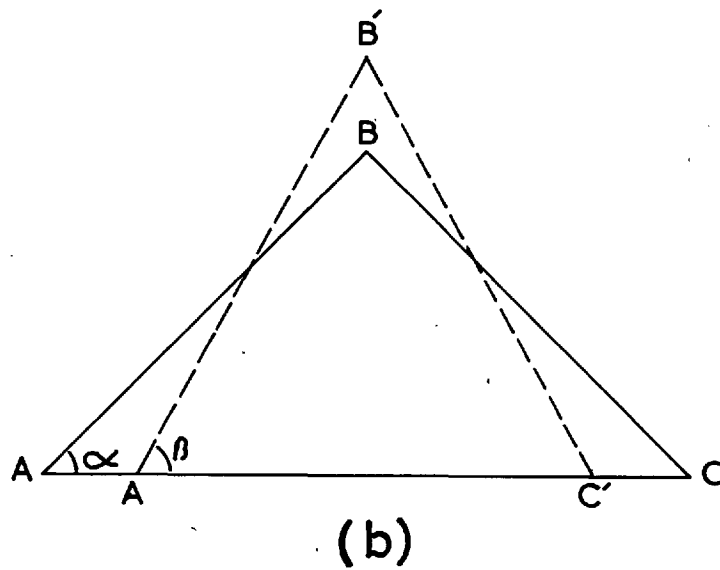
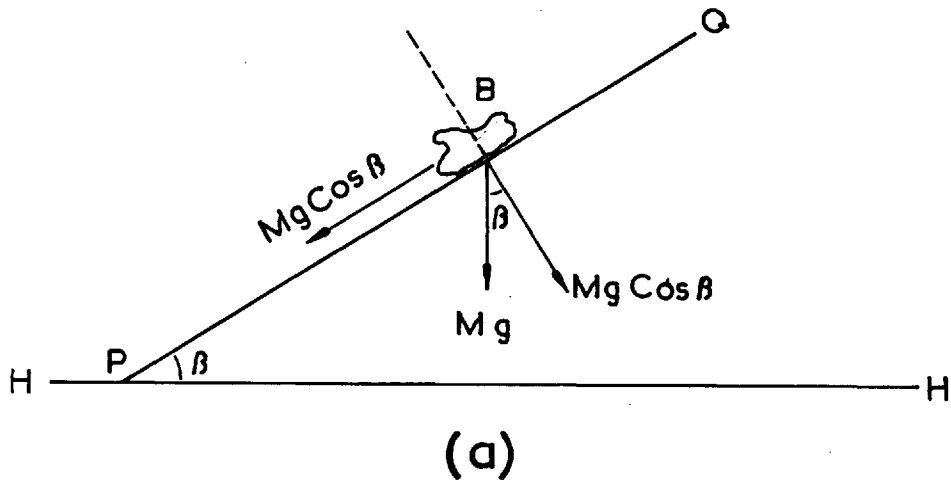
The latter force tends to cause the particle to move down the plane ; as long as it is at rest, it is resisted by an equal and opposite force known as ^{the} tangential frictional force. As the slope of the plane is gradually increased a point is reached when the tangential force just balances the frictional force, and any further increase causes the particle to move downwards. Fig. (12a)

If β represents the angle of the plane at this moment, then

$$\frac{\text{Frictional Force}}{\text{Normal Force}} = \tan \beta = \mu \quad (16)$$

and μ is called the dynamic coefficient of friction.

Fig(12)



β is called the dynamic angle of repose and is synonymous with the angle of friction. In most Engineering applications, it is used only to designate the maximum slope taken up by heaps of materials before sliding occurs.

When the heap is being formed, it is in an unstable condition and the angle of the surface is greater than β . When the flow ceases, and the material settles down to a more stable configuration, with a base angle β (Fig. 12 b) the gravitational pull acting on the particle is balanced by the friction between them.

The angle of repose may, therefore, be defined as the angle assumed by the boundaries of an unconstrained material in static equilibrium with the surrounding medium (usually air) when it slides over itself on being poured in the form of a heap onto a horizontal surface, under specified conditions.

METHOD OF MEASUREMENT:

The angle of repose of a heap of granular material depends upon its particle size, size distribution, shape, density, moisture content and mode of

formation. Reproducible results, therefore, can be obtained only when the method of measurement is rigidly defined and adhered to.

In this work, the angle of repose was measured by the moving funnel method. A glass funnel of 3" diameter with a 6" long stem drawn out to about 4 mm diameter was held vertically in a clamp which could be raised or lowered as desired by means of a gear mechanism. Before each experiment, the material was dried for at least one hour in an oven to 110°C to ensure that it was free of uncombined moisture. The funnel was raised slowly during the flow of material, the stem of the funnel touching the apex of the heap to ensure that the impact of the falling material was a minimum. The heap was formed on a horizontal plate with a rough surface, supported on rubber pads so as to minimise the effect of random vibrations in the laboratory.

The angle of repose of the resultant cone was measured with the help of an 8" protractor fitted with a slide. A plane mirror was placed vertically behind the heap, and the angle of repose was measured by removing the parallex between the edge of the slide, the inclined surface of the heap and its image in the mirror.

It was observed that while the heap was being formed, the surface particles were in a state of continuous motion and the heap in an unstable condition. The angle measured while the particles are still in motion is called the "dynamic angle of repose" and is higher than the "static angle of repose", which is the angle measured when the heap has settled to its most stable configuration. In all cases an average of at least 12 readings was taken as a measure of the angle.

The external factors which can cause a small variation in the angle of repose have been eliminated as follows:

(1) Although the particles resting on the free surface of a heap of material are in a state of equilibrium, a slight vibration may set them in motion again. To avoid any changes due to vibration, the plate on which the heap was formed was placed on a horizontal platform of asbestos sheet, with a rubber foam lining on the base and supported on rubber pads. The heap was formed on the plate and the angle of repose was measured at various intervals of time. It was found that normal vibrations present in the laboratory had no effect on the angle even when the heap was left overnight.

- (2) Alterations in the angle due to the impact of falling material was minimised by raising the stem of the funnel slowly so as to keep the distance of the fall of the material the same throughout.
- (3) A rough surface was used on top of which the heap was formed to avoid the rolling of particles at the base of the cone.
- (4) Even a small amount of moisture is liable to alter the angle of repose. All materials were heated in an oven at 110°C for at least one hour before the start of the experiment.

Observing the above precautions, the angle of repose was found to be reproducible to $\pm 1^{\circ}$, a statistical analysis performed on two sets of observations is given in the Appendix (I).

A ~~large~~ number of materials were chosen such that they gave a wide range of particle sizes, densities and ~~the~~ shape factors. A summary of their physical properties is given in Table (VI).

TABLE (VI)

NO.	MATERIALS	DENSITY ρ	SURFACE SHAPE COEFFICIENT f_s	VOLUME SHAPE COEFFICIENT f_v	SHAPE FACTOR $f = f_s/f_v$
1	BALLOTINE	2.95 gm/cc	3.82	0.547	6.98
2	COAL	1.3 gm/cc	3.17	0.306	10.05
3	CORN	1.4 gm/cc	3.45	0.447	7.72
4	FELDSPAR	2.57 gm/cc	2.82	0.287	9.82
5	GRAPHITE	2.51 "	2.75	0.41	6.71
6	HEMATITE	3.72 gm/cc	3.19	0.329	9.70
7	LEAD SHOTS	11.34 gm/cc	3.14	0.524	5.98
8	LIMESTONE	2.66 gm/cc	3.01	0.261	11.54
9	MAGNETITE	4.39 gm/cc	2.59	0.31	8.39
10	SAND	2.64 gm/cc	3.20	0.389	8.23
11	SEEDS	2.65 gm/cc	3.12	0.464	6.72

RESULTS:

In Table (VII), a comparison of the values of the angle of repose determined by this and three alternative methods are given from which it can be seen that the values determined by all the four methods are reasonably in agreement.

EFFECT OF PARTICLE SIZE ON THE ANGLE OF REPOSE:

To investigate the effect of particle size on the angle of repose, four different materials, i.e. coal, graphite, magnetite and sand of varying particle sizes between 80 and 1080 were used (Ballotine was available in two sizes only). The results are summarised in Table (VIII) and are shown graphically in Fig. (13).

It is known that particles in a granular mass are held together inter alia by cohesive forces and mechanical forces due to interlocking. The magnitude of these forces is a function of the particle size, the former increasing as the particle size diminished and the latter increasing with the particle size; and both may be expected to influence

TABLE (VI)

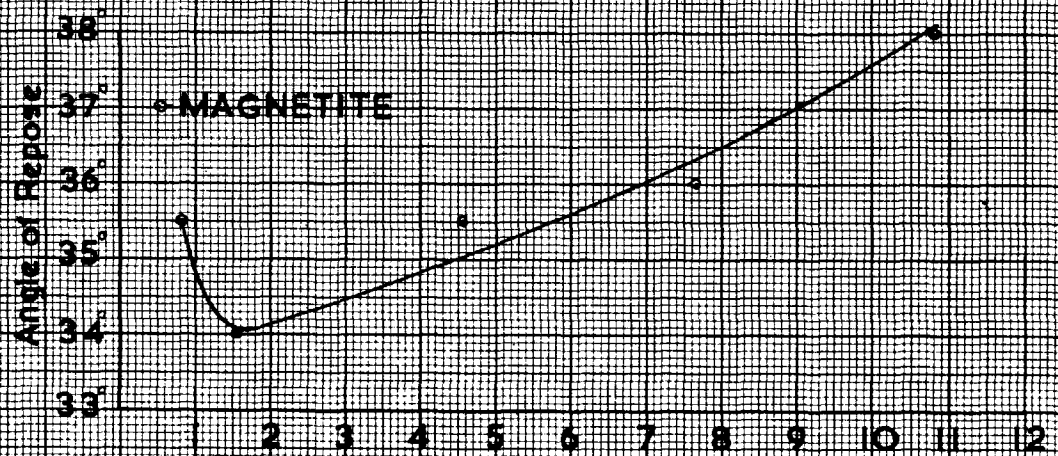
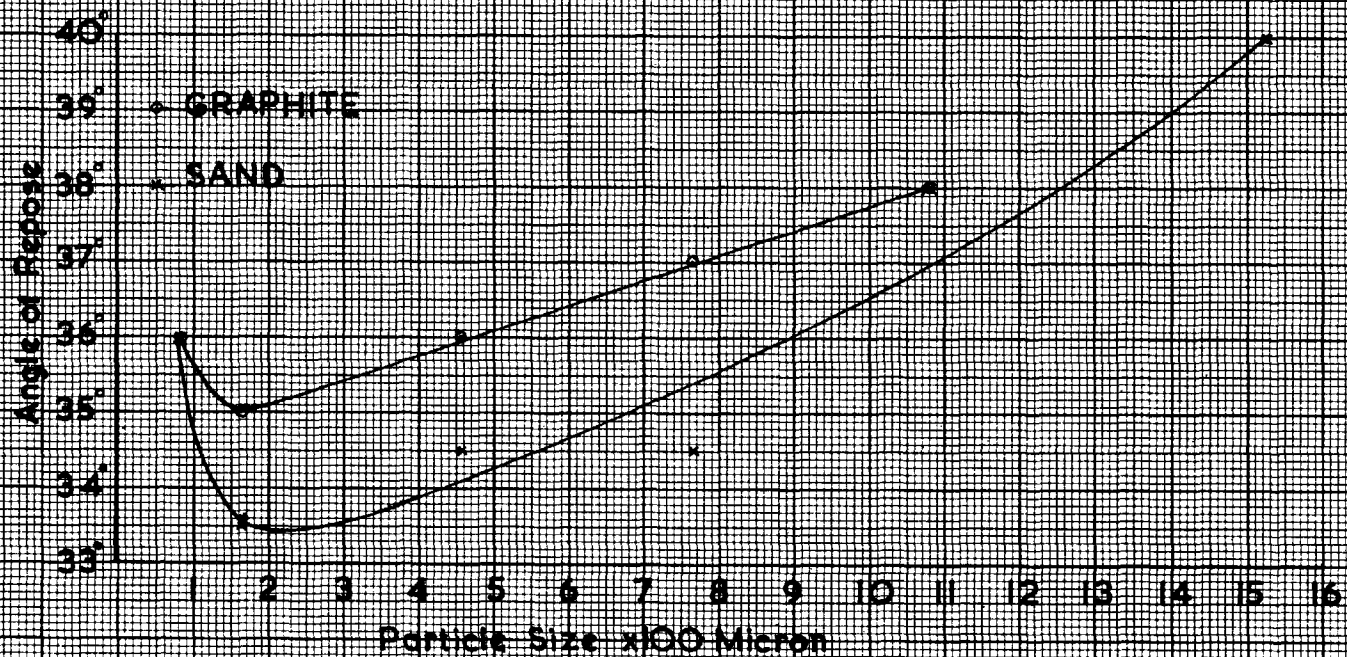
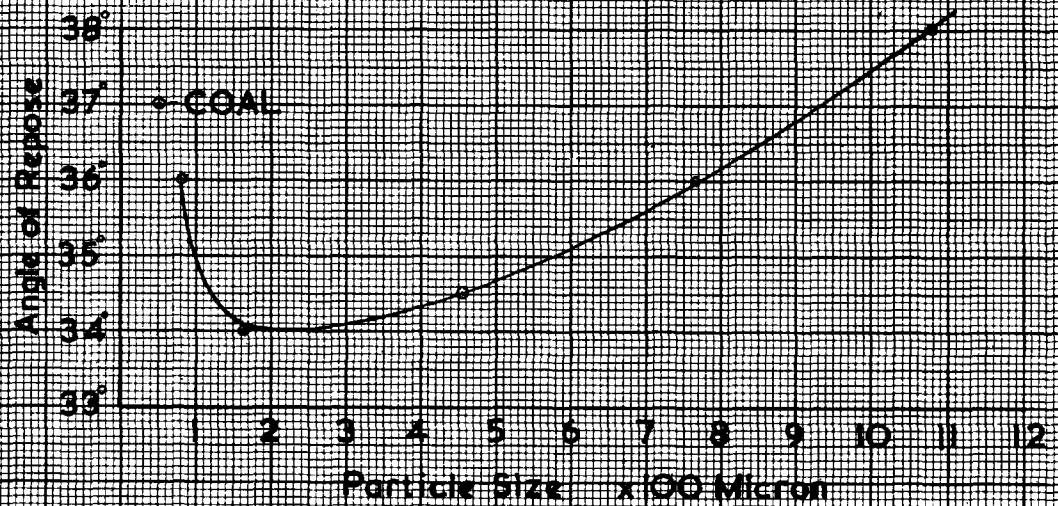
NO.	MATERIALS	MESH SIZE	ANGLE OF REPOSE - DEGREES			
			THIS WORK	BOX METHOD	DISC METHOD	CYLINDER METHOD
1	SEEDS	22/25	32.1	31.0	30.3	31.0
2	HEMATITE	18/22	38.5	37.5	38.0	37.0
3	YELLOW SAND	18/22	36.8	-	-	-
4	PINK SAND	18/22	37.4	37.5	34.5	38.0
5	COAL	18/22	35.6	36.5	36.8	35.0
6	LEAD SHOTS	16/18	27.5	28.5	-	29.0
7	CORN	18/22	36.0	-	-	-
8	BALLOTINE	14/16	24.5	25.5	-	27.0
9	FELD SPAR	52/60	36.5	38.0	-	-
10	SAND	22/25	34.5	34.0	33.8	34.0

TABLE (VIII)

NO.	PARTICLE SIZE OF THE MATERIAL			THE ANGLE OF REPOSE - DEGREES				
	MESH SIZE	DIA (INCHES)	MICRONS	BALLOTINE	COAL	GRAPHITE	MAGNETITE	SAND
1	10/12	606.5×10^{-4}	1524	x	x	x	x	40.0
2	12/14	513.5×10^{-4}	1282	x	x	x	x	38.0
3	14/16	434.5×10^{-4}	1080	24.5	38.0	38.0	38.0	35.0
4	18/22	305.5×10^{-4}	767	x	36.0	37.0	36.0	34.5
5	30/36	181.5×10^{-4}	456	x	34.5	36.0	35.5	34.5
6	52/60	107.5×10^{-4}	270	23.0	x	x	x	34.0
7	85/100	65.0×10^{-4}	161	x	34.0	35.0	34.0	33.5
8	120/150	45.0×10^{-4}	114	x	x	x	x	35.0
9	170/200	32.5×10^{-4}	81	x	36.0	36.0	35.5	36.1

Fig(13)

ANGLE OF REPOSE VS PARTICLE SIZE



the angle of repose. The curves in Fig. (13) suggest that both cohesive and interlocking effects are a minimum for particle sizes in the region of 100 microns, and that the angle of repose may be markedly influenced by the presence of small quantities of the other.

The results for graphite are rather unexpected since it might have been anticipated that its low internal friction and lubricative properties would result in a low angle of repose particularly for particles of intermediate sizes.

EFFECT OF ADDITIONS OF FINES ON THE ANGLE OF REPOSE:

To ascertain the effect of a wide size^{range}/on the angle of repose, various proportions of fines were added to coarse particles and the angles of repose of the mixtures measured. The particle size of fines in one case was less than 100 microns and in the other greater than 100 microns i.e. on either side of the minimum shown in the curve in Fig. (13).

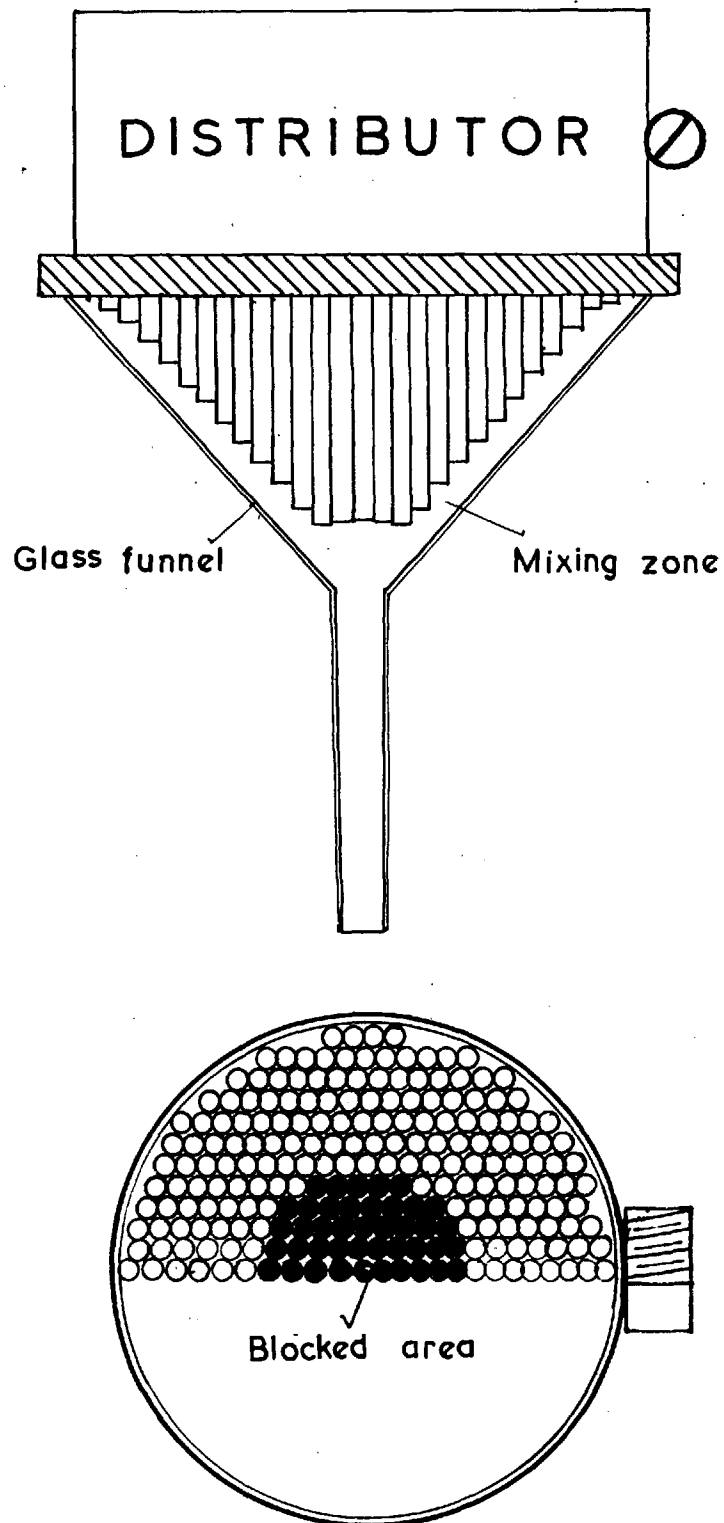
When using a mixture of particles of varying sizes, a distributor was used to fill the funnel to avoid any segregation of the material at this stage.

The distributor (see Fig. 14) was made in the shape of a funnel from a bundle of glass tubes of inside ^{meter} dia/ greater than the blocking diameter (usually 10 times the average particle size) to ensure free flow. An area of one inch in diameter in the centre of the distributor was blocked so that the material could not pass straight through the centre. The space between the ends of the distributor tubes and the inside surface of the funnel acted as a mixing zone.

In order to test the efficiency of the distributor, 25 percent by weight of fine sand (particle size 85/100 mesh) was mixed with 75 percent by weight of coarse sand (mesh size 18/22). The mixture was spread onto the distributor and samples were taken at regular intervals of time from the stream of particles issuing from the funnel, and analysed. The experiment was repeated with 50 percent and 75 percent mixtures. The results of a typical analysis of each set are given in Table (IX) and shown graphically in Figure (15).

It will be seen from a plot of composition versus the sample number that a mixture of fairly

Fig(14)



constant composition could be obtained, by neglecting the first small portion of the stream. The standard deviation for 25%, 50% and 75% mixtures being 7.9, 7.0 and 4.7 respectively.

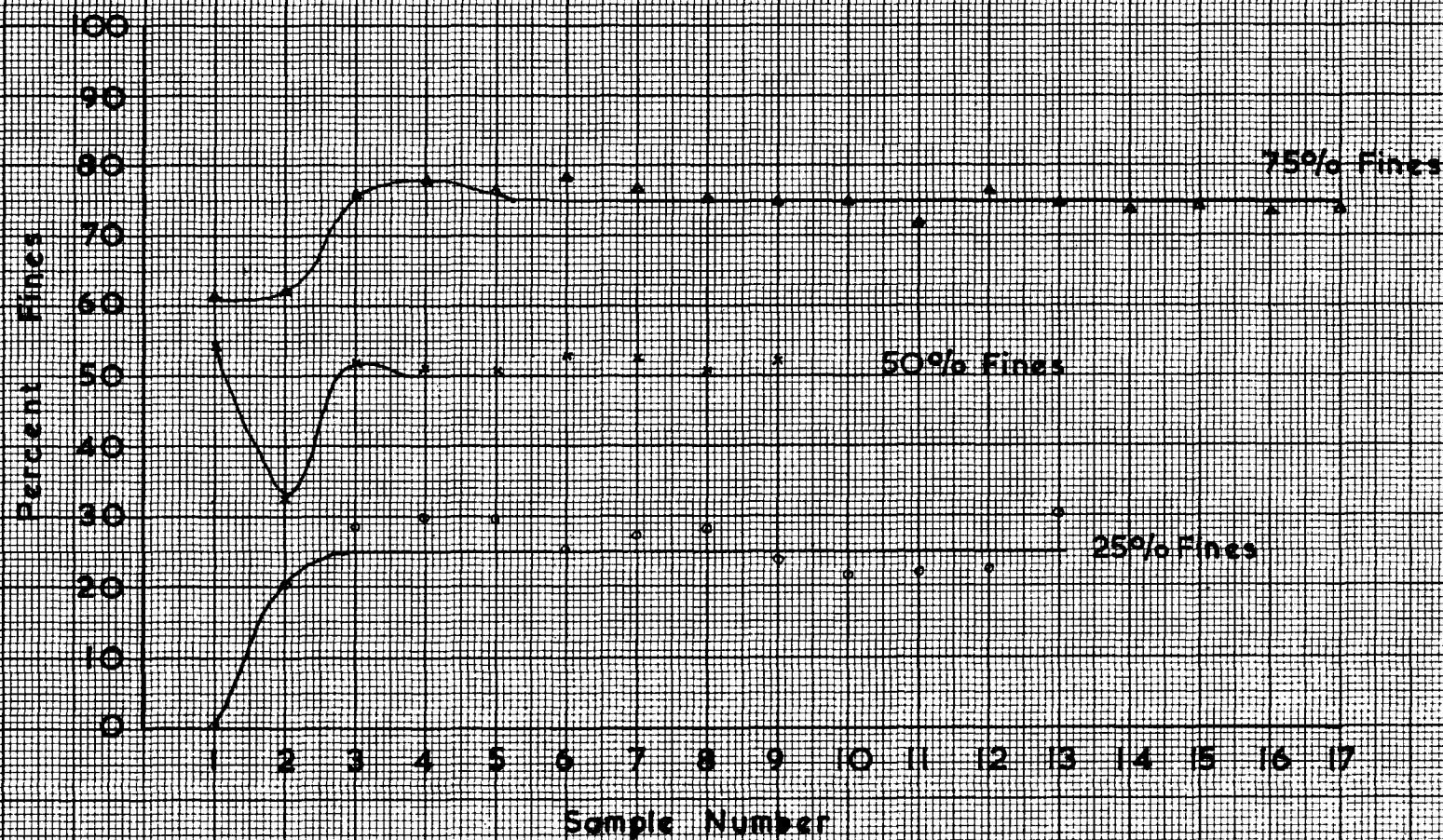
TABLE (IX)

SAMPLE No.	ORIGINAL MIXTURE		(FINES)
	25%	50%	75%
(1)	0.24 %	54.4 %	61.2 %
(2)	20.3 "	32.5 "	62.0 "
(3)	28.5 "	39.4 "	76.0 "
(4)	29.8 "	51.8 "	77.8 "
(5)	29.5 "	51.1 "	76.4 "
(6)	25.2 "	50.7 "	78.1 "
(7)	27.3 "	52.9 "	76.6 "
(8)	28.2 "	52.8 "	75.2 "
(9)	23.6 "	50.7 "	78.1 "
(10)	21.5 "	52.2 "	74.8 "
(11)	22.0 "		71.6 "
(12)	22.3 "		76.4 "
(13)	30.4 "		74.6 "
(14)			73.6 "
(15)			74.2 "
(16)			73.3 "
(17)			73.6 "

Fig (15)

ANALYSIS OF STREAM OF PARTICLES

FROM THE DISTRIBUTOR



Two sets of experiments were carried out with coal and magnetite respectively. A summary of the results is given in Table (X) and shown graphically in Figure (16).

TABLE (X)

ANGLE OF REPOSE OF MIXTURES OF COARSE AND FINE MATERIAL..

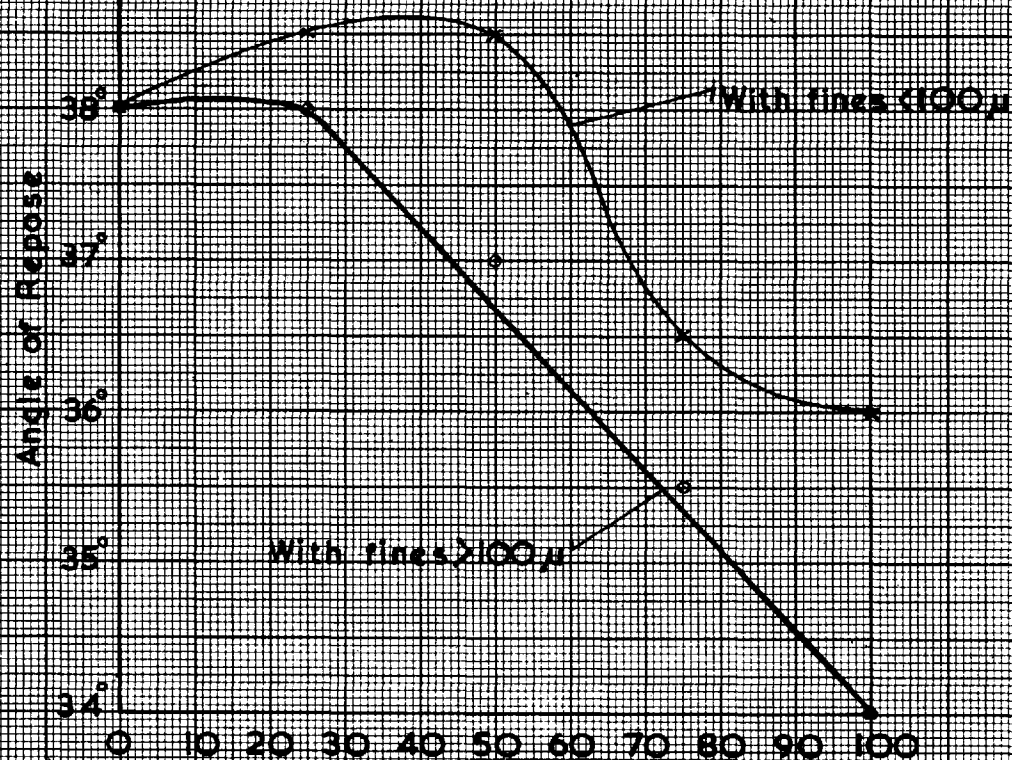
COAL MESH SIZE 14/16

% AGE FINES	A N G L E O F R E P O S E	
	PARTICLE SIZE >100 μ	PARTICLE SIZE <100 μ
0	38.0°	38.0°
25	38.0°	38.5°
50	37.0°	38.5°
75	35.5°	36.5°
100	34.0°	36.0°

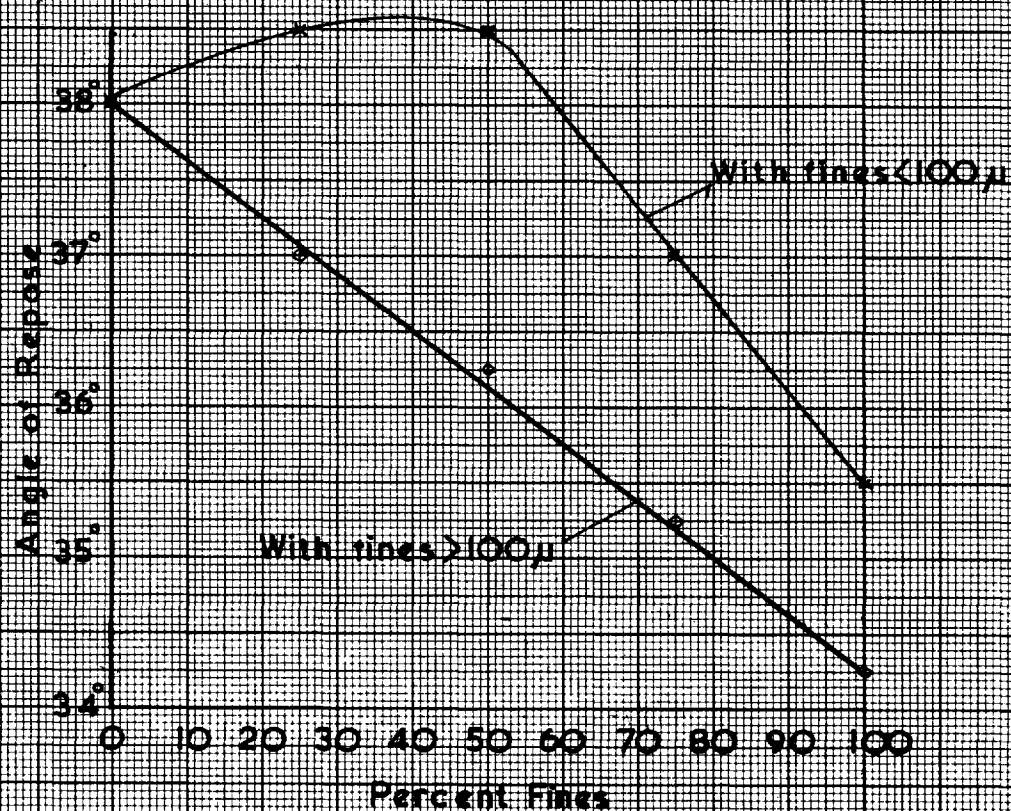
Fig(16)

EFFECT OF ADDITION OF FINES ON THE ANGLE OF REPOSE

COAL
(14/16)



MAGNETITE
(14/16)



MAGNETITE MESH SIZE 14/16

% AGE FINES	A N G L E O F R E P O S E	
	PARTICLE SIZE >100 μ	PARTICLE SIZE <100 μ
0	38.0°	38.0°
25	37.0°	38.5°
50	36.5°	38.5°
75	35.5°	37.0°
100	34.5°	35.5°

Figure (16) shows the effect of addition of fines of 2 different sizes of the same material on the angle of repose of coarse coal and magnetite respectively. It can be seen that the addition of fines of particle size 85/100 mesh (less than 100 microns) decreases the angle of repose linearly. An initial slight increase in the angle of repose in case of coal is probably due to the fact that this coal was brittle and gave additional fine dust due to attrition. Addition of 75 percent by weight of 85/100 mesh size fine material lowered the angle of repose in both cases by 2.5 degrees.

It will be relevant here to discuss the effect of fines on the bulk density, which is a characteristic of the packing of a granular material in which each particle is supported by direct contact with the surrounding particles. If spheres of equal sizes are stacked in a hexagonal arrangement, which is the closest type of packing, each sphere is in contact with 12 others and the porosity is 26 percent, while if they are piled in a cubical arrangement, which is the loosest form of packing, each sphere has 4 points of contact, its porosity being 48 percent.

White and Walton (44), from a mathematical analysis, determined the number and sizes of particles necessary to fill the interstices and indicated that voids as low as 15% are theoretically possible. Secondary spheres, which can be fitted between the voids of a packing do not completely fill the cavity and allow for more spheres of still smaller diameters, called tertiary and quaternary spheres etc. to be inserted about it. The diameters of secondary, tertiary and quaternary spheres being $0.414 d$, $0.225 d$ and $0.177 d$ (where d is the diameter of ^{the} primary spheres of which the packing is composed ~~of~~) and their relative numbers being one, two, and eight respectively.

Furnas (45) has shown that when fines spherical particles having in bulk a voidage v , are blended with a mass of larger spherical particles, of the same voidage, without a change in volume, the binary mixture of maximum bulk density results when the proportion of the large sized particles in the mixture equals $\frac{1}{1+v}$ (17)

$$\text{where } v = \text{voidage} = 1 - \frac{\text{Bulk Density}}{\text{True Density}} = 1 - \frac{e_B}{e_t}$$

The above equation (17) holds as long as the particles have the same shape and the voidage is the same for the two components.

For a multi-component (having particles of more than two sizes) system, the total volume of solids is given by

$$\Phi = \frac{1}{1+v} + \frac{v}{1+v} + \frac{v^2}{1+v} + \dots \quad n \quad (18)$$

Each term applies to a single component and there are n terms for n -components. It holds only when the voids of each component are the same. In addition to the number of components, the bulk density of a material will also be affected by the size ratio of the n -components.

For varying voids and densities, for a 3-component system, for example, the total volume of solids, , is given by

$$\Phi = \varphi_1 + (1 - \varphi_1) + (1 - \varphi_1) \frac{(1 - \varphi_2)}{2} \quad (19)$$

where φ_1 = Degree to which the voidage of the 1st component is saturated by the 2nd component.

$$= \frac{(1 - v_1) \rho_1}{(1 - v_1) \rho_1 + v_1 (1 - v_2) \rho_2} \quad (20)$$

and φ_2 = Degree to which the voidage of the 2nd component is saturated by the 3rd component

$$= \frac{(1 - v_2) \rho_2}{(1 - v_2) \rho_2 + v_2 (1 - v_3) \rho_3} \quad (21)$$

where v's and ρ 's are the voids and densities, respectively of the components identified by the subscripts.

The above equation can be applied to a binary system. For example,

I. COAL

	PARTICLE SIZE	DENSITY	EXPERIMENTAL BULK DENSITY	CALCULATED VOIDAGE
COARSE	14/16	1.3 ~~gr/cc~~	0.644 ~~gr/cc~~	0.505
FINE	85/100	"	0.581 "	0.553

Applying equation number (20)

the amount of coarse particles, the voidage of which is saturated by fine particles, is given by

$$\varphi = \frac{(1-v_1) \rho_1}{(1-v_1) \rho_1 + v_1(1-v_2) \rho_2} ; \text{ as } \rho_1 = \rho_2$$

$$\varphi = \frac{1-v_1}{(1-v_1) + v_1(1-v_2)}$$

substituting the values from above table

$$\begin{aligned} \varphi &= \frac{1-.505}{(1-.505) + .505(1-.553)} = \frac{.495}{.495 + 0.247} \\ &= \frac{.495}{.742} = \underline{\underline{66.7}} \% \end{aligned}$$

$$\text{Percentage of fines} = 100 - 66.7 = \underline{\underline{33.3}}$$

II. MAGNETITE

	SIZE	DENSITY	EXPERIMENTAL BULK DENSITY	VOIDAGE
COARSE	14/16	4.39 g/cc	2.43 g/cc	0.447
FINE	85/100	" "	2.06 "	0.531

$$\phi = \frac{1-0.447}{(1-0.447) + 0.447 (1-0.531)} = \frac{.553}{.553 + .21}$$

$$= \frac{.553}{.763} = 72.48 = \underline{\underline{72.5}} \%$$

$$\text{Percentage of fines} = 100 - 72.5 = \underline{\underline{27.5}}$$

The calculated values of the amount of coarse material whose voidage will be saturated by the fines, hence giving a maximum bulk density, is found to be nearly equal to the experimental value. Pratap (12) has found that in the case of materials of irregular shapes, a maximum bulk density is obtained when the mixture contains 70-85 percent of coarse material in case of a binary system. This result has been confirmed in this work.

The angle of repose of a mixture of coal and magnetite with fines of the same material increases with bulk density giving a maximum value of the angle for a mixture where the bulk density is a maximum i.e. 70-75 percent, of coarse material after which it approaches the value of that of the coarse material, although the bulk density of the coarse material is less than the highest value obtained (Table (XI a) and (XI) b). In the light of above facts, a qualitative explanation of the effect of fines on the angle of repose is as follows:

The angle of repose of a granular material is a property of the interface i.e. the surface over which the material slides and also of the density of the material. The properties of this surface depend upon the particle size distribution, and roughness of the surface. Other factors remaining the same, in a binary system, the angle of repose will, therefore, depend upon ^{the} roughness of the surface formed by the particles.

Consider a mixture of particles of different sizes being poured into a heap. The nature of the surface will keep changing due to the segregation of

TABLE (XI)

NO.	MATERIAL		(a) COAL		(b) MAGNETITE	
	PERCENTAGE COMPOSITION		ANGLE OF REPOSE DEGREES	BULK DENSITY g/cc	ANGLE OF REPOSE DEGREES	BULK DENSITY g/cc
	COARSE(14/16)	FINE(85/100)				
1	ZERO	100	34.0	0.581	34.5	2.06
2	25	75	35.5	0.661	35.5	2.33
3	50	50	37.0	0.723	36.5	2.564
4	75	25	38.0	0.737	37.0	2.60
5	100	ZERO	38.0	0.644	38.0	2.43

particles of varying sizes, the bigger particles rolling to the sides while the finer ones remain as a core in the heap. The angle of repose of the mixture will, therefore, depend on the conditions of the surface whether it is wholly or partially composed of fines.

From the results obtained for the segregation of particles in heaps (Chapter 6) it will be seen that the inclined surface of the heap over which the material slides is almost saturated with the fines except ~~at~~ the extreme edges, irrespective of the original composition of the mixture. As it is the top portion of the heap and not the bottom, which decides the fate of the falling material, the angle of repose of the resultant cone will depend on the condition of the upper region and the degree to which it varies as to the amount of fines present. As the roughness of the surface finally approaches that of the fine material only, the angle of repose tends to reach a value equal to that of the fines.

This explanation is applicable to binary systems in which the particle size of the fines present is greater than 100 microns. When fines of

particle size less than 100 microns are added to coarse particles, another property i.e. cohesion comes into play. the additional cohesive force changes the relative value of that of the mixture. Some of the fines adhere to the surface of coarse particles, as observed under the microscope, markedly changing the surface properties. An increased cohesion and surface roughness therefore causes the angle of repose to increase upto an addition of 50 percent fines. Further additions of fines persist as a bulk and as the surface roughness of the mixture approaches that of the fine material, so does the angle of repose.

EFFECT OF ADDITION OF AN ADDITIVE (GRAPHITE FINES) ON THE ANGLE OF REPOSE.

Graphite of particle size 85/100 mesh (> 100 microns) and 170/200 mesh (< 100 microns) in various proportions was mixed with coal and magnetite and the angle of repose of the heap formed from a mixture of the two components was measured. The angle of repose of graphite of /85/100 mesh and 170/200 mesh was 35° and 36° respectively.

A Summary of the results is given in table (XII) and shown graphically in figure (17) .

TABLE (XII) THE ANGLE OF REPOSE OF COARSE
MATERIAL IN THE PRESENCE OF
FINE GRAPHITE.

COAL. PARTICLE SIZE 14/16 .

PERCENTAGE FINES	ANGLE OF REPOSE OF MIXTURE WITH GRAPHITE	
	>100 MICRONS	<100 MICRONS
1. 0	38.0	38.0
2. 25	37.5	37.5
3. 50	36.0	36.5
4. 75	35.0	34.5
5. 100	35.0	36.0

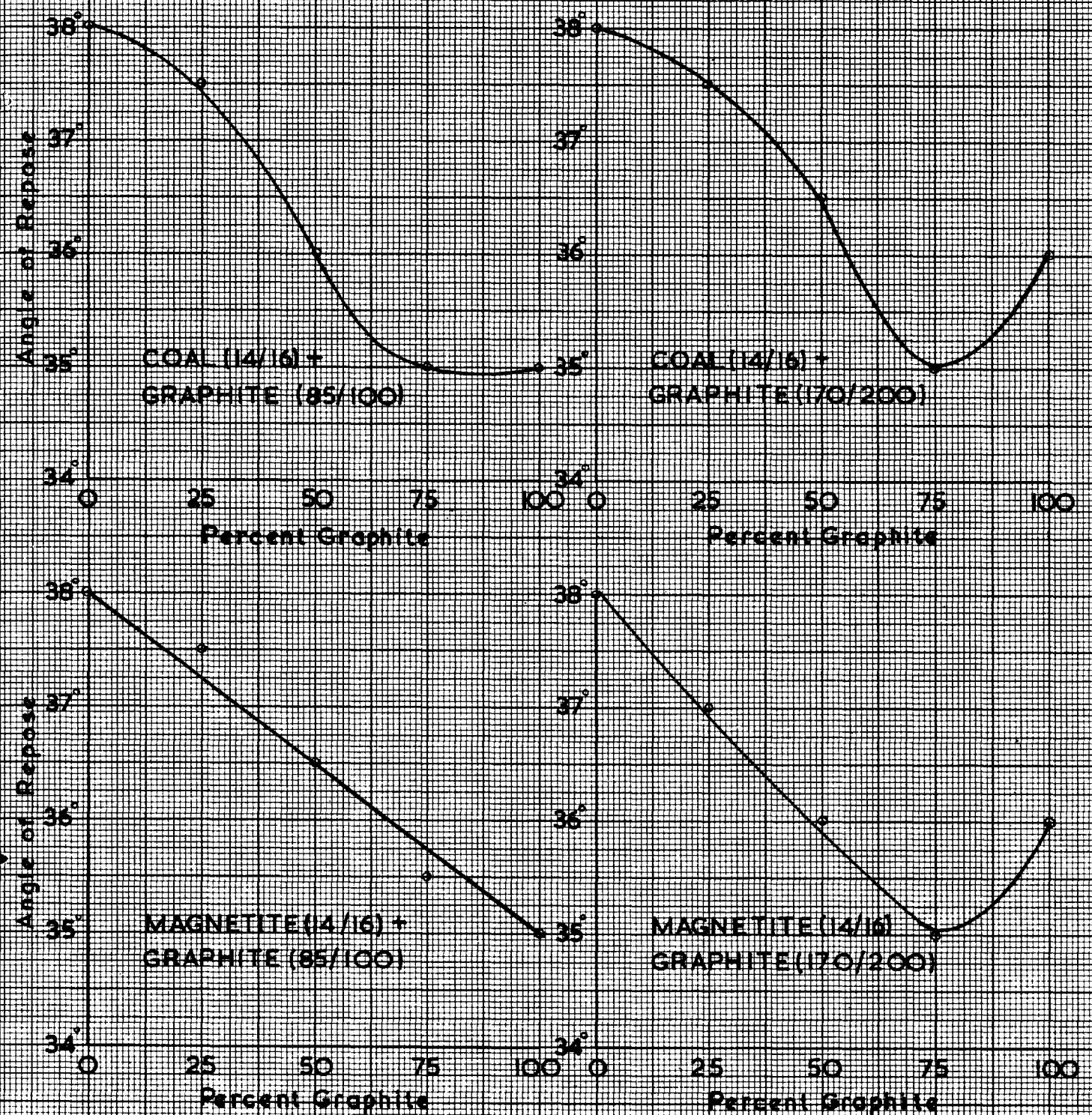
MAGNETITE PARTICLE SIZE 14/16

1. 0	38.0	38.0
2. 25	37.5	37.0
3. 50	36.5	36.0
4. 75	35.5	35.0
5. 100	35.0	36.0

If graphite of the same particle size as the coarse material (coal or magnetite mesh size 14/16) ~~and~~ is mixed in various proportion, it was found that it did not alter the angle of repose of either of them. In the case of 85/100 mesh graphite particles, the angle of repose of coarse coal and graphite mixtures varied linearly and so did the angle of repose of coarse magnetite when mixed with ^{the same} graphite in various proportions. But the presence of fine graphite did not affect the angle of repose of the mixtures to an appreciable degree (Fig. 17).

Fig (17)

EFFECT OF ADDITION OF GRAPHITE ON THE ANGLE OF REPOSE



The behaviour of graphite particles of size 170/200 mesh (less than 100 microns) was quite different. There was a marked decrease in the angle of repose of both coarse coal and coarse magnetite in its presence, 75 percent graphite lowering the angle by 3 to 3.5 degrees. This may be attributed to the lubricating qualities of graphite.

Graphite acts as a solid lubricant both as a dry powder and in the presence of fluids like oil and water, the lubrication properties increasing with a decrease in the particle size. A colloidal suspension of graphite in oil is used for a great variety of purposes.

CHAPTER 6.SEGREGATION IN HEAPSGENERAL:

As already mentioned it is a common experience that when a granular mass composed of particles of varying size or density is disturbed, there is a tendency for segregation to occur and if the movement is regular and continuous, a state of equilibrium will eventually be reached at which the composition of the mass, though not uniform, will remain constant with time. The extent of the segregation produced depends upon a number of factors amongst which are the size, shape and density of the particles, and the nature of the motion imparted to the mass. It will be clear, therefore, that the angle of repose of the material, which is determined by the above factors, is a quantity of importance, when attempting to give a quantitative expression to the phenomenon.

The method in general use for measuring the angle of repose of a granular material is that of allowing it to escape from a container and form a conical heap, the angle at the base of the cone being the required angle. It is, therefore, of importance to know

the extent of segregation produced when such a heap is formed under regulated conditions and a number of attempts to ascertain this are described in the literature and have already been referred to in Chapter (4).

The main difficulty in carrying out such a determination is that of obtaining representative samples from different locations in the heap without disturbing the distribution. Thus in the case of the experiments described by Holmes (36), although no detailed account is given of his sampling arrangement, it is almost certain that not only would the distribution be altered by dividing the heap into sections but also the samples would be too large to give a detailed picture of the extent of segregation in all parts of the cone. In Williams (33) and Starimand's (32) work on the other hand the use of a two-dimensional model introduces surface effects which may materially distort the general picture. In both cases there is also the possibility of segregation occurring both in the feed hopper and in the stream of emerging material prior to the formation of ^{the} cone.

EXPERIMENTAL:

According to Donald and Roseman (40), Rose (43) and Coulson and Maitra (41) for appreciable segregation to occur the ratio of particle size or density must exceed a certain limiting value, which the former two quote^{as} 1.2 whilst Coulson and Maitra give 2.5. In the present work, the larger of these values has been adopted.

MATERIALS:

In determining the effect of particle size, coarse sand of particle size 18/22 mesh (767 microns) was mixed with fine sand of particle size 85/100 (161 microns), the size ratio being 4.7:1. The sand particles were roughly angular in shape, the shape factor being 8.2.

To determine the effect of density coal (density 1.3) and magnetite (density 4.39) were mixed in various proportions the density ratio being 1:3.32. The particle size was 18/22 in both cases. Viewed under the microscope, the shape of coal particles was angular (shape factor 10.38) and of the magnetite particles also angular (shape factor 8.38).

The method of ensuring constancy of the composition during the formation of heap was as follows:

Sand:- The two sizes were premixed by hand and transferred to the special distributor (See Chapter 5).

The composition of the emergent stream was checked and shown to be constant after slight variation at the beginning of flow.

Coal and Magnetite:- In this case much greater care had to be exercised in premixing and even then only the middle portion from the distributor had a sufficiently uniform composition to be employed.

In table (XIII) and Figure (18) the data is given of the analysis of samples of three different compositions taken at regular intervals of time during the discharge from the distributor. It will be seen that middle fractions (sample 6 to 12) are reasonably uniform in composition and these were used in the formation of the cone .

METHOD OF SAMPLING THE CONE:-

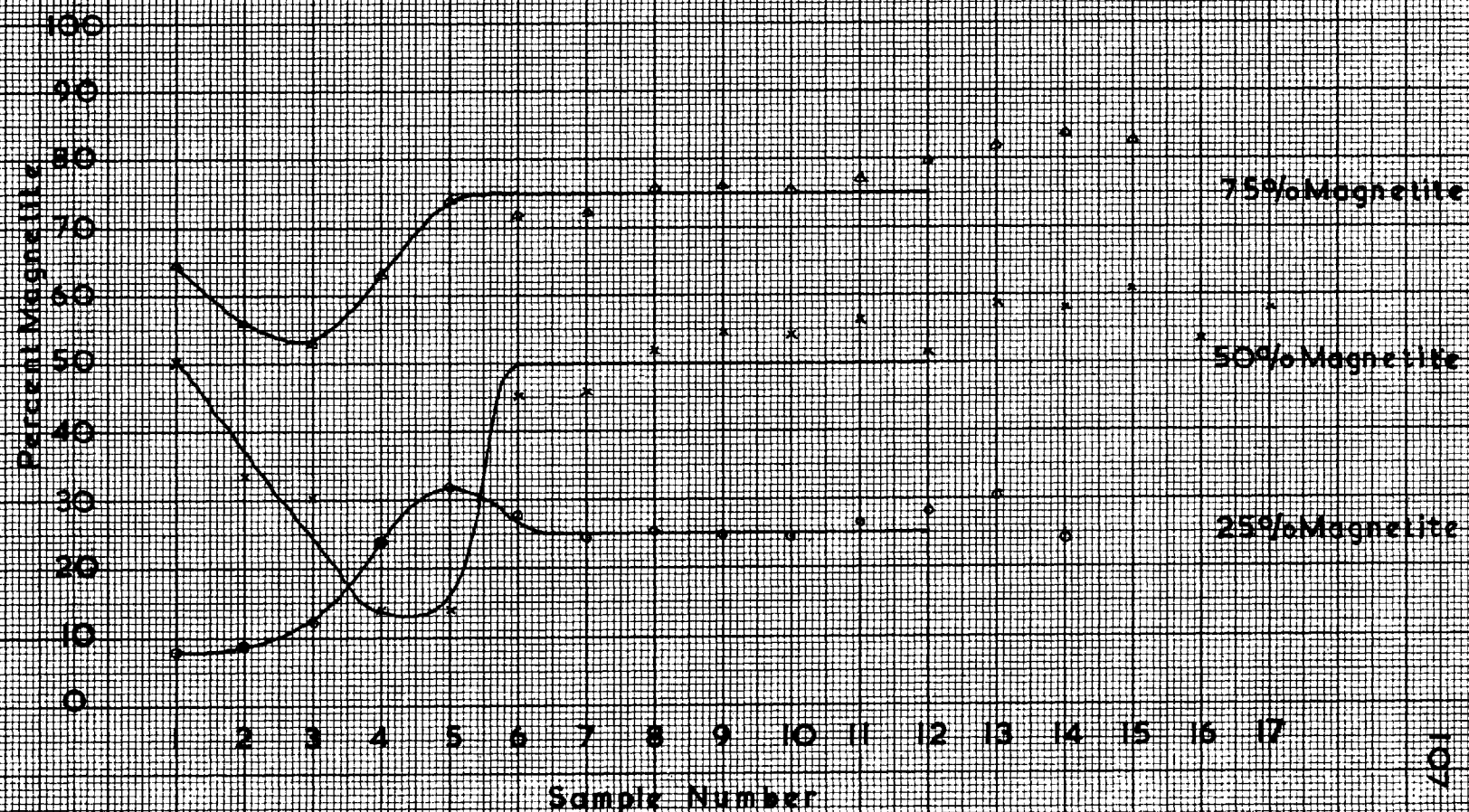
The following methods were used

1. Forming the cone in a box with transparent sides and then making a visual count of particles in small areas

TABLE XIIIPERCENTAGE COMPOSITION OF A STREAM OF MAGNETITE & COALORIGINAL COMPOSITION OF THE MIXTURE

<u>Sample</u> <u>No.</u>	<u>25% MAGNETITE</u>	<u>50% MAGNETITE</u>	<u>75% MAGNETITE</u>
1	7.9 % MAG:	50.4% MAG:	64.5% MAG:
2	8.9 "	33.5 "	55.9 "
3	12.2 "	30.2 "	53.0 "
4	23.6 "	13.9 "	63.0 "
5	31.8 "	13.9 "	73.9 "
6	27.7 "	45.3 "	71.7 "
7	24.2 "	45.9 "	72.0 "
8	25.0 "	51.8 "	75.7 "
9	24.7 "	54.5 "	76.1 "
10	24.4 "	54.2 "	75.5 "
11	26.4 "	56.3 "	77.1 "
12	28.1 "	51.6 "	79.8 "
13	30.4 "	58.8 "	82.0 "
14	24.3 "	58.1 "	83.7 "
15	--	60.8 "	82.7 "
16	--	53.6 "	--
17	--	58.1 "	--

Fig (18)
ANALYSIS OF STREAM OF PARTICLES
FROM THE DISTRIBUTOR

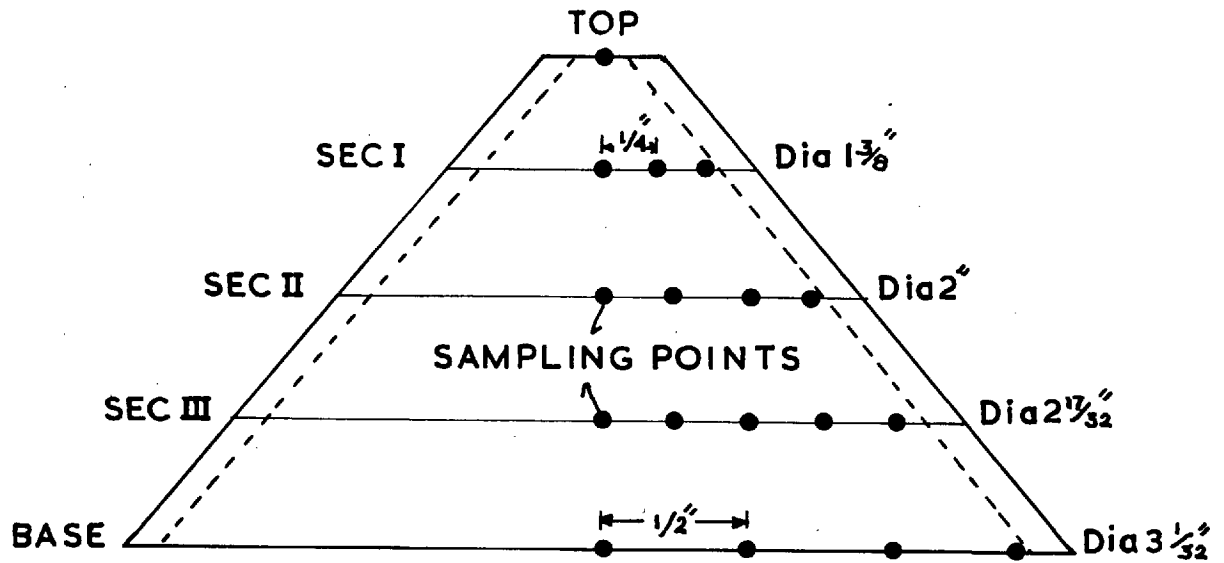


in different parts of the cone. By this method, only the surface area of the cone could be analysed and it was found difficult to obtain reproducible results.

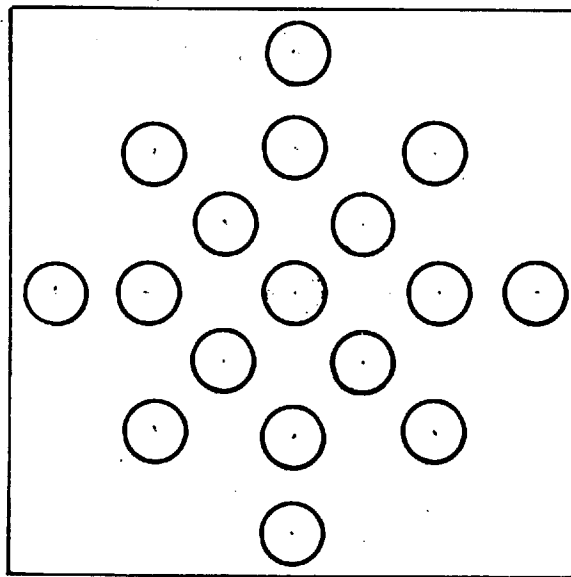
2. Agglomerating the particles by spraying the cone with a penetrating adhesive and then cutting it up into sections from which samples could be taken for analysis. A clear lacquer was used for the purpose and was applied in the form of a very fine spray produced by a spray gun of special design. The lacquer was subsequently removed from the samples by burning off and the residual granules analysed for composition by one of the methods described below. The method was satisfactory save for a zone near the centre of the cone which the adhesive had failed to penetrate.

3. The conical heap was formed inside a hollow cone made of plastic ~~steel~~ and having a base angle equal to the angle of repose. The ^{hollow cone} ~~substance~~ was made up of a number of sections (Fig. 19) which could be removed in succession from the top thus exposing a series of cross section of the heap from which samples could be taken by means of a micro-grab. A guide plate was used to locate the position of the samples and it was assumed

Fig(19)



(a) HOLLOW CONE



(b) GUIDE PLATE

DIAMETER OF EACH HOLE = $\frac{19}{64}$ "

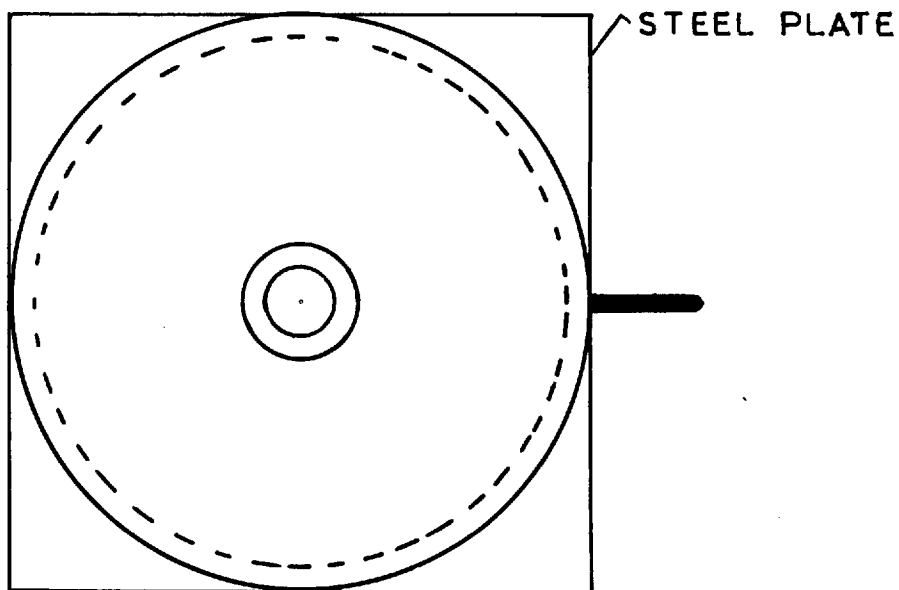
that there would be in any one plane a symmetrical distribution about the vertical axis. This was confirmed by experiment.

In order to take samples at the base of the conical heap a special device was used. This consisted of

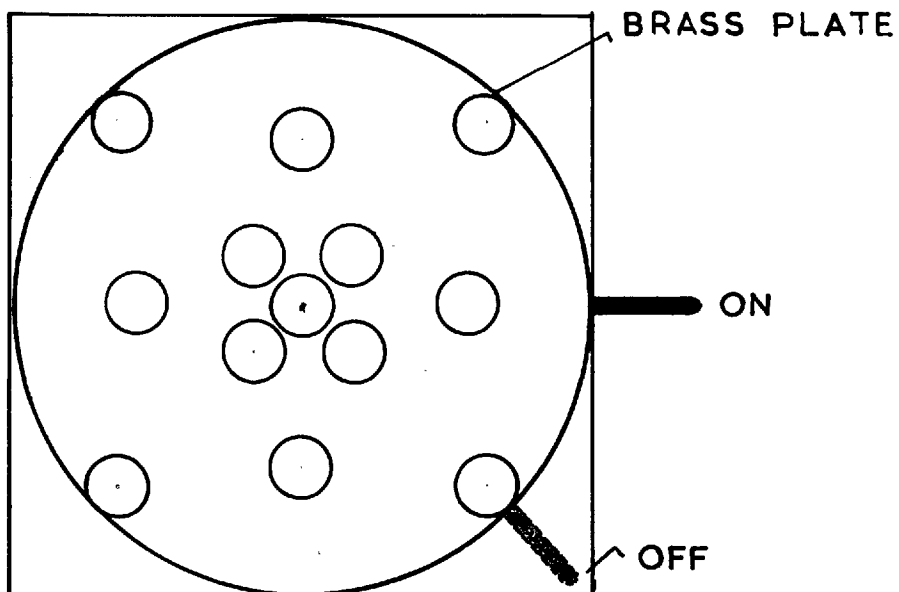
- (a) a roughened steel plate $1/16$ inch thick perforated by $19/64$ inch diameter holes, there being one hole at the centre of the plate and four holes each on concentric circles of diameter 1, 2 and 3 inch (See Fig.20)
- (b) Below the steel plate, a second brass plate $1/4$ inch thick drilled with holes to correspond with the upper plate. A sheet of paper stuck to the bottom of the brass plate served to close the holes. The brass plate was pivoted so that in the 'off' position, the holes in the upper plate were blocked off and in the 'on' position the two sets of holes synchronised.

The heap was formed with the brass plate in the 'off' position and after it had assumed an equilibrium position, the brass plate was rotated to its 'on' position. The holes then filled up and in this way gave samples from known positions at the base with^a minimum disturbance of the heap. The apparatus was mounted on an asbestos plate supported on a foam rubber pad to minimise the effect of stray vibrations.

Fig(20)



(a) UPPER PLATE



(b) LOWER PLATE

Size of each Hole = $19/64$ "

In the subsequent analysis the samples from each concentric circle of holes were mixed to give one representative sample. The location of sampling points was as shown in Fig. (19).

In the case of sand the samples were analysed by sieving and with coal and magnetite by magnetic separation.

PRESENTATION OF RESULTS:

The results could be presented either in the form of percentage of fines present in the samples or on the basis of degree of segregation. The extent of segregation is defined as

$$\phi_{+ve} = \frac{f - f_o}{100 - f_o} \times 100 \quad (22)$$

if the fines in the sample are in excess of that present in the original mixture and

$$\phi_{-ve} = \frac{f_o - f}{f_o} \times 100 \quad (23)$$

if the fines in the sample are less than that present in the original mixture. In these equations

ϕ = degree of segregation (+ve or -ve values denote increase or decrease in the fines, respectively)

$\mathcal{F}$ = amount of fines present in a sample and

$\mathcal{F}_0$ = amount of fines present in the original mixture.

For mixtures of varying densities, the above equations can be written as

$$\phi_{+ve} = \frac{\mathcal{H} - \mathcal{H}_0}{100 - \mathcal{H}_0} \times 100 \quad \text{when } \mathcal{H} > \mathcal{H}_0 \quad (24)$$

and

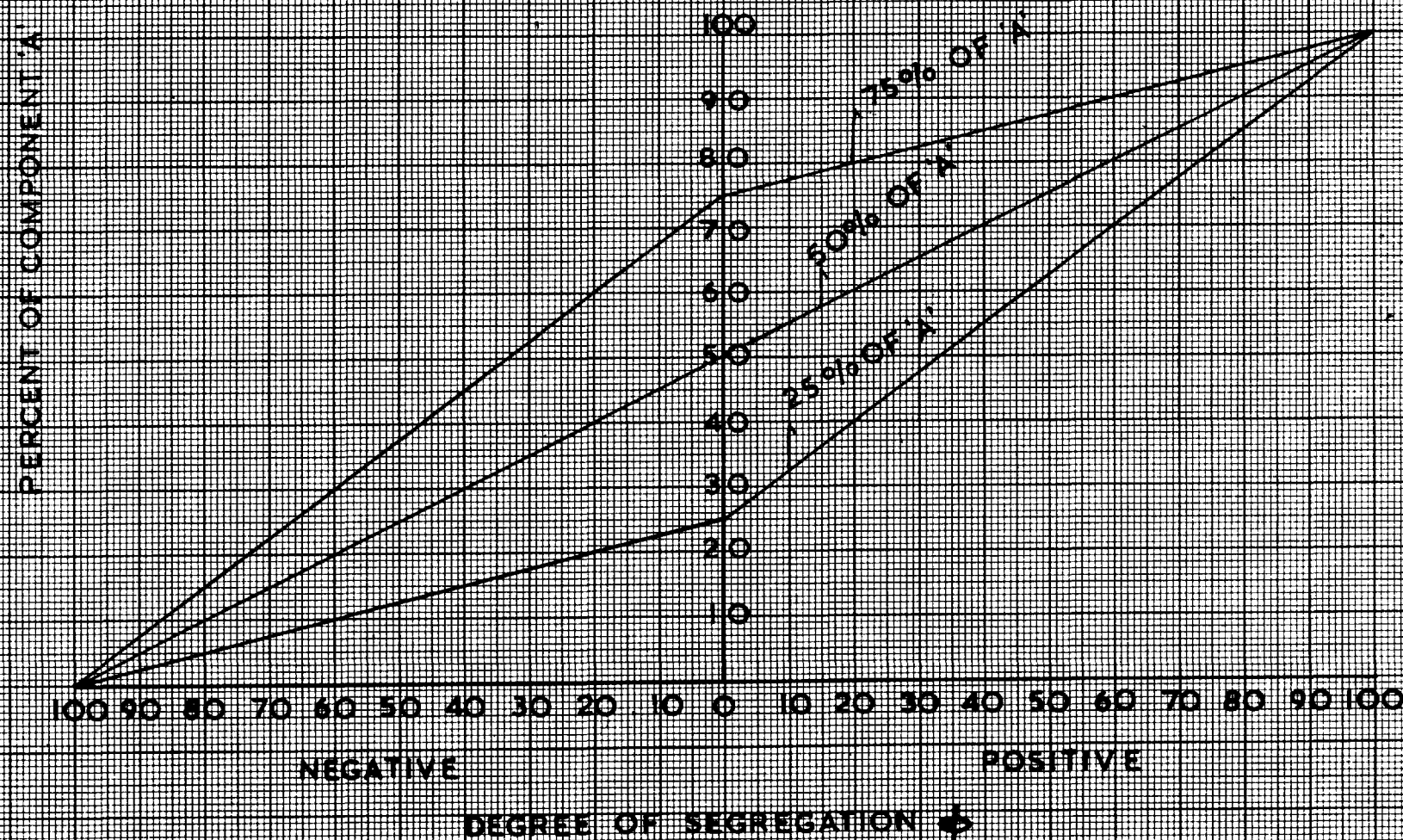
$$\phi_{-ve} = \frac{\mathcal{H}_0 - \mathcal{H}}{\mathcal{H}_0} \times 100 \quad \text{where } \mathcal{H} < \mathcal{H}_0 \quad (25)$$

where $\mathcal{H}$ = Amount of denser material present in a sample
and $\mathcal{H}_0$ = Amount of denser material present in the original mixture.

The relation between the percentage composition of a mixture and the degree of segregation as given by equations (22, 23) and (24, 25) is shown in Fig. (21). It will be seen that there are both negative and positive values, the former denoting that the percentage of fines or the denser material is less than that in the original mixture.

Fig (21)

DEGREE OF SEGREGATION VS PERCENTAGE OF COMPONENT 'A' FOR VARIOUS COMPOSITIONS OF THE ORIGINAL MIXTURE



RESULTS:-

The results of the analysis of heaps formed from mixtures containing 25, 50 and 75 percent fine (particle size 85/100) sand with coarse sand (particle size 18/22) are given in tables (XIV a), (XV a) and (XVI a), the values of percentage of fines in a sample being an average of 7 analysis of heaps formed under exactly similar experimental conditions.

Similar experiments were performed with mixtures containing 25, 50 and 75 percent of magnetite (particle size 18/22) with coal of the same particle size. The results in terms of percentage of magnetite present in a sample, (an average of 7 analysis of heap formed under exactly the same conditions) are given in tables (XVIIa) , (XVIIIa) and (XIX a), respectively.

REPRODUCIBILITY OF RESULTS:-

In order to indicate the degree of reproducibility, the results of seven successive experiments with materials containing 25, 50 and 75 percent are given in Tables (XX), (XXI) and (XXII). The last column in these tables is the standard deviation. The sample numbers on the left hand side correspond to the ones given in Tables (XIV a-XIXa).

TABLE XIV aSEGREGATION OF A MIXTURE OF FINE AND COARSE SAND

COMPOSITION OF ORIGINAL MIXTURE. 25% FINES, 75% COARSE

PARTICLE SIZE. FINE - 85/100 MESH, COARSE 18/22 MESH

PARTICLE SIZE RATIO. 1: 4.7

PERCENTAGE OF FINES

<u>TOP</u>	<u>20.0</u>								
	25.3								
	30.2								
	34.0								
<u>SEC I</u>	<u>37.2</u>	38.8	<u>39.1</u>	38.0	<u>35.4</u>				
	39.3	39.6	39.4	39.0	37.7				
	40.7	40.4	40.2	40.2	40.4				
	41.6	41.3	41.5	42.3	43.5				
<u>SEC II</u>	<u>42.2</u>	42.5	<u>43.3</u>	44.8	<u>45.5</u>	44.0	<u>38.3</u>		
	42.2	43.7	46.0	48.1	48.4	46.4	40.4		
	42.2	45.5	48.7	50.7	50.7	48.1	42.0		
	42.2	46.6	50.7	52.7	52.5	49.8	43.3		
<u>SEC III</u>	<u>42.5</u>	47.8	<u>51.9</u>	53.6	<u>53.3</u>	50.5	<u>43.7</u>	34.5	<u>23.8</u>
	43.0	47.9	51.7	53.2	52.8	50.0	43.3	33.6	23.3
	44.5	47.7	50.5	51.7	51.2	48.2	41.8	32.6	22.7
	46.3	47.4	48.0	47.9	47.2	44.4	39.4	33.2	22.3
<u>BASE</u>	<u>49.0</u>	45.5	42.5	38.8	<u>36.3</u>	32.0	29.0	25.2	<u>21.7</u>
Sample No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<u>BASE</u>						18.2	15.0	11.5	<u>7.9</u>
Sample No.						(10)	(11)	(12)	(13)

The data underlined are the experimental values. Intermediate values have been obtained by linear interpolation.

TABLE XIV b

SEGREGATION OF A MIXTURE OF FINE AND COARSE SAND

COMPOSITION OF ORIGINAL MIXTURE - 25% FINES, 75% COARSE
PARTICLE SIZE. FINE - 85/100 MESH, COARSE - 18/22 MESH
PARTICLE SIZE RATIO - 1:4.7

DEGREE OF SEGREGATION

		FORMULAE USED									
<u>TOP</u>	-20										
	0.4										
	6.9	$\phi_{+ve} = \frac{f - f_0}{100 - f_0} \times 100$									
	12.0	for $f > f_0$									
<u>SEC I</u>	16.3	18.4	18.8	17.4	13.9						
	19.1	19.5	19.2	18.7	16.9	$\phi_{-ve} = \frac{f_0 - f}{f_0} \times 100$					
	20.9	20.6	20.3	20.3	20.6	for $f_0 > f$					
	22.2	21.8	22.0	23.1	24.7						
<u>SEC II</u>	22.9	23.4	24.4	26.4	27.4	25.3	17.8				
	22.9	25.0	28.0	30.8	31.2	28.6	20.6				
	22.9	27.4	31.6	34.3	34.3	30.8	22.7				
	22.9	28.8	34.3	36.7	36.7	33.1	24.4				
<u>SEC III</u>	23.4	30.4	35.9	38.2	27.8	34.0	24.9	12.8	-4.8		
	24.0	30.6	35.6	37.6	37.1	33.4	24.4	11.5	-6.8		
	26.0	30.3	34.0	35.6	34.9	31.0	22.4	10.1	-9.2		
	28.4	29.9	30.7	30.6	29.6	25.9	19.2	10.9	-10.8		
<u>BASE</u>	32.0	27.4	23.4	18.4	15.1	9.3	5.3	0.27	-13.2		
Sample No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)		
<u>BASE</u>						-27.2	-40.0	-54.0	-68.4	-82.0	
Sample No.						(10)	(11)	(12)	(13)		

TABLE XV aSEGREGATION OF A MIXTURE OF FINE AND COARSE SAND

COMPOSITION OF ORIGINAL MIXTURE. 50% FINES, 50% COARSE
 PARTICLE SIZE - FINES - 85/100 MESH, COARSE - 18/22 MESH
 PARTICLE SIZE RATIO - 1: 4.7

PERCENTAGE OF FINES

<u>TOP</u>	<u>37.9</u>								
	42.7								
	46.5								
	49.0								
<u>SEC I</u>	<u>50.8</u>	50.4	<u>51.3</u>	54.0	<u>60.3</u>				
	51.5	52.8	54.8	57.1	60.4				
	51.8	52.7	54.5	57.0	60.7				
	52.0	53.0	54.8	57.5	61.5				
<u>SEC II</u>	<u>52.3</u>	53.5	<u>55.6</u>	58.9	<u>62.7</u>	65.2	<u>66.2</u>		
	53.4	59.7	57.5	61.9	65.7	67.3	68.5		
	54.7	56.7	60.5	66.0	69.4	70.5	70.3		
	56.4	58.6	63.4	69.0	72.0	72.3	71.4		
<u>SECIII</u>	<u>57.9</u>	61.0	<u>65.5</u>	70.3	<u>73.5</u>	74.0	<u>71.7</u>	68.5	<u>65.4</u>
	59.0	61.8	66.5	71.3	73.8	73.5	70.8	67.5	63.5
	60.9	63.0	66.7	71.0	72.7	71.8	68.9	65.3	61.7
	62.3	63.2	65.5	68.7	69.7	68.3	65.2	62.4	59.8
<u>BASE</u>	<u>63.9</u>	63.2	62.0	61.1	<u>59.8</u>	58.6	57.0	55.1	<u>52.7</u>
Sample No. (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
<u>BASE</u>						49.4	45.0	36.0	<u>14.1</u>
Sample No.						(10)	(11)	(12)	(13)

The data underlined are the experimental values.
 Intermediate values have been obtained by linear
 interpolation.

TABLE XV b

SEGREGATION OF A MIXTURE OF FINE AND COARSE SAND

COMPOSITION OF ORIGINAL MIXTURE - 50% FINES, 50% COARSE

PARTICLE SIZE - FINES 85/100 MESH, COARSE - 18/22 MESH.

PARTICLE SIZE RATIO - 1: 4.7

DEGREE OF SEGREGATION

TOP	FORMULAE USED									
-24.2										
-14.6										
- 7.0	$\phi_{+ve} = \frac{f - f_0}{100 - f_0} \times 100$									
- 2.0	for $f > f_0$									
SEC I	1.6	0.8	2.6	8.0	20.6	$\phi_{-ve} = \frac{f_0 - f}{f_0} \times 100$				
	3.0	5.6	9.6	14.2	20.8	for $f < f_0$				
	3.6	5.4	9.0	14.0	21.4					
	4.0	6.0	9.6	15.0	23.0					
SEC II	4.6	7.0	11.2	17.8	25.4	30.4	32.4			
	6.8	9.4	15.0	23.8	31.4	34.6	37.0			
	9.4	13.0	21.0	32.0	38.8	41.0	40.6			
	12.8	17.2	26.8	38.0	44.0	44.6	42.8			
SEC III	15.8	22.0	31.0	40.6	47.0	48.0	43.4	37.0	30.8	
	18.0	23.6	33.0	42.6	47.6	47.0	41.6	35.0	27.0	
	21.8	26.0	33.4	42.0	45.4	43.6	37.8	30.6	23.4	
	24.6	26.4	31.0	37.4	39.4	36.6	30.4	24.8	19.6	
BASE	27.8	26.4	24.0	22.2	19.6	17.2	14.0	10.2	5.4	
Sample No	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
BASE						-1.2	-10.0	-28.0	-71.8	
Sample No.						(10)	(11)	(12)	(13)	

TABLE XVI aSEGREGATION OF A MIXTURE OF FINE AND COARSE SAND

COMPOSITION OF ORIGINAL MIXTURE - 75% FINES, 25% COARSE
 PARTICLE SIZE - FINES - 85/100 MESH, COARSE - 18/22 MESH.
 PARTICLE SIZE RATIO - 1:4.7

PERCENTAGE OF FINES

<u>TOP</u>	<u>63.3</u>								
	63.6								
	64.0								
	64.3								
<u>SEC I</u>	<u>64.6</u>	66.2	<u>69.0</u>	73.5	<u>80.2</u>				
	64.7	65.5	67.2	71.5	79.3				
	64.8	64.7	66.2	70.2	79.0				
	65.0	64.7	65.8	69.5	79.2				
<u>SEC II</u>	<u>64.7</u>	64.0	<u>65.6</u>	72.6	<u>79.7</u>	82.1	<u>82.2</u>		
	64.7	65.3	67.3	74.0	81.2	83.7	84.0		
	64.8	66.1	69.5	77.0	83.0	85.3	85.3		
	65.3	67.6	72.3	79.6	84.5	86.3	85.6		
<u>SEC III</u>	<u>66.1</u>	69.0	<u>74.4</u>	81.5	<u>85.0</u>	85.7	<u>85.3</u>	85.0	<u>84.3</u>
	67.0	70.2	75.3	81.0	84.3	85.0	84.4	83.5	82.5
	68.8	71.4	75.3	79.8	82.5	83.0	82.6	82.2	81.7
	71.0	72.2	74.4	77.0	78.8	79.5	74.7	79.5	78.9
<u>BASE</u>	<u>73.7</u>	72.7	72.5	72.3	<u>72.9</u>	74.0	75.5	77.0	<u>77.2</u>
Sample No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<u>BASE</u>						75.0	70.0	62.2	<u>54.8</u>
Sample No.						(10)	(11)	(12)	(13)

The data underlined are the experimental values.
 Intermediate values have been obtained by linear interpolation.

TABLE XVI bSEGREGATION OF A MIXTURE OF FINE AND COARSE SAND

COMPOSITION OF ORIGINAL MIXTURE - 75% FINES, 25% COARSE
 PARTICLE SIZE - FINES - 85/100 MESH, COARSE - 18/22 MESH.
 PARTICLE SIZE RATIO - 1:4.7

DEGREE OF SEGREGATION

<u>TOP</u>	-15.6	FORMULAE USED							
	-14.2								
	-14.7	$\phi_{+ve} = \frac{f - f_0}{100 - f_0} \times 100$ for $f > f_0$							
	-14.3								
<u>SEC I</u>	-13.9	-11.7	- 8.0	- 2.0	20.8	$\phi_{-ve} = \frac{f_0 - f}{f_0} \times 100$			
	-13.7	-12.7	-10.4	- 4.7	17.2	for $f_0 > f$			
	-13.6	-13.7	-11.7	- 6.4	16.0				
	-13.3	-13.7	-12.3	- 7.4	16.8				
<u>SEC II</u>	-13.7	-14.7	-12.5	- 3.2	18.8	28.4	28.8		
	-13.7	-12.9	-10.3	- 1.3	24.8	34.8	36.0		
	-13.6	-11.9	- 7.4	8.0	32.0	41.2	41.2		
	-12.9	- 9.9	- 3.6	18.4	36.0	45.2	42.4		
<u>SEC III</u>	-11.9	- 8.0	- 0.8	26.0	40.0	42.8	41.2	40.0	37.2
	-10.7	- 6.4	1.2	24.0	37.2	40.0	37.6	34.0	30.0
	- 8.3	- 4.8	1.2	19.2	30.0	32.0	30.4	28.8	26.8
	- 5.4	- 3.7	- 0.8	8.0	15.2	18.0	0.4	18.0	15.6
<u>BASE</u>	- 1.7	- 3.1	- 3.3	-3.6	-2.8	-1.3	2.0	8.0	8.8
Sample No. (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
<u>BASE</u>	ZERO -6.7 $\pm$ 17.1 -26.9								
Sample No.	(10)	(11)	(12)	(13)					

TABLE XVII aSEGREGATION OF A MIXTURE OF MAGNETITE AND COAL

COMPOSITION OF ORIGINAL MIXTURE - 25% MAGNETITE, 75% COAL,
 PARTICLE SIZE - 18/22 MESH FOR EACH COMPONENT
 DENSITY RATIO - COAL: MAGNETITE - 1: 3.38

PERCENTAGE OF MAGNETITE

<u>TOP</u>	<u>27.6</u>								
	28.5								
	29.5								
	36.7								
<u>SEC I</u>	<u>32.4</u>	33.0	<u>33.1</u>	32.3	<u>30.1</u>				
	34.1	34.1	34.1	34.4	35.2				
	36.0	35.3	35.6	37.0	39.3				
	38.3	37.3	37.7	39.4	42.2				
<u>SEC II</u>	<u>41.1</u>	39.7	<u>40.5</u>	42.8	<u>44.2</u>	42.7	<u>36.4</u>		
	44.7	43.7	43.7	44.6	45.1	44.0	39.2		
	48.6	48.2	48.5	46.5	45.1	43.5	41.4		
	51.0	51.0	50.5	49.4	44.0	45.7	42.6		
<u>SEC III</u>	<u>51.9</u>	51.6	<u>50.6</u>	44.5	<u>41.5</u>	41.8	<u>42.5</u>	40.9	<u>27.5</u>
	51.5	51.7	49.0	41.1	37.8	39.8	41.0	38.7	25.5
	50.1	48.2	44.7	37.2	32.9	35.2	36.7	34.8	23.4
	47.9	42.5	37.0	31.7	26.5	28.0	30.0	28.7	21.3
<u>BASE</u>	<u>45.1</u>	32.6	24.4	20.8	<u>19.2</u>	18.9	19.0	19.1	<u>19.2</u>
Sample No. (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
<u>BASE</u>						18.0	15.1	10.8	<u>3.3</u>
Sample No.						(10)	(11)	(12)	(13)

The data underlined are the experimental values.
 Intermediate values have been obtained by linear
 interpolation.

TABLE XVII bSEGREGATION OF A MIXTURE OF MAGNETITE AND COAL

COMPOSITION OF ORIGINAL MIXTURE - 25% MAGNETITE, 75% COAL
 PARTICLE SIZE - 18/22 MESH FOR EACH COMPONENT.

DENSITY RATIO - COAL: MAGNETITE 1:3.38

DEGREE OF SEGREGATION

<u>TOP</u>	3.5	FORMULAE USED							
	4.7	$\phi_{+ve} = \frac{x - x_o}{100 - x_o} \times 100 \text{ for } x > x_o$							
	6.0								
	4.1								
<u>SEC I</u>	9.9	10.7	10.8	9.7	6.8	$\phi_{-ve} = \frac{x_o - x}{x_o} \times 100 \text{ for } x_o > x$			
	12.1	12.1	12.1	12.5	13.6				
	14.7	13.7	14.1	16.0	19.1				
	17.7	16.4	16.9	19.2	12.9				
<u>SEC II</u>	21.5	19.6	20.6	23.7	25.6	23.6	15.2		
	26.3	24.9	24.9	26.1	26.8	25.3	18.9		
	31.5	30.9	30.0	28.7	26.8	24.7	21.9		
	34.7	34.7	34.0	32.5	25.3	27.6	23.5		
<u>SEC III</u>	35.9	35.5	34.1	26.0	22.0	22.4	23.3	21.2	3.3
	35.4	35.6	32.0	21.5	17.1	19.7	21.3	18.3	0.7
	33.5	30.9	26.3	16.3	10.5	13.6	15.6	13.1	-6.4
	30.6	23.3	16.0	8.9	2.0	4.0	6.6	4.9	-15.8
<u>BASE</u>	26.8	10.1	-2.4	16.8	-23.2	24.4	-24.0	-23.6	-23.2
Sample No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<u>BASE</u>						-28.0	-39.6	-58.0	-86.8
Sample No.						(10)	(11)	(12)	(13)

TABLE XVIIIaSEGREGATION OF A MIXTURE OF MAGNETITE AND COAL

COMPOSITION OF ORIGINAL MIXTURE - 50% MAGNETITE, 50% COAL

PARTICLE SIZE - 18/22 MESH FOR EACH COMPONENT

DENSITY RATIO - COAL: MAGNETITE - 1: 3.38.

PERCENTAGE OF MAGNETITE

<u>TOP</u>	<u>47.1</u>								
	50.8								
	54.6								
	58.2								
<u>SEC I</u>	<u>61.6</u>	64.5	<u>65.9</u>	66.2	<u>65.8</u>				
	64.5	64.7	65.2	66.1	67.0				
	68.0	65.5	64.8	65.4	68.5				
	69.4	65.7	64.6	65.6	69.2				
<u>SEC II</u>	<u>70.9</u>	65.5	<u>64.5</u>	66.7	<u>69.4</u>	68.5	<u>64.4</u>		
	71.4	66.8	64.6	67.0	68.8	68.1	64.9		
	71.2	67.5	65.0	66.4	67.6	67.2	65.0		
	70.6	67.5	65.1	65.4	66.0	65.8	64.9		
<u>SEC III</u>	<u>69.4</u>	66.7	<u>64.8</u>	63.8	<u>63.7</u>	64.3	<u>64.4</u>	62.4	<u>57.3</u>
	67.2	64.6	62.2	60.7	60.6	61.9	62.5	60.7	55.4
	64.2	60.0	57.2	56.3	57.0	59.0	59.7	57.9	53.3
	60.5	53.0	50.0	50.9	53.2	55.4	56.0	55.0	51.2
<u>BASE</u>	<u>55.8</u>	46.5	40.1	48.0	<u>49.2</u>	51.0	51.5	50.9	<u>49.2</u>
Sample No. (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
<u>BASE</u>						45.0	37.5	26.0	<u>12.0</u>
Sample No.						(10)	(11)	(12)	(13)

The data underlined are the experimental values.

Intermediate values have been obtained by linear interpolation.

TABLE XVIII bSEGREGATION OF A MIXTURE OF MAGNETITE AND COAL

COMPOSITION OF ORIGINAL MIXTURE - 50% MAGNETITE, 50% COAL

PARTICLE SIZE - 18/22 MESH FOR EACH COMPONENT

DENSITY RATIO - COAL: MAGNETITE : 1:3.38.

DEGREE OF SEGREGATION

<u>TOP</u>	-5.8									FORMULAE USED
	1.6									
	9.2									$\phi_{+ve} = \frac{H - H_0}{100 - H_0} \times 100$
	16.4									for $H > H_0$
<u>SEC I</u>	23.2	29.0	31.8	32.4	31.6					
	29.0	29.4	30.4	32.2	34.0					$\phi_{-ve} = \frac{H_0 - H}{H_0} \times 100$
	36.0	31.0	29.6	30.8	37.0					for $H_0 > H$
	38.8	31.4	29.2	31.2	38.4					
<u>SEC II</u>	41.8	31.0	29.0	33.4	38.8	37.0	28.8			
	42.8	33.6	29.2	34.0	37.6	36.2	29.8			
	42.4	35.0	30.0	32.8	35.2	34.4	30.0			
	41.2	35.0	30.2	30.8	32.0	31.6	29.8			
<u>SEC III</u>	38.8	33.4	29.6	27.6	27.4	28.6	28.8	24.8	14.6	
	34.4	29.2	24.4	21.4	21.2	23.4	25.0	21.4	10.8	
	28.4	20.0	14.4	12.6	14.0	18.0	19.4	15.8	6.6	
	21.0	6.0	ZERO	1.8	6.4	10.8	12.0	10.0	2.4	
<u>BASE</u>	11.6	-7.0	-19.8	-4.0	-1.6	2.0	3.0	1.8	-1.6	
Sample No. (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)		
<u>BASE</u>						-10.0	-25.0	-10.0	-76.0	
Sample No.						(10)	(11)	(12)	(13)	

TABLE XIX aSEGREGATION OF A MIXTURE OF MAGNETITE AND COAL

COMPOSITION OF ORIGINAL MIXTURE - 75% MAGNETITE, 25% COAL
 PARTICLE SIZE - 18/22 MESH FOR EACH COMPONENT
 DENSITY RATIO - COAL: MAGNETITE - .1: 3.38

PERCENTAGE OF MAGNETITE

<u>TOP</u>	<u>79.9</u>								
	80.7								
	81.0								
	81.2								
<u>SEC I</u>	<u>81.1</u>	<u>81.1</u>	<u>81.3</u>	<u>81.6</u>	<u>82.2</u>				
	80.8	79.8	79.6	79.9	82.6				
	80.0	78.8	78.6	78.9	83.0				
	79.3	78.7	78.4	78.9	83.3				
<u>SEC II</u>	<u>79.2</u>	<u>79.1</u>	<u>79.1</u>	<u>80.0</u>	<u>83.5</u>	<u>81.9</u>	<u>80.5</u>		
	79.6	80.1	81.0	83.1	83.4	83.2	82.1		
	81.9	83.1	83.3	83.2	83.1	82.9	82.7		
	82.4	84.4	85.0	84.3	82.2	82.3	82.5		
<u>SEC III</u>	<u>82.6</u>	<u>84.9</u>	<u>85.3</u>	<u>83.3</u>	<u>80.3</u>	<u>80.5</u>	<u>81.5</u>	<u>80.5</u>	<u>77.1</u>
	82.5	84.7	84.2	80.8	77.5	78.3	79.2	78.4	74.5
	82.2	82.7	81.3	77.0	73.5	74.5	75.5	74.7	71.8
	81.3	79.3	76.0	70.8	67.5	68.5	70.3	70.5	69.2
<u>BASE</u>	<u>79.7</u>	<u>70.0</u>	<u>63.0</u>	<u>60.0</u>	<u>59.4</u>	<u>61.0</u>	<u>63.0</u>	<u>65.0</u>	<u>66.5</u>
Sample No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<u>BASE</u>						66.5	64.3	59.0	<u>42.1</u>
Sample No.						(10)	(11)	(12)	(13)

The data underlined are the experimental values.
 Intermediate values have been obtained by linear interpolation.

TABLE XIX b

SEGREGATION OF A MIXTURE OF MAGNETITE AND COAL

COMPOSITION OF ORIGINAL MIXTURE - 75% MAGNETITE, 25% COAL

PARTICLE SIZE - 18/22 MESH FOR EACH COMPONENT

DENSITY RATIO - COAL: MAGNETITE 1:3.38

DEGREE OF SEGREGATION

<u>TOP</u>	19.6									$\phi_{+ve} = \frac{x - x_0}{100 - x_0} \times 100$
	22.8									
	24.0									$\phi_{-ve} = \frac{x_0 - x}{x_0} \times 100$
	24.8									$x > x_0$
<u>SEC I</u>	24.4	24.4	25.2	26.4	28.8					for $x_0 > x$.
	23.2	19.2	18.4	19.6	30.4					
	20.0	15.2	14.4	15.6	32.0					
	17.2	14.8	13.6	15.6	33.2					
<u>SEC II</u>	16.8	16.4	16.4	20.0	34.0	27.6	22.0			
	18.4	20.4	24.0	32.4	33.6	32.8	28.4			
	27.6	32.4	33.2	32.8	32.4	31.6	30.8			
	29.6	37.6	40.0	37.2	28.8	29.2	30.0			
<u>SEC III</u>	30.4	39.6	41.2	33.2	21.2	22.0	26.0	22.0	8.4	
	30.0	38.8	36.8	23.2	10.0	13.2	16.8	13.6	-0.7	
	28.8	30.8	25.2	8.0	-2.0	-0.7	2.0	-0.4	-4.3	
	25.2	17.2	4.0	-5.6	-10.0	-8.7	-6.3	-6.0	-7.7	
BASE	18.8	-6.7	-16.0	-20.0	-20.8	-18.7	16.0	-13.3	-11.4	
Sample No.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	
BASE							-11.4	-14.3	-21.3	-43.8
Sample No.							(10)	(11)	(12)	(13)

TABLE XX

ORIGINAL COMPOSITION 25% FINES. (COLUMNS 1 - 8 EXPRESSED AS PERCENT FINES.)

	SAMPLE NO.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	AVE	S.D
TOP	(1)	17.1	16.1	24.0	13.2	24.3	20.2	22.1	<u>20.0</u>	4.25
SEC I	(1)	-	-	-	-	28.2	38.5	34.6	<u>37.2</u>	6.68
	(3)	35.3	40.6	41.9	42.7	36.6	40.9	36.9	<u>39.1</u>	2.83
	(5)	37.8	37.6	34.2	38.2	31.2	39.0	31.5	<u>35.4</u>	3.31
SEC II	(1)	-	-	-	-	43.4	39.8	43.4	<u>42.3</u>	2.07
	(3)	48.3	43.6	40.6	33.3	45.7	44.8	45.2	<u>43.3</u>	4.89
	(5)	50.9	48.3	37.2	31.3	43.5	49.1	47.1	<u>45.5</u>	7.39
	(7)	48.3	37.8	33.5	37.8	33.2	37.2	41.6	<u>38.3</u>	5.12
SEC III	(1)	-	-	-	-	33.7	39.4	54.5	<u>42.5</u>	7.27
	(3)	58.2	54.5	43.0	53.5	48.1	49.3	56.7	<u>51.9</u>	5.36

128 a.

TABLE XX (Continued)

	SAMPLE NO.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	AVE	S
	(5)	62.8	55.7	48.4	63.2	38.6	54.2	54.5	53.3	9.71
	(7)	55.8	50.0	28.1	48.7	49.8	45.1	49.9	<u>43.7</u>	9.41
	(9)	27.0	28.1	15.6	26.6	19.7	10.8	39.2	<u>23.8</u>	9.37
BASE	(1)	49.3	51.5	45.7	50.6	46.0	46.8	53.6	<u>49.0</u>	3.02
	(5)	50.4	25.4	33.6	41.2	24.9	33.6	46.2	<u>36.3</u>	9.86
	(9)	23.1	22.4	19.6	21.8	16.8	12.4	34.0	<u>21.7</u>	6.69
	(13)	7.4	7.6	12.1	6.6	16.8	1.5	3.5	<u>7.9</u>	5.15

128 b.

TABLE XXI

ORIGINAL COMPOSITION 50% FINES.

COLUMNS 1 - 8 EXPRESSED AS PERCENT FINES

	SAMPLE NO.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	AVE	S
TOP	(1)	40.2	39.2	44.9	36.8	34.1	35.0	35.2	<u>37.9</u>	3.81
SEC I	(1)	52.3	55.2	56.7	46.5	49.3	50.0	45.9	<u>50.8</u>	4.12
	(3)	58.1	50.8	53.3	50.2	48.1	50.3	43.5	<u>51.3</u>	2.38
	(5)	59.3	62.0	59.8	60.1	58.7	59.4	63.0	<u>60.3</u>	1.57
SEC II	(1)	53.1	47.9	52.6	52.2	54.1	53.4	53.1	<u>52.3</u>	2.04
	(3)	57.5	49.4	55.5	57.8	55.5	55.7	58.1	<u>55.6</u>	2.97
	(5)	62.5	58.9	59.9	61.5	62.7	63.4	70.3	<u>62.7</u>	3.69
	(7)	65.9	65.8	62.5	70.4	67.3	64.6	67.0	<u>66.2</u>	2.44
SEC III	(1)	57.7	55.7	58.5	64.9	64.2	61.3	42.8	<u>51.9</u>	7.45
	(3)	69.3	62.5	65.0	64.9	67.9	63.3	65.6	<u>65.5</u>	2.40
	(5)	72.8	73.9	70.0	77.4	74.7	72.8	72.6	<u>73.5</u>	2.23

TABLE XX1 (Continued)

	SAMPLE NO.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	AVE	S
	(7)	72.7	73.7	73.9	75.7	65.4	67.8	72.9	<u>71.7</u>	3.70
	(9)	73.9	63.6	64.3	70.2	64.4	61.1	64.0	<u>65.9</u>	4.45
BASE	(1)	65.2	61.3	63.3	67.3	62.9	67.0	60.1	63.9	2.57
	(5)	60.9	51.7	57.4	65.4	53.6	66.4	63.0	59.8	5.86
	(9)	50.8	40.7	56.4	56.7	51.5	62.6	48.1	52.7	7.04
	(13)	21.2	12.7	16.9	16.1	13.0	11.2	7.6	14.1	4.39

129 b.

TABLE XXII

ORIGINAL COMPOSITION 75% FINES. COLUMNS (1) - 8 EXPRESSED AS PERCENT FINES

	SAMPLE NO.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	AVE	S
TOP	(1)	70.3	56.7	64.7	59.2	65.7	61.3	65.5	<u>63.3</u>	4.7
SEC I	(1)	58.3	67.5	68.0	66.1	70.2	63.4	59.0	<u>64.6</u>	4.58
	(3)	63.8	68.5	73.2	63.1	73.5	68.4	72.2	<u>69.0</u>	4.29
	(5)	76.5	81.2	79.0	80.3	81.0	82.3	80.5	<u>80.2</u>	1.98
SEC II	(1)	64.8	66.3	63.6	63.4	65.2	67.6	62.8	<u>64.7</u>	1.88
	(3)	68.6	69.4	69.8	67.5	71.0	67.1	46.9	<u>65.6</u>	8.42
	(5)	78.6	79.1	75.8	76.8	76.0	78.1	83.2	<u>79.7</u>	2.97
	(7)	82.3	77.9	82.0	84.0	83.8	84.5	80.4	<u>82.2</u>	2.34
SEC III	(1)	66.3	63.5	76.2	61.4	62.5	68.2	64.8	<u>66.1</u>	4.98
	(3)	74.3	76.4	77.7	76.8	70.8	75.2	69.9	<u>74.4</u>	3.01

130 a.

TABLE XXII (Continued)

	SAMPLE NO.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	AVE	S
	(5)	84.4	84.9	87.7	88.0	78.0	84.4	87.4	<u>85.0</u>	3.45
	(7)	86.6	84.6	89.1	88.0	79.1	85.6	84.2	<u>85.3</u>	3.25
	(9)	86.2	84.2	85.5	82.6	83.4	86.5	81.4	<u>84.3</u>	1.91
BASE	(1)	81.0	69.0	70.3	77.5	71.7	75.5	71.1	<u>73.7</u>	4.39
	(5)	75.6	68.3	78.0	75.0	66.7	76.4	70.2	<u>72.9</u>	4.41
	(9)	77.2	75.6	80.3	77.8	75.6	79.5	74.0	<u>77.2</u>	2.28
	(13)	51.2	50.2	58.7	55.6	57.6	59.7	59.9	<u>54.8</u>	4.02

130 b.

It will be seen that the standard deviations lie between 2.07 - 9.87, 1.57 - 7.45 and 1.88 - 8.42 for 25, 50 and 75 percent mixtures of fine and coarse sand respectively, the lower limit in all cases lying on a one percent significance level.

That the standard deviation in some instances is so high as to make the samples significantly different from the mean value may be attributed to a number of causes amongst which are unexplained fluctuations in the rate of flow, extraneous vibrations and disturbances during sampling. On the whole it is considered that the results obtained are as reproducible as can be expected in experiments of this kind.

The calculated values of degree of segregation based on equations (22), (23), (24), and (25) for both mixtures of fine and coarse sand and magnetite and coal are given in Tables (XIV b-XIX b) for varying compositions of sand and magnetite, respectively, in the original mixtures.

These values have been used to draw cross sections of heap both in terms of percentage of fines and magnetite in the samples taken at various points and also in terms of degree of segregation Fig. (22a &b-27 a&b).

Fig(22)a

SEGREGATION OF A MIXTURE OF FINE & COARSE SAND

Original Composition

25% FINES, 75% Coarse

Particle size ratio

Fines : Coarse = 1:4.7

Results expressed as

Percent of Fines

< 25%

25-50%

> 50%

Section I

35.4 38.0 39.1 39.8 37.2 36.8 39.1 38.0 35.4

37.7 39.0 39.4 39.6 39.3 39.6 39.4 39.0 37.7

40.4 40.2 40.2 40.4 40.7 40.4 40.2 40.2 40.4

43.5 42.3 41.5 41.3 41.6 41.3 41.5 42.3 43.5

Section II

38.3 44.0 45.5 44.8 43.3 42.5 42.2 42.5 43.3 44.8 45.5 44.0 38.3

40.4 46.4 48.4 48.1 46.0 43.7 42.2 43.7 46.0 48.1 48.4 46.4 40.4

42.0 48.1 50.7 50.7 48.0 45.5 42.2 45.5 48.0 50.7 50.7 48.1 42.0

43.3 49.8 52.5 52.7 50.7 46.6 42.2 46.6 50.7 52.7 52.5 49.8 43.3

Section III

23.9 34.5 43.7 50.5 53.3 53.6 51.9 47.8 42.5 47.8 51.9 53.6 53.3 50.5 43.7 34.5 23.9

23.3 33.6 43.3 50.1 52.8 52.2 51.7 47.9 43.0 47.9 51.7 53.2 52.8 50.0 43.3 33.6 23.3

22.7 32.6 41.8 48.2 51.2 51.7 50.5 47.7 44.5 47.7 50.5 51.7 51.2 49.2 41.8 32.6 22.7

22.3 33.2 39.4 44.4 47.2 47.9 48.0 47.4 46.3 47.4 48.0 47.9 47.2 44.4 39.4 33.2 22.3

BASE

7.9 11.5 15.0 18.2 21.7 25.2 29.0 32.0 36.3 38.8 42.5 45.5 49.0 45.5 42.5 38.8 36.3 32.0 29.0 25.2 21.7 18.2 15.0 11.5 7.9

1 2 3 4 5 6 7 8 9 10 11 12 13

Fig(22)b

SEGREGATION OF A MIXTURE OF COARSE & FINE SAND

Original Composition

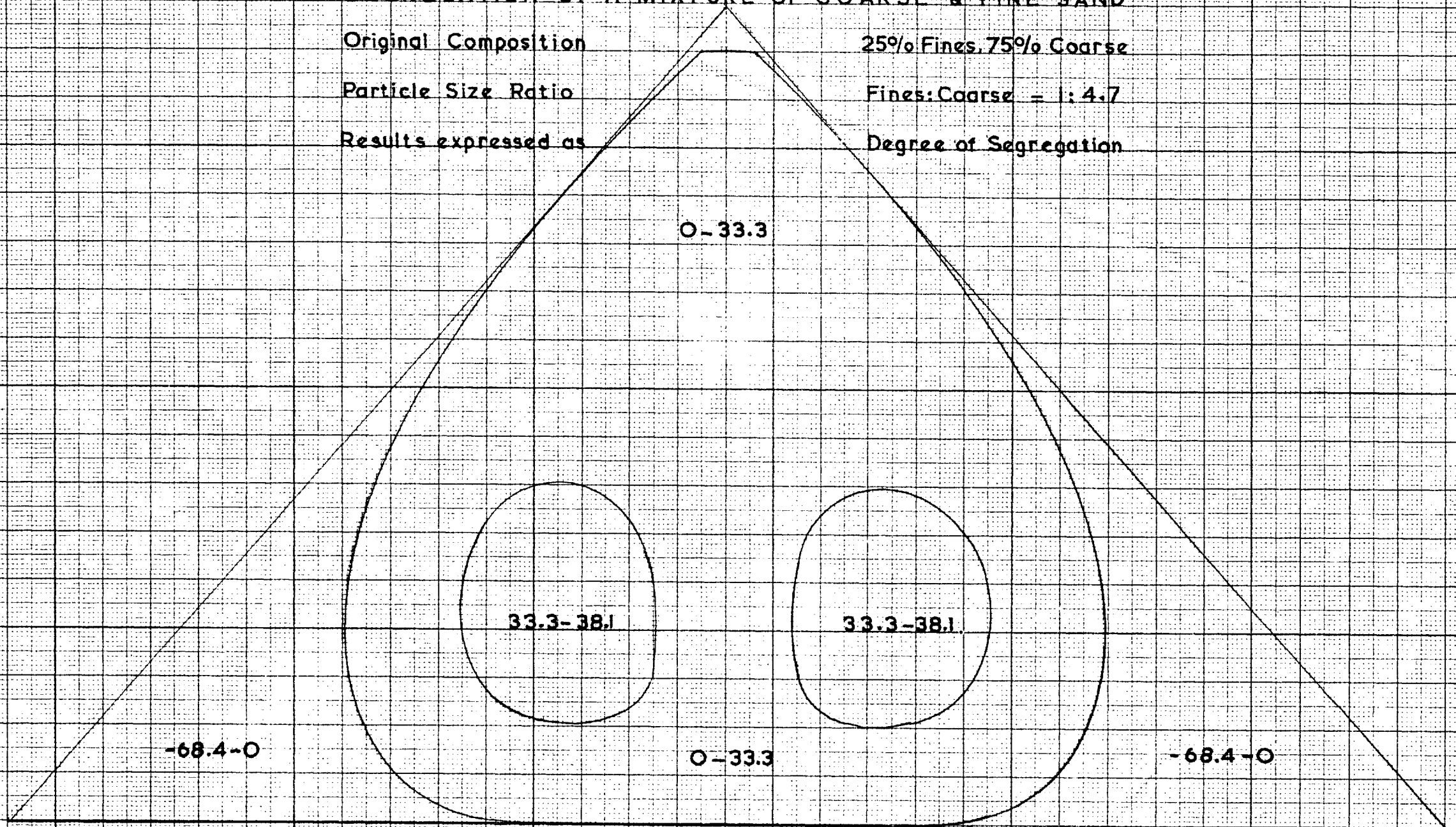
25% Fines, 75% Coarse

Particle Size Ratio

Fines:Coarse = 1:4.7

Results expressed as

Degree of Segregation



Fig(23)a

SEGREGATION OF A MIXTURE OF FINE & COARSE SAND

Original Composition

31.9

50% Fines, 50% Coarse

Particle Size Ratio

42.7

Fines : Coarse = 1 : 4.7

Results expressed as

46.5

Percent of Fines

49.0

< 50%

50-70%

> 70%

Section I

60.3 54.0 51.3 50.4 50.8 50.4 51.3 54.0 60.3
60.4 57.1 54.0 52.8 51.5 52.8 54.8 57.1 60.4
60.7 57.0 54.5 52.7 51.8 52.7 54.5 57.0 60.7
61.5 57.5 54.8 53.0 52.0 53.0 54.8 57.5 61.5

Section II

66.2 65.2 62.7 58.9 55.6 53.5 52.3 53.5 55.6 58.9 62.7 65.2 66.2
68.5 67.3 65.1 61.9 57.5 59.7 53.4 59.7 57.3 61.9 65.7 67.3 68.5
70.3 70.5 69.4 66.0 60.5 56.5 54.7 56.5 60.5 66.0 69.4 70.5 70.3
71.4 72.3 72.0 69.0 63.4 58.6 56.4 58.6 63.4 69.0 72.0 72.3 71.4

Section III

65.4 68.5 70.7 74.0 72.5 70.3 65.5 61.8 57.9 61.8 65.5 70.3 72.5 74.0 70.7 68.5 65.4
68.5 67.5 70.8 73.5 71.8 71.3 66.5 61.8 59.0 61.8 66.5 71.3 73.5 75.8 70.8 67.5 68.5
61.7 65.3 68.9 71.8 72.7 71.0 66.7 63.0 60.9 63.0 66.7 71.0 72.7 71.8 68.9 65.3 61.7
59.8 62.4 65.2 68.3 69.1 68.7 65.5 63.2 62.3 63.2 65.5 68.7 69.7 68.3 65.2 62.4 59.8

BASE

14.1 36.0 45.0 44.4 52.7 55.1 57.0 58.6 59.8 61.1 62.0 63.2 63.9 63.2 62.0 61.1 59.8 58.6 57.0 55.1 52.7 44.4 45.0 36.0 14.1

1 2 3 4 5 6 7 8 9 10 11 12 13

Fig(23) b

SEGREGATION OF A MIXTURE OF FINE & COARSE SAND.

Original Composition

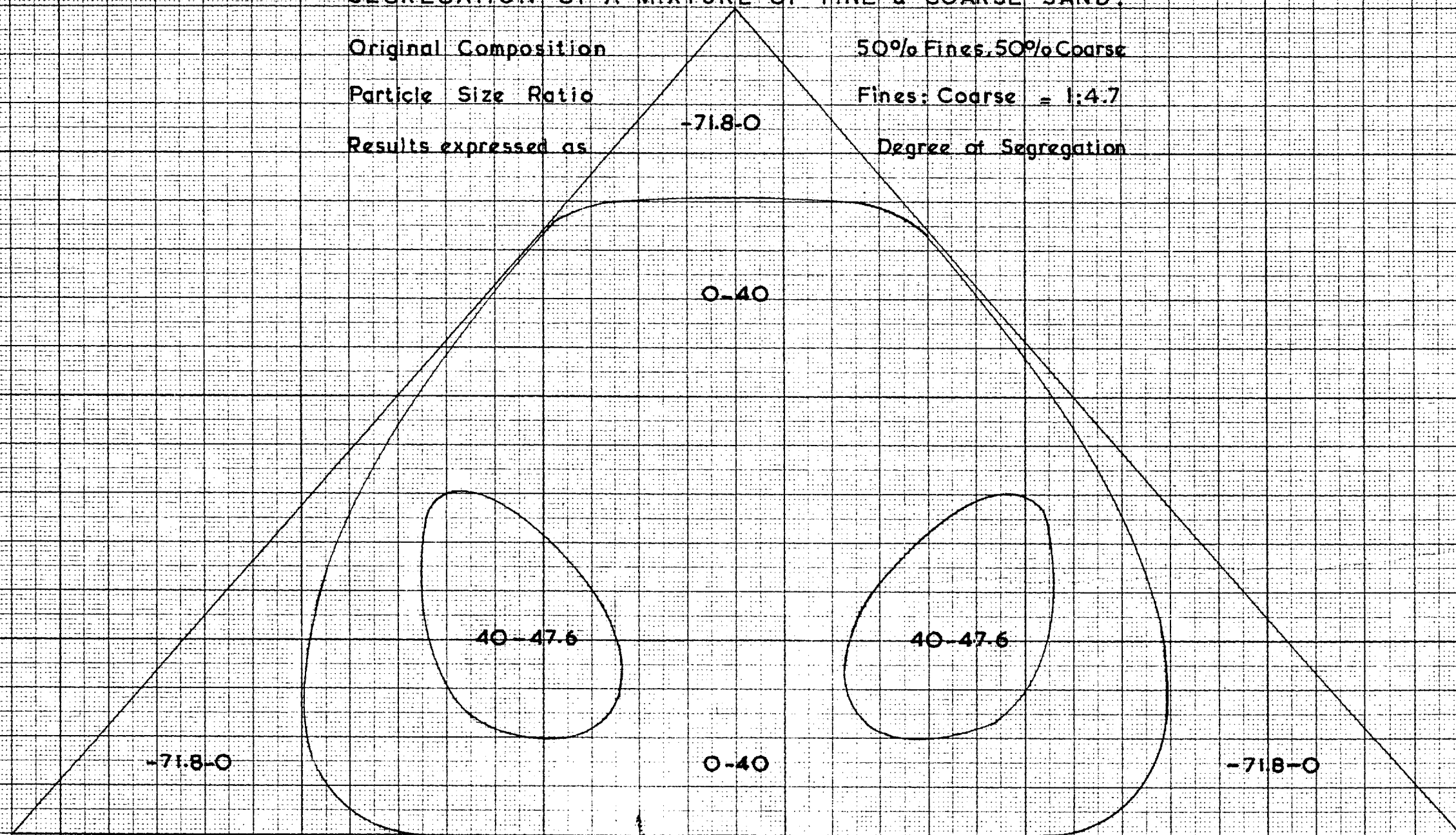
50% Fines, 50% Coarse

Particle Size Ratio

Fines: Coarse = 1:4.7

Results expressed as

Degree of Segregation



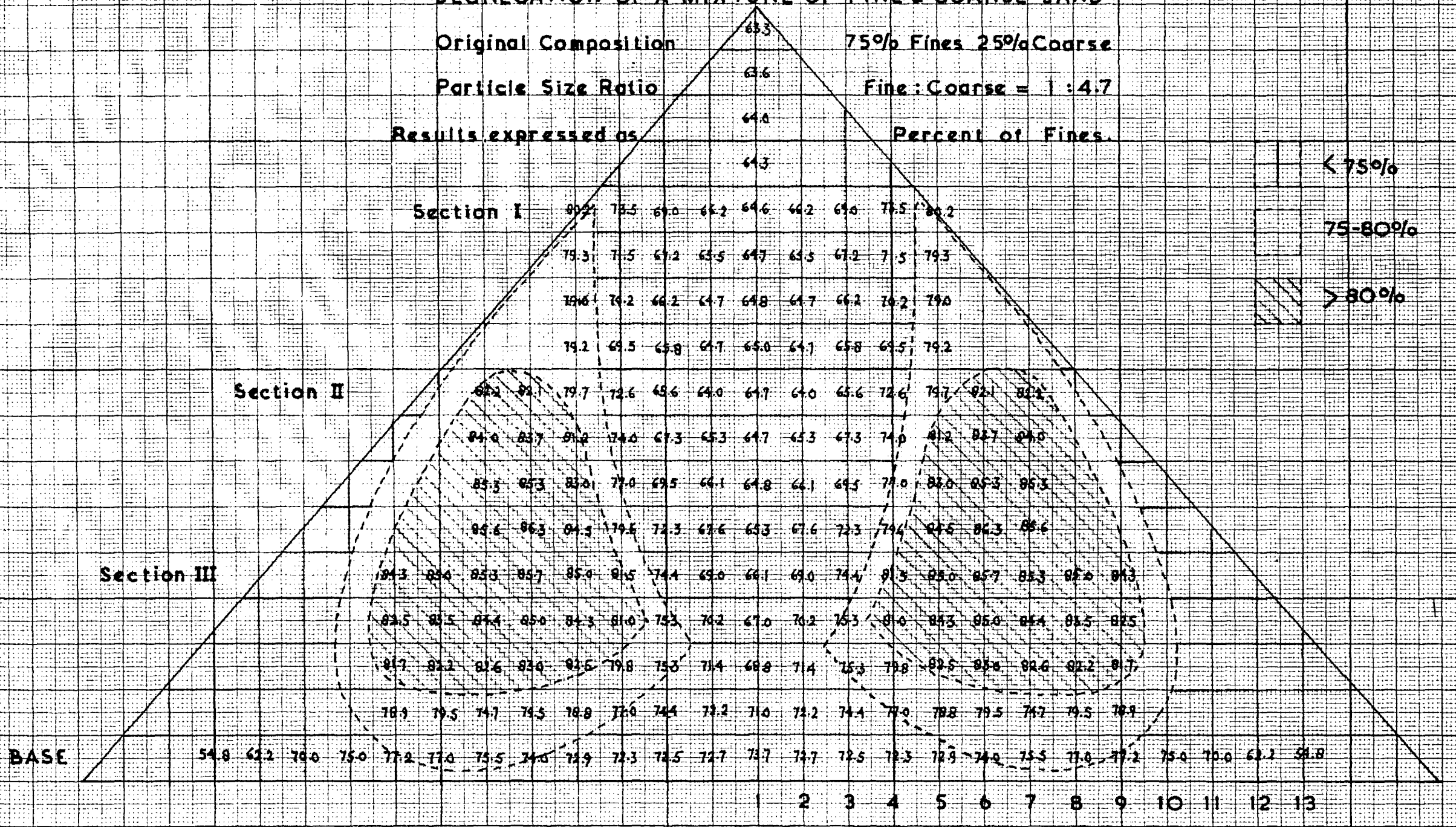
Fig(24)a

SEGREGATION OF A MIXTURE OF FINE & COARSE SAND

Original Composition 65.3 75% Fines 25% Coarse

Particle Size Ratio 63.6 Fine: Coarse = 1:4.7

Results expressed as Percent of Fines.



Fig(24) b

SEGREGATION OF A MIXTURE OF FINE & COARSE SAND.

Original Composition

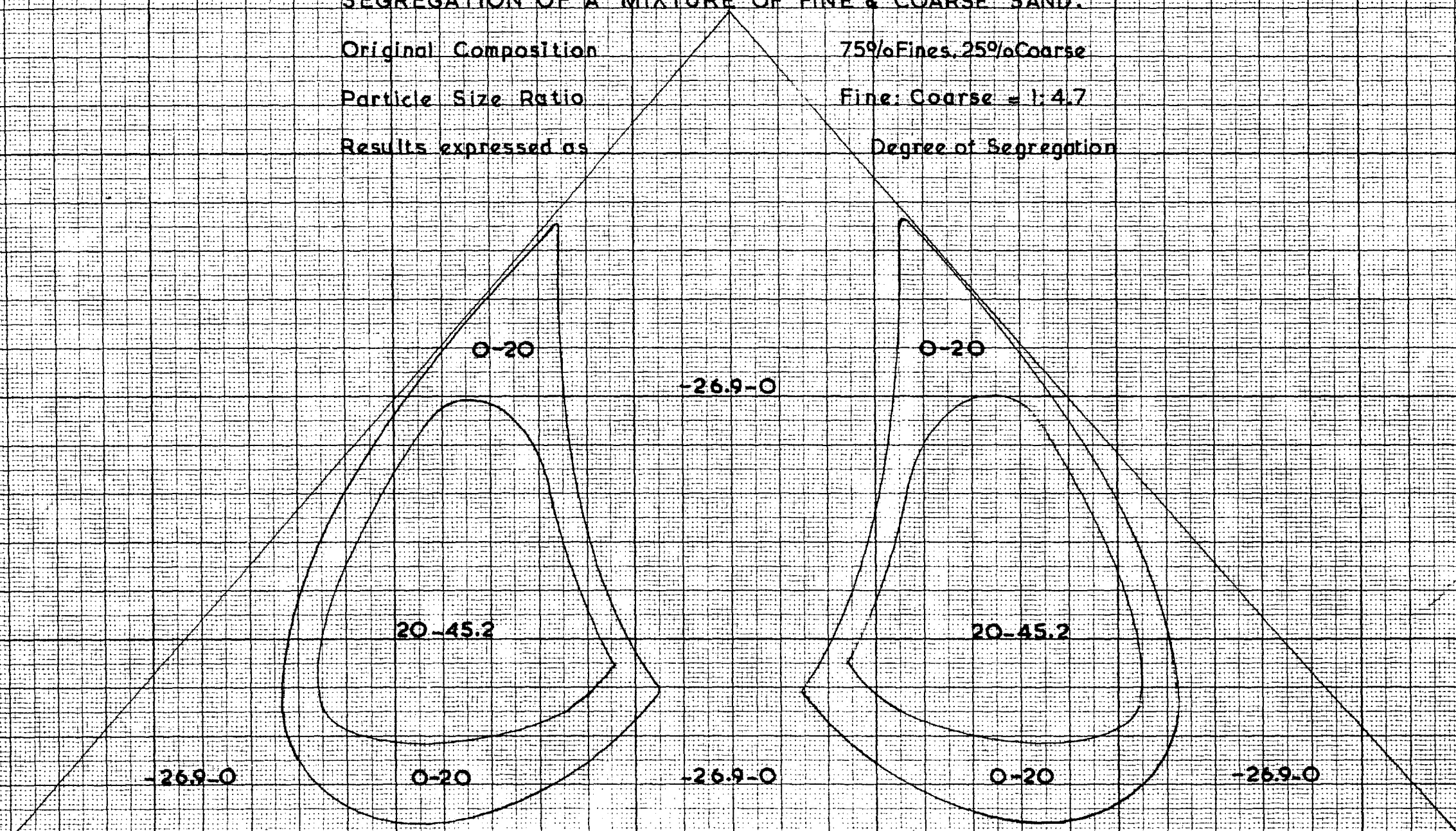
75% Fines, 25% Coarse

Particle Size Ratio

Fine: Coarse = 1:4.7

Results expressed as

Degree of Segregation



Fig(25)a

SEGREGATION OF A MIXTURE OF MAGNETITE & COAL

Original Composition

25% Magnetite, 75% Coal

Results expressed as

Percent of Magnetite

< 25%

25-50%

> 50%

Section I

30.1 32.3 33.1 33.0 32.4 33.0 33.1 32.3 30.1

35.2 34.4 34.1 34.1 34.1 34.1 34.1 34.4 35.2

39.3 37.0 35.6 35.3 36.0 35.3 35.6 37.0 39.3

42.2 39.4 37.7 37.3 38.3 37.3 37.7 39.4 42.2

Section II

36.4 42.7 44.2 42.8 40.5 39.7 41.1 39.7 40.5 42.8 44.2 42.7 36.4

39.2 44.0 45.1 44.6 43.7 43.7 44.7 43.7 43.7 44.6 45.1 44.0 39.2

41.4 43.5 45.1 46.5 47.5 48.2 48.6 48.2 47.5 46.5 45.1 43.5 41.4

42.6 45.7 44.0 49.4 50.5 51.0 51.0 51.0 50.5 49.4 44.0 45.7 42.6

Section III

27.5 40.9 42.5 41.8 44.5 44.5 50.6 51.6 51.9 51.6 50.6 44.5 44.5 41.8 42.5 40.9 27.5

25.5 38.7 41.0 39.8 37.8 41.1 49.0 51.7 51.5 51.7 49.0 41.1 37.8 39.8 41.0 38.7 25.5

23.4 34.8 34.7 35.2 32.9 37.2 44.7 48.2 50.1 48.2 44.7 37.2 32.9 35.2 34.7 34.8 23.4

21.3 29.7 30.0 28.0 26.5 31.7 37.0 42.5 47.9 42.5 37.0 31.7 26.5 28.0 30.0 29.7 21.3

BASE

3.5 10.8 15.1 18.0 19.2 19.1 18.0 18.9 19.2 20.8 24.4 32.6 45.1 32.6 24.4 20.8 19.2 18.9 19.0 19.1 19.2 18.0 15.1 10.8 3.5

1 2 3 4 5 6 7 8 9 10 11 12 13

Fig(25)b

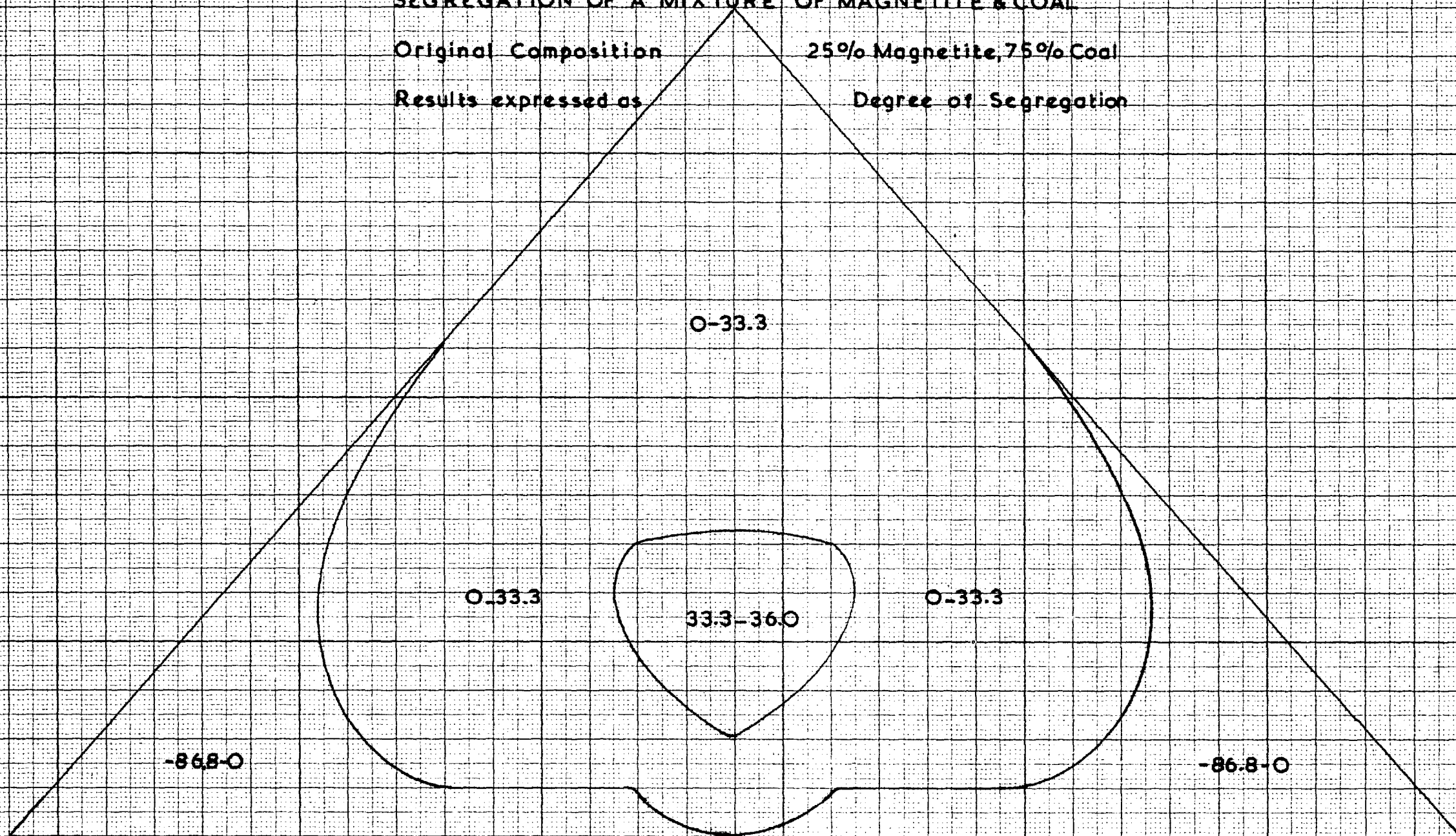
SEGREGATION OF A MIXTURE OF MAGNETITE & COAL

Original Composition

25% Magnetite, 75% Coal

Results expressed as

Degree of Segregation



Fig(26)a

SEGREGATION OF A MIXTURE OF MAGNETITE & COAL

Original Composition

50% Magnetite, 50% Coal

Results expressed as

Percent of Magnetite

< 50%

50-70%

> 70%

Section I

65.8 66.2 65.9 64.5 61.6 64.5 65.9 66.2 65.8

67.0 66.1 65.2 64.7 61.5 64.7 65.2 66.1 67.0

68.5 65.4 64.8 65.5 68.0 65.5 64.8 65.4 68.5

69.2 65.6 64.6 65.7 69.4 65.7 64.6 65.6 69.2

Section II

64.4 68.5 69.4 64.7 64.5 65.5 70.9 65.5 64.5 66.7 69.4 68.5 64.4

64.9 68.1 68.8 67.0 64.6 66.8 71.4 64.8 64.6 67.0 68.8 68.1 64.9

65.0 67.2 67.6 64.4 65.0 67.5 71.2 67.5 65.0 66.4 67.6 67.2 65.0

64.9 65.8 64.0 65.4 65.1 67.5 70.6 67.5 65.1 65.4 66.0 65.8 64.9

Section III

57.3 62.4 64.4 64.3 63.7 63.8 64.8 66.7 69.4 66.7 64.8 63.8 63.7 64.3 64.4 62.4 57.3

55.4 60.7 62.5 61.9 60.6 60.7 62.2 61.6 67.2 64.6 62.2 60.7 60.6 61.9 62.5 60.7 55.4

53.3 57.9 59.7 59.0 57.0 58.3 57.2 60.0 64.2 64.0 57.2 56.3 57.0 59.0 59.7 57.9 53.3

51.0 55.0 56.0 55.4 53.2 50.9 50.0 53.0 60.5 53.0 50.0 50.9 53.2 55.4 56.0 55.0 51.0

BASE

12.0 26.0 37.5 45.0 49.2 50.9 51.5 51.0 49.2 48.0 40.1 46.5 55.8 46.5 40.1 48.0 48.2 51.0 51.5 50.9 49.2 45.0 37.5 26.0 12.0

1 2 3 4 5 6 7 8 9 10 11 12 13

Fig(26)b

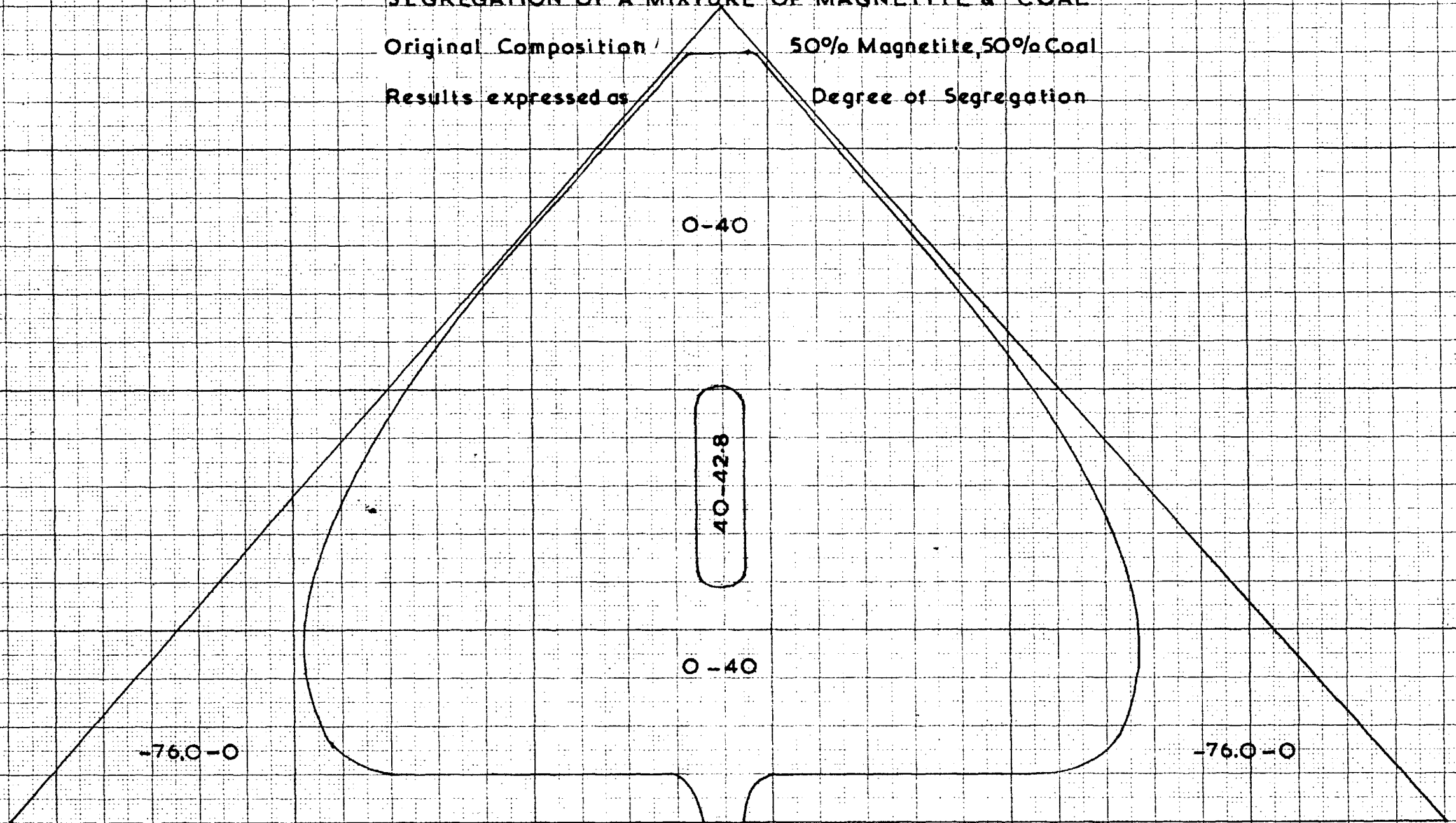
SEGREGATION OF A MIXTURE OF MAGNETITE & COAL

Original Composition /

50% Magnetite, 50% Coal

Results expressed as

Degree of Segregation



Fig(27)a

SEGREGATION OF A MIXTURE OF MAGNETITE & COAL

Original Composition

75% Magnetite, 25% Coal

Results expressed as

Percent of Magnetite

< 75%

75-80%

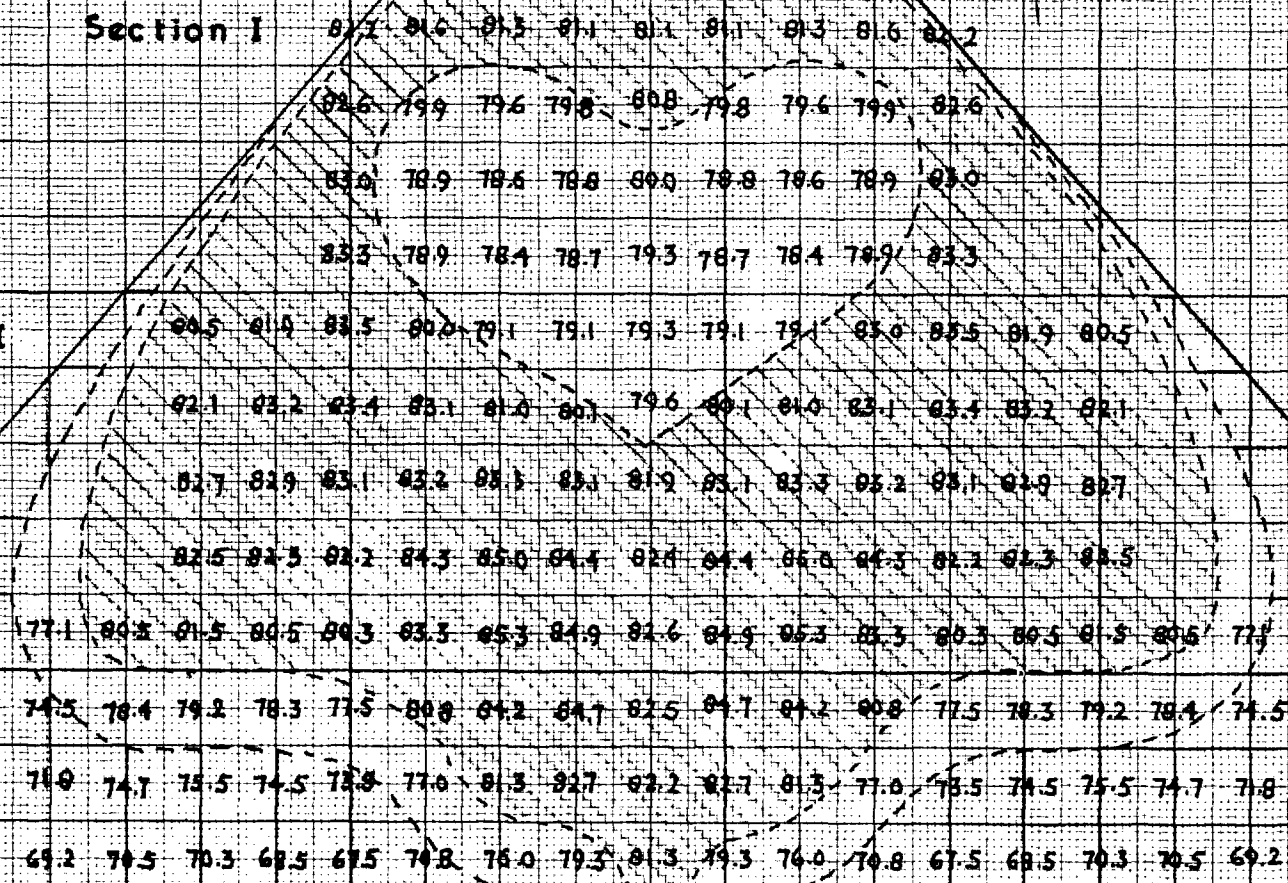
> 80%

Section I

Section II

Section III

BASE



1 2 3 4 5 6 7 8 9 10 11 12 13

Fig(27)b

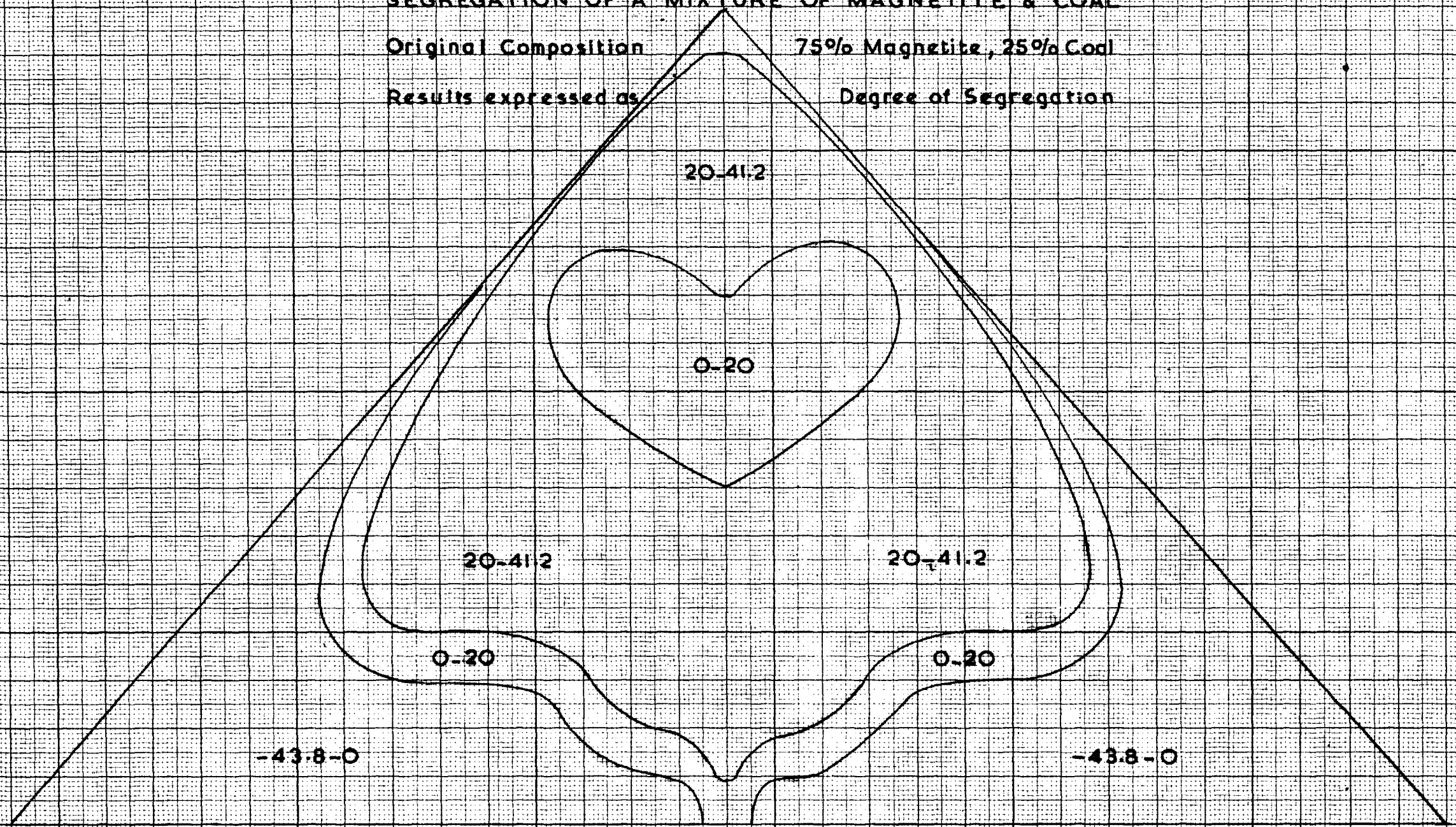
SEGREGATION OF A MIXTURE OF MAGNETITE & COAL

Original Composition

75% Magnetite, 25% Coal

Results expressed as

Degree of Segregation



Considering first the case of mixtures of varying particle sizes Fig. (22-24a), it will be seen that ^{the} maximum segregation in any area is -71.8 while the minimum is zero. The general pattern of segregation is similar in all three mixtures and may be described by reference to figures (22-24). At each corner of the triangular cross-section, there is an area of maximum negative segregation i.e. an area in which the percentage of coarse particles has increased. A second area of maximum positive segregation lies entirely within the cone and takes the form of a ring of material concentric with the vertical axis and about $2/3$ rd of the distance from the apex of the cone. In between these two areas segregation occurs to an intermediate level. At the boundaries between areas of maximum positive and negative segregation, no demixing occurs.

The maximum and minimum values of degree of segregation achieved in the three series of experiments are given in Table (XXIII)a.

In the case of mixtures of particles of varying densities, Fig. (25-27a) it will be seen that the maximum segregation in any area is -86.8 and the minimum is zero. The general pattern of segregation is again similar in all three cases. By reference to Fig. (25-27b)

TABLE XXIIIa

MAXIMUM AND MINIMUM

DEGREE OF SEGREGATION.

MIXTURE OF FINE (85/100) SAND AND COARSE (18/22) SAND

ORIGINAL COMPOSITION			DEGREE OF SEGREGATION				OVERALL
FINE	COARSE	FINE/ COARSE	POSITIVE		NEGATIVE		RANGE
			MIN:	MAX:	MIN:	MAX:	
25	75	1:3	0.4	38.2	-4.8	-68.4	106.6
50	50	1:1	0.8	48.0	-1.2	-71.8	119.8
75	25	1.0.33	0	45.2	0	-26.9	72.1

TABLE XXIIIbMIXTURE OF MAGNETITE (18/22) AND COAL (18/22).

ORIGINAL COMPO- SITION		RATIO	DEGREE OF SEGREGATION				OVERALL
MAG- NETITE	COAL	DENSE/ LIGHT	POSITIVE	NEGATIVE			RANGE
			MIN:	MAX :	MIN:	MAX:	
25	75	1:3	0.7	35.9	-2.4	-86.8	122.7
50	50	1:1	0	42.8	0	-76.0	118.0
75	25	1:0.33	0.7	41.5	-0.4	-43.0	84.0

it is seen that at each corner of the triangular cross section, there is an area of maximum negative segregation i.e. an area where the percentage of coal particles has increased considerably. It will also be observed from these figures that the lighter particles for all three mixtures tend to form a zone at the base and round the periphery of the cone, whilst the heavier particles are found in the centre and towards the apex, giving another area of maximum positive segregation.

Referring to table (~~XVIII~~) a and b, the last column represents the overall range of segregation (taking into consideration the maximum positive and negative values of degree of segregation), it will be seen, by comparison, that the overall range of segregation is approximately the same for 50 percent mixtures in the two systems, while this is higher for mixtures of 25 and 75 percent magnetite and coal than that for the corresponding mixtures of fine and coarse particles of sand.

The results of the above experiments indicate that a complete separation of the components of the two systems is not achieved by the process of forming a heap although a partial segregation occurs in well defined areas.

Considering the possible mechanisms of segregation, the significant areas are the layers of material which move continuously down the inclined surface of the cone with an appreciable velocity gradient in a horizontal plane. Segregation is essentially due

a) to the fact that when a small heap has been formed, further material reaching the top rolls down the inclined surface, in which there are voids of varying sizes, depending upon the arrangement of bigger and smaller (or lighter and denser) particles on this surface. The larger (or lighter) particles travelling down the slope of the cone with relatively high velocities and jumping these voids in the surface reach the bottom of the cone, while the fines stop at some intermediate position, and

b) to the probability that a fine (or dense) particle while rolling down the surface will drop into a void and stay there, which is large. The mechanism is aided by the velocity gradient of the moving layers which assists a process of percolation in which the fine (or dense) particles are being continuously filtered through the voids in the moving layers and penetrate inwards.

If this mechanism of segregation is essentially correct, then in order to obtain complete separation of a mixture, it would be necessary to conduct the operation in such a way as to recirculate the partially separated mixture by a continuous process and draw off the separated components at a rate equal to the feed rate. This process of separation of particles in a continuous system has been investigated in the present work and a detailed discussion is given in the following chapter.

CHAPTER (7)SEGREGATION IN ROTATING VESSELS
OF MATERIAL OF DIFFERENT SIZE RATIO.GENERAL

The movement of particles in a rotating horizontal cylinder has been described in detail by Qureshi (17) and Donald and Roseman (40).

In this work we are concerned with rates of rotation producing a cascading movement similar to that observed when forming a cone of particles as described in the previous Chapter. In general the surface of the whole mass will be inclined at near the dynamic angle of repose and there will be a surface layer of finite thickness across which there will be a velocity gradient. If the L/D ratio of the cylinder is ≤ 5 end effects will persist along the whole length and will give rise to axial velocity gradients. Fig (10) Beneath the moving surface layers there will be a static mass which rotates with the cylinder, the particles retaining their relative positions until they reach the moving surface layer when they join up with it.

Donald and Roseman (40) have shown that under such conditions and for particles of different sizes or densities three final forms of segregation are possible as illustrated in Figure (11 & 28).

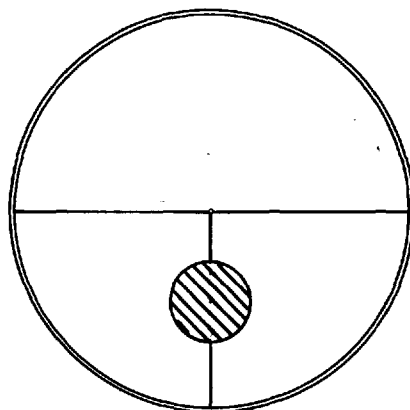
- A. Smaller (or denser) particles form a horizontal core.
- B. Smaller (or denser) particles form a horizontal core with bands at either end.
- C. Smaller (or denser) particles form alternative bands with the larger (or lighter) particles.

All three forms of segregation are essentially due to

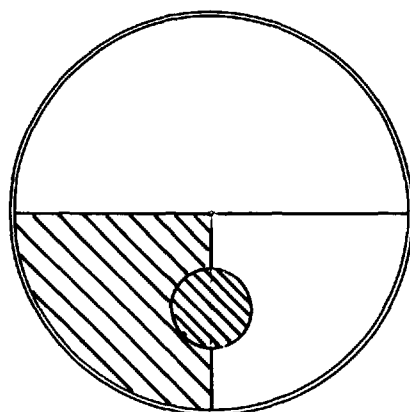
- a) the end effects propagated along the axis of the cylinder
- b) the percolation of fine particles taking place through the moving layers, and
- c) the angle of repose aiding segregation by causing larger (or lighter) particles to roll in a different direction to the smaller (or denser) particles.

The magnitude of the end effect, the speed of rotation and the relative values of the angle of repose determine the final form of segregation into bands. Thus when the smaller (or denser) particles have a higher angle, they will travel with a high velocity down

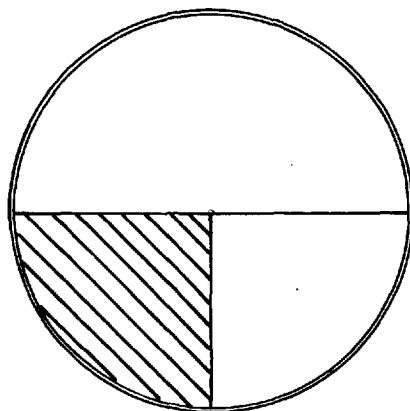
Fig(28)
PATTERNS OF SEGREGATION



(a)



(b)



(c)

the surface of the mixing zone, and the velocity gradient across the surface layers will be too great to allow any radial percolation (or axial mixing). The number of alternate bands of segregation will also depend on the nature of the charge.

The principal forces acting on the particles constituting the charge are

- a) Centrifugal forces ($\frac{mv^2}{r}$) acting in a radial direction
- b) Gravitational forces mg acting vertically downwards and its component down the inclined surface ($mg \cos \theta$),
- c) Frictional forces (μ) between the particles.

In addition the particle in contact with or near the end surfaces of the cylinder will be acted upon by the horizontal component of the drag force. Other forces that may, in certain circumstances affect the velocity distribution are cohesive forces between the particles and forces due to electrostatic charges.

For reasons, which will be given later, it is necessary to determine ^{the} segregation in a rotating conical vessel. As far as is known, no previous work has been carried out on this system, but it may be anticipated from a consideration of the velocity distribution

along the cone that segregation into bands would occur in a similar way to that described for ^a/cylinder. There will, however, be an additional force called into play due to gravity acting on the particles in contact with the inclined plane of the cone.

APPARATUS AND EXPERIMENTAL:-

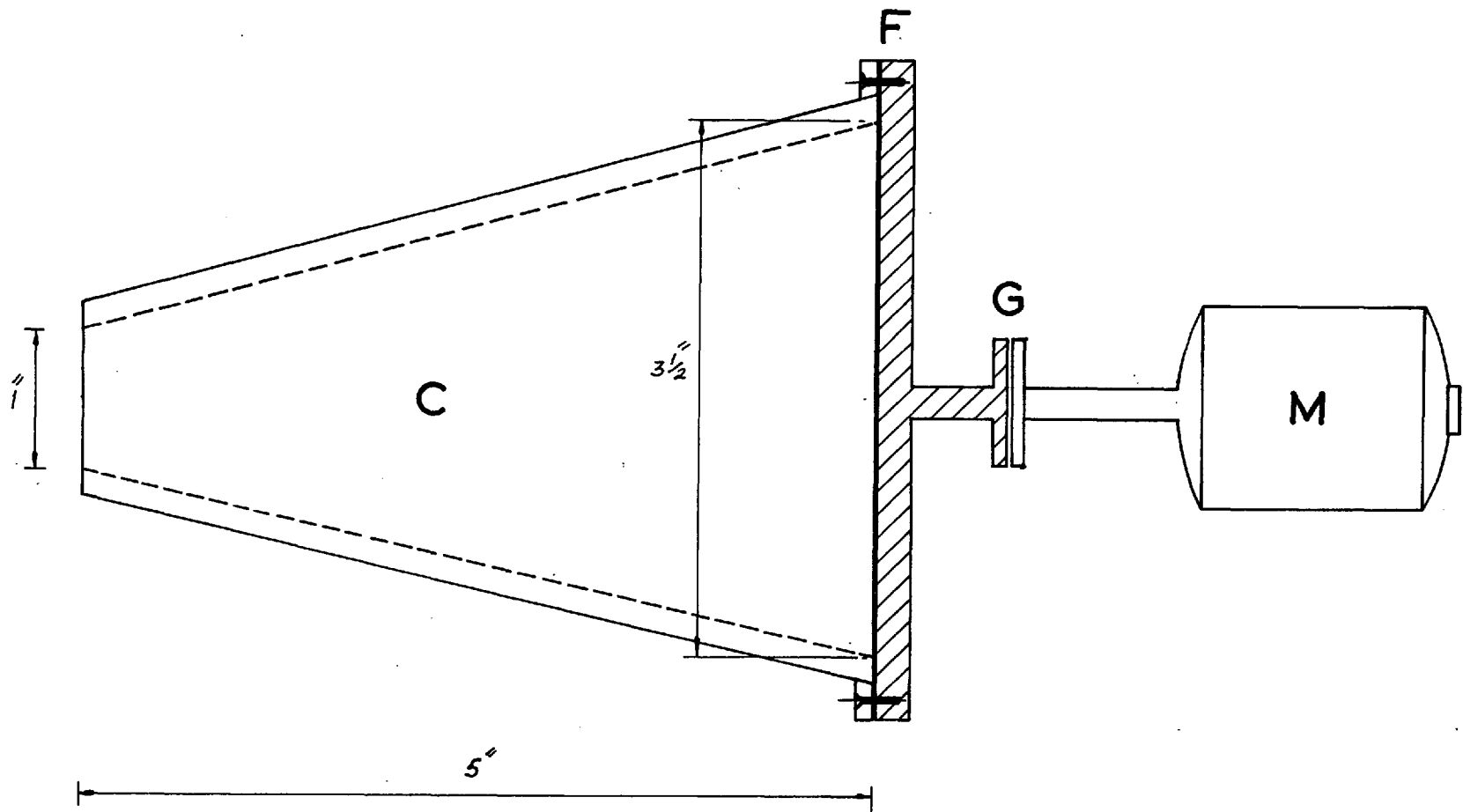
A number of experiments with mixtures of different particle sizes or densities, were carried out in a rotating cylinder, which confirmed the findings of Donald and Roseman and need not, therefore, be further described.

The apparatus used for studying the segregation in a rotating conical vessel is illustrated in Figure (29). It consists of a perspex cone C, fitted with a blind flange F onto which is welded a horizontal shaft. The shaft is driven through a gear box G by a 0.25 H.P., A.C motor M.

The conical vessel has a base angle of 75° , is $3\frac{1}{2}$ inches in diameter at the wider end and is 5 inches long. The opening at the narrow end can be closed by a rubber stopper. The whole apparatus is mounted on an iron base (28 in. x 7 in.), pivoted at one end so that the angle of inclination of the cone to the horizontal can be varied Fig. (30) .

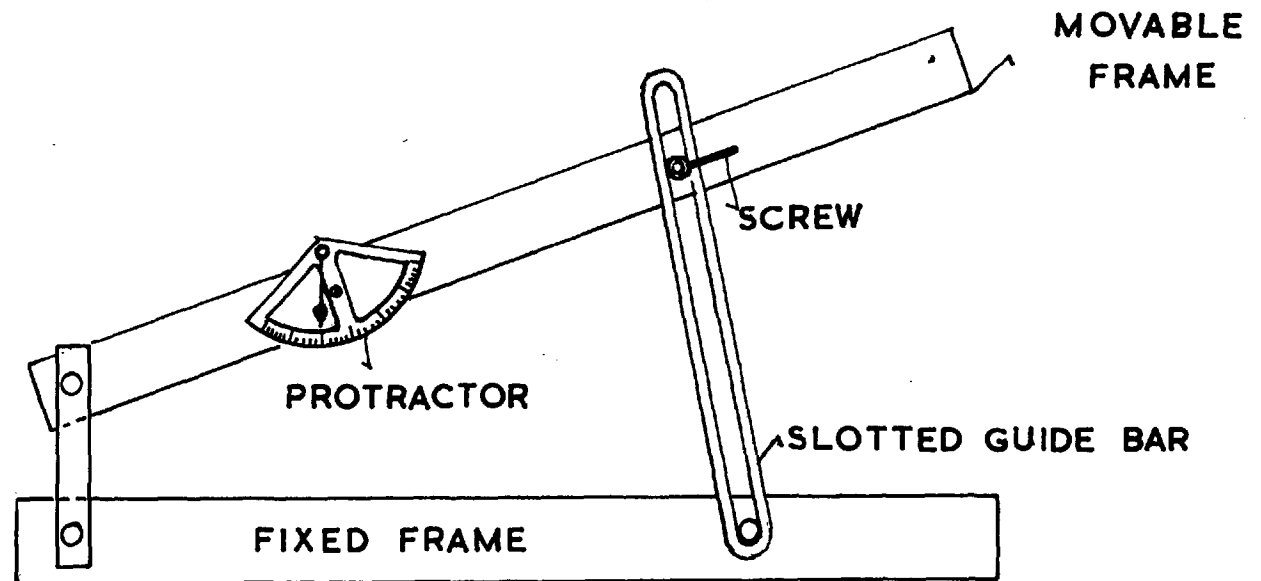
Fig(29)

ROTARY CONE



Fig(30)

ADJUSTABLE STAND FOR CONE



In all experiments, the vessel was one third filled with the required charge, the angle of inclination was fixed to the desired value, and the cone was then rotated until equilibrium conditions had been reached. This usually required about 10 minutes^t, but the vessel was rotated for 20 minutes to be on the safe side. The cone was then brought to rest and the number and width of the segregated bands measured. Each band was then sampled at four different locations by means of a scoop and the samples subsequently analysed for composition as described in Chapter (5). Several repeat experiments were carried out under each set of experimental conditions, and the results averaged.

RESULTS

Mixtures of sand containing 25, 50 and 75 per-cent fine (85/100 mesh) sand and the remainder coarse (18/22 mesh) were employed and the angle of inclination of the cone was adjusted to 0° , 8° , and 15° in different series. It should be noted that at 15° , the lower surface of the conical vessel is horizontal. The speed of rotation was adjusted to 28, 54 and 82 rpm in different series of experiments.

The data have been converted into degrees of segregation by using equations (22, 23) and the degree of segregation has been plotted against various widths ~~lengths~~ of bands formed under specified conditions. The results are summarised in tables (XXIVa), (XXIVb) and (XXIVc). The graphic representation of these is given in Figures (31a,b,c)(32a,b,c) and (33a, b, c).

From these plots, it is seen that both the speed of rotation and the angle of inclination of the cone with the horizontal have an appreciable effect on the position of the segregation bands in the cone. An increase in speed tends to shift the fines from bands of higher concentration to bands of lower concentration. This phenomenon is more prominent in the case of a mixture having 25 percent fine (85/100) sand and to a lesser extent in the case of 50 and 75 percent mixtures. A detailed discussion is given below.

ANGLE OF INCLINATION - ZERO°.

It will be seen that when the axis of rotation of the cone is horizontal, at low speeds (28 rpm) the number of bands formed for 25, 50 and 75 percent mixtures is 4, 3 and 2 respectively. As the speed is increased

TABLE (XXIV) a

ORIGINAL COMPOSITION OF THE MIXTURE 25% FINES, 75% COARSE

P.M.	NO. OF BANDS	ANGLE OF INCLINATION ZERO			ANGLE OF INCLINATION 8°			ANGLE OF INCLINATION 15°		
		WIDTH INCHES	COMPONENT: % FINES	φ	WIDTH INCHES	COMPONENT: % FINES	φ	WIDTH INCHES	COMPONENT: % FINES	φ
28	1	3/8	5.9	-76.4	7/8	Zero	-100	1-17/32	Zero	-100
	2	1	77.5	70.0	1 1/4	85.7	81.0	1-7/16	90.5	87.4
	3	3	2.0	-92.0	2-7/8	14.1	-43.0	2-1/32	6.9	-72.4
	4	5/8	43.0	24.0	-	-	-	-	-	-
54	1	5/8	1.3	-94.8	9/16	Zero	-100	1-7/8	Zero	-100
	2	1-3/32	64.6	52.8	5/8	60.2	46.9	1 1/2	78.5	71.4
	3	2-3/32	1.3	-94.8	1-7/8	20.2	-6.4	1-5/8	24.5	-2.0
	4	1-3/16	43.3	24.4	23/32	82.2	76.3	-	-	-
	5	-	-	-	17/32	31.9	9.2	-	-	-

TABLE (XXIV)
a (Continued)

R.P.M.	NO. OF BANDS	ANGLE OF INCLINATION ZERO			ANGLE OF INCLINATION 8°			ANGLE OF INCLINATION 15°		
		WIDTH INCHES	COMPEN: % FINES	φ	WIDTH INCHES	COMPEN: % FINES	φ	WIDTH INCHES	COMPEN: % FINES	φ
82	1	13/16	0.16	-99.44	2-9/32	Zero	-100	3-1/16	Zero	-100
	2	11/16	56.9	42.6	2.0	80.2	73.5	1-15/16	76.8	69.1
	3	1-23/32	8.7	-65.2	23/32	15.0	40.0	-	-	-
	4	1-23/32	97.2	96.3	- -	-	-	-	-	-

TABLE (XXIV) b

ORIGINAL COMPOSITION OF THE MIXTURE - 50% FINES, 50% COARSE

R.P.M.	NO. OF BANDS	ANGLE OF INCLINATION ZERO			ANGLE OF INCLINATION 8°			ANGLE OF INCLINATION 15°		
		WIDTH INCHES	COMPN: % FINES	φ	WIDTH INCHES	COMPN: % FINES	φ	WIDTH INCHES	COMPN: % FINES	φ
28	1	1-23/32	75.9	51.8	2-13/32	76.5	53.0	11/16	Zero	-100
	2	2-13/16	1.5	-97.0	2-19/32	2.9	-94.2	2-9/16	94.8	89.6
	3	15/32	34.6	-30.8	-	-	-	1-3/4	14.6	-70.8
54	1	13/32	Zero	-100	2-3/8	58.8	17.6	1/4	Zero	-100
	2	2-5/16	86.5	73.0	1-3/8	16.6	-66.8	2-5/16	81.3	62.6
	3	1-1/8	9.2	-81.6	5/8	83.8	67.6	1-3/16	20.8	-58.4
	4	1-5/32	62.8	25.6	5/8	1.7	-96.6	-	-	-
82	1	3/4	0.4	-99.2	3/16	Zero	-100	1-5/16	Zero	-100
	2	1-13/16	84.9	69.8	1-3/8	37.1	-25.8	15/16	45.3	-9.4
	3	5/8	38.7	-22.6	2 1/2	79.4	58.8	2-3/4	87.7	75.4
	4	1-13/16	98.5	97.0	15/16	1.5	-97.0	-	-	-

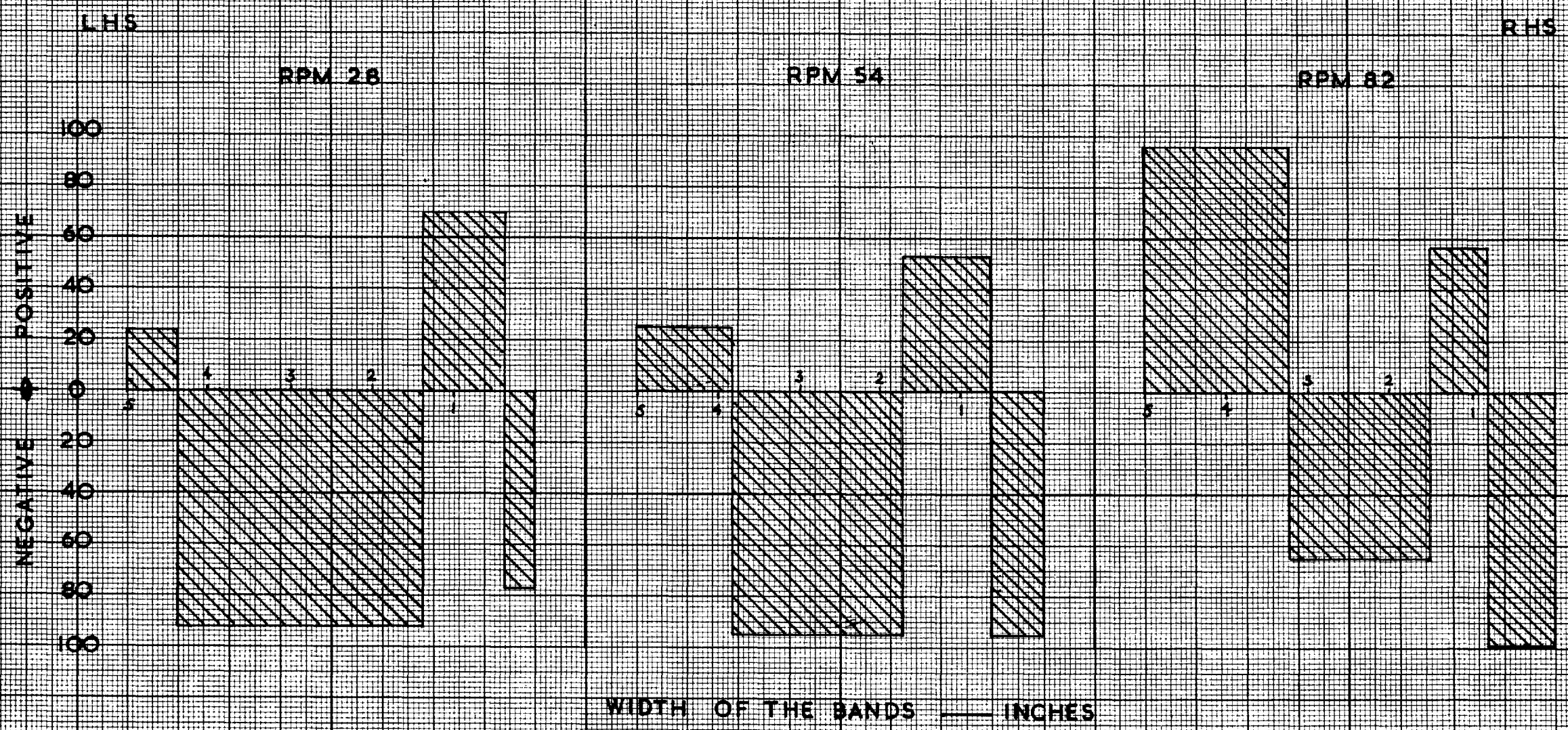
TABLE (XIV)C

ORIGINAL COMPOSITION OF THE MIXTURE - 75% FINES, 25% COARSE

R.P.M.	NO. OF BANDS	ANGLE OF INCLINATION ZERO			ANGLE OF INCLINATION 8°			ANGLE OF INCLINATION 15°		
		WIDTH INCHES	COMP: % FINES	φ	WIDTH INCHES	COMP: % FINES	φ	WIDTH INCHES	COMP: % FINES	φ
28	1	2-3/4	89.3	57.2	3-7/8	83.8	35.2	1/8	Zero	-100
	2	2 1/4	4.3	-94.3	1-1/8	Zero	-100	4-1/8	86.1	44.4
	3	-	-	-	-	-	-	3/8	40.4	-46.1
	4	-	-	-	-	-	-	3/8	53.2	-29.1
54	1	3-7/16	83.8	35.2	3-7/8	80.5	22.0	5/32	Zero	-100
	2	1-9/16	17.6	-76.5	1-1/8	1.0	-98.7	3-23/32	71.0	-5.3
	3	-	-	-	-	-	-	7/16	87.8	51.2
	4	-	-	-	-	-	-	1/2	75.6	2.4
82	1	1-3/16	61.1	-18.5	4-19/32	74.8	-0.37	3-7/8	74.3	-0.9
	2	3-13/16	91.1	64.4	13/32	20.1	-46.6	7/8	77.2	8.8
	3	-	-	-	-	-	-	1/4	69.9	-6.8

Fig(31)a DEGREE OF SEGREGATION VS WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE - 25% FINE (85/100) & 75 % COARSE (18/22) SAND
ANGLE OF INCLINATION OF THE CONE = 0°

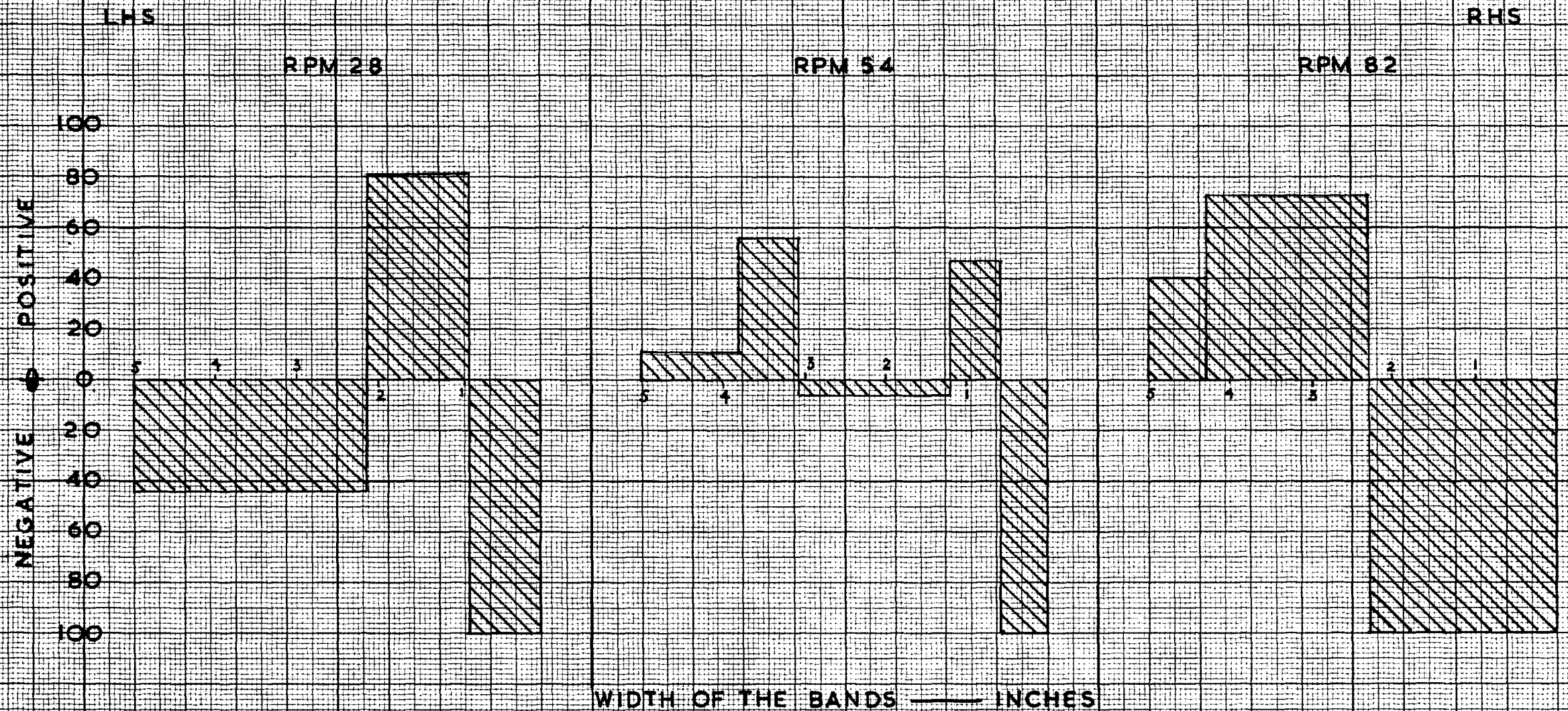


Fig(31)b

DEGREE OF SEGREGATION Vs WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE - 25% FINE (85/100) & 75% COARSE 18/22 SAND

ANGLE OF INCLINATION OF THE CONE = 8°



Fig(31)c

DEGREE OF SEGREGATION VS WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE 25% FINE (85/100) & 75% COARSE (18/22) SAND

ANGLE OF INCLINATION OF THE CONE 15°

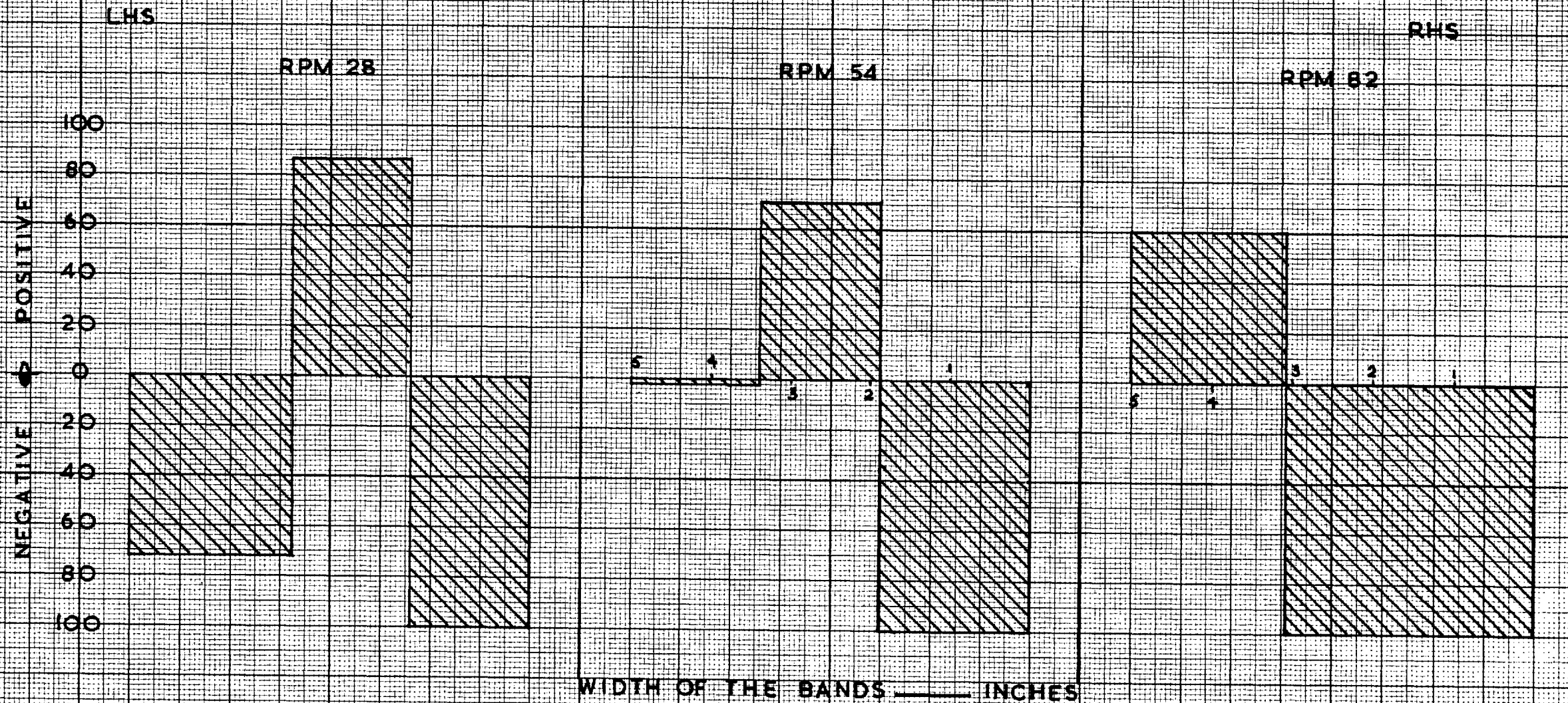
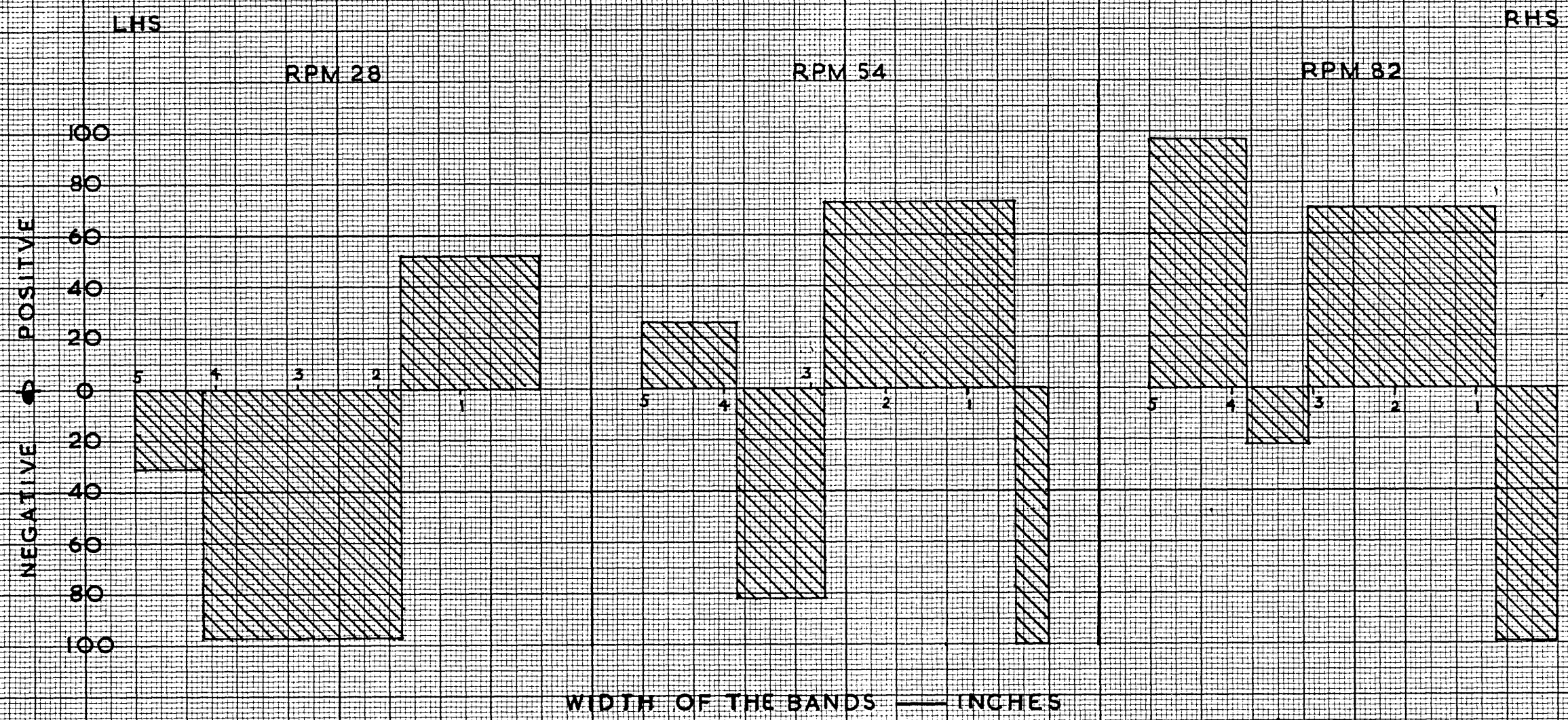


Fig (32)a

DEGRE OF SEGREGATION VS WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE 50% FINES (85/100) & 50% COARSE (18/22) SAND

ANGLE OF INCLINATION OF THE CONE 0°

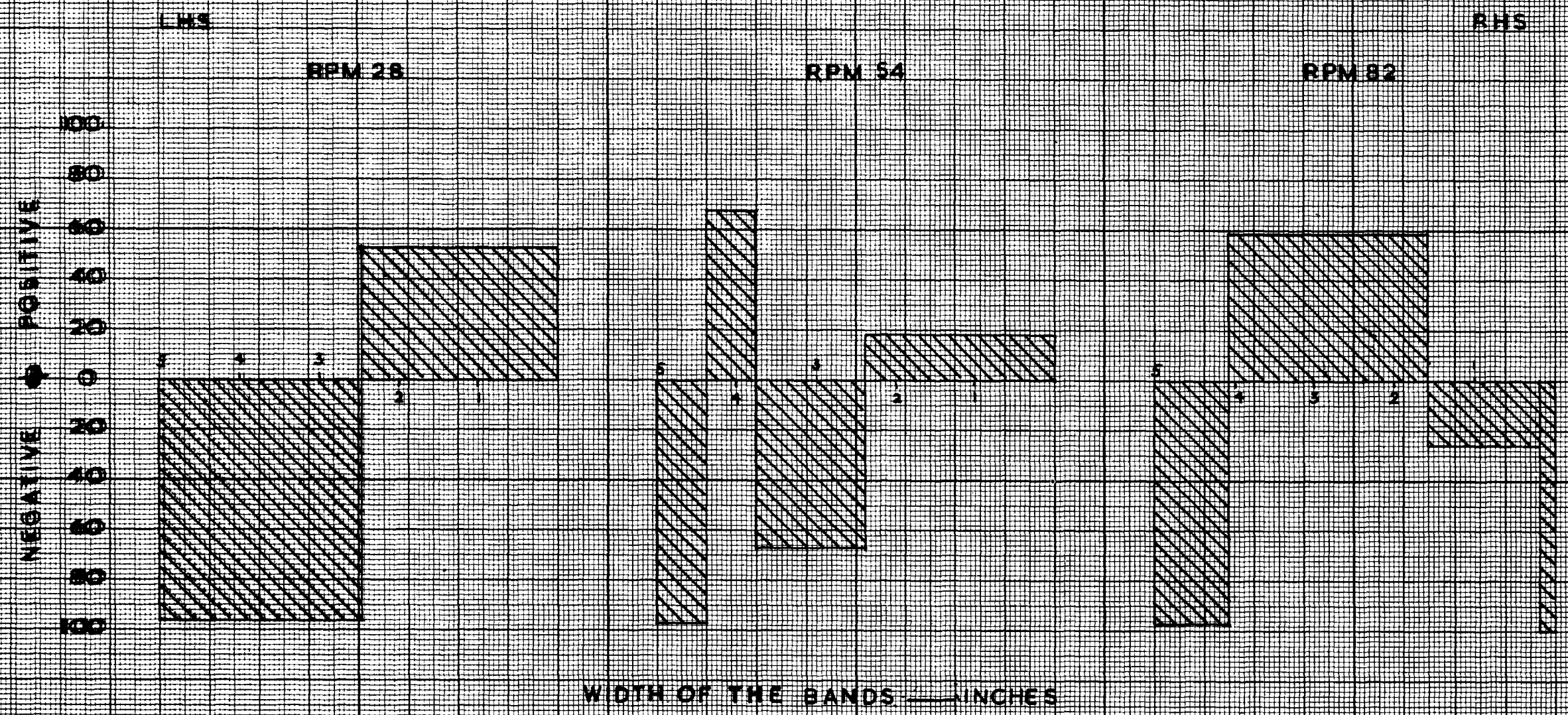


Fig(32)b

DEGREE OF SEGREGATION Vs WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE 50% FINE (85/100) & 50% COARSE (18/22) SAND.

ANGLE OF INCLINATION OF THE CONE α°

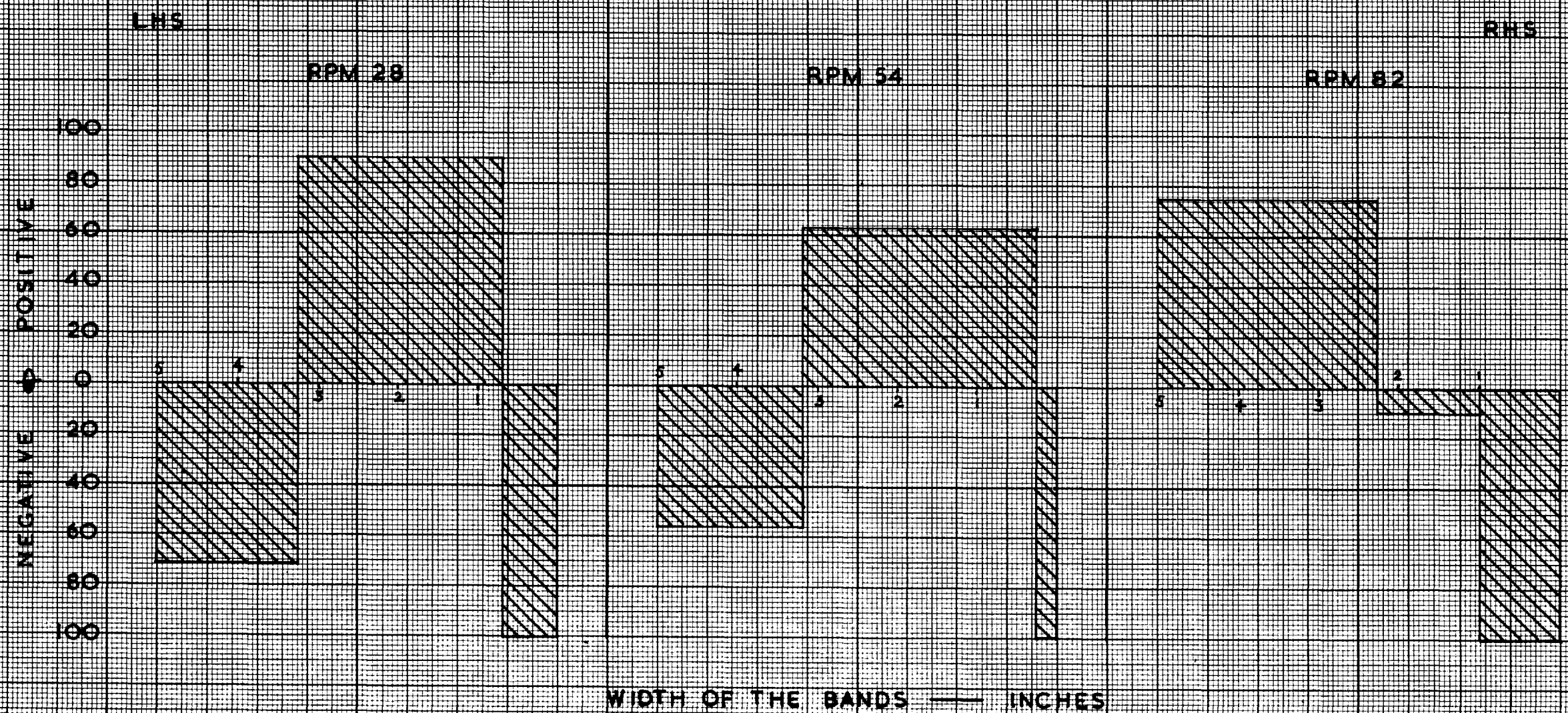


Fig(32)c

DEGREE OF SEGREGATION Vs WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE 50% FINE (85/100) & 50% COARSE (18/22) SAND

ANGLE OF INCLINATION OF THE CONE = 15°



Fig(33)a

DEGREE OF SEGREGATION Vs WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE - 75% FINE (85/100) & 25% COARSE (18/22) SAND

ANGLE OF INCLINATION OF THE CONE - 0°

LHS

RHS

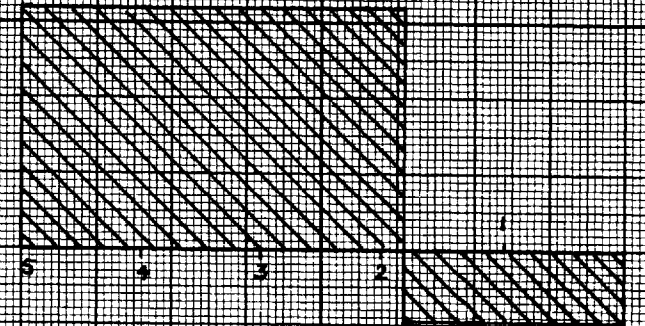
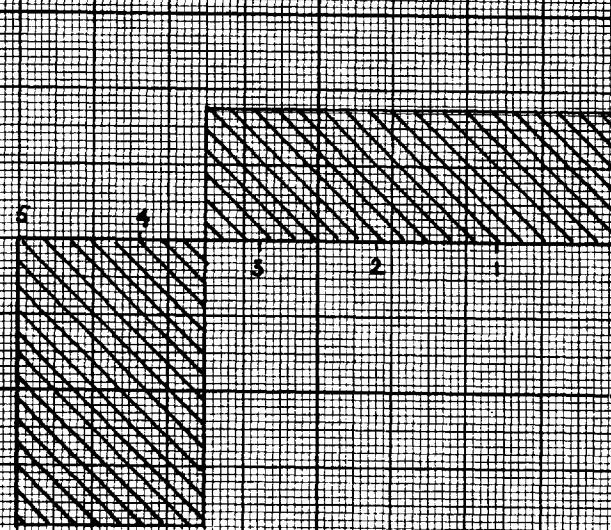
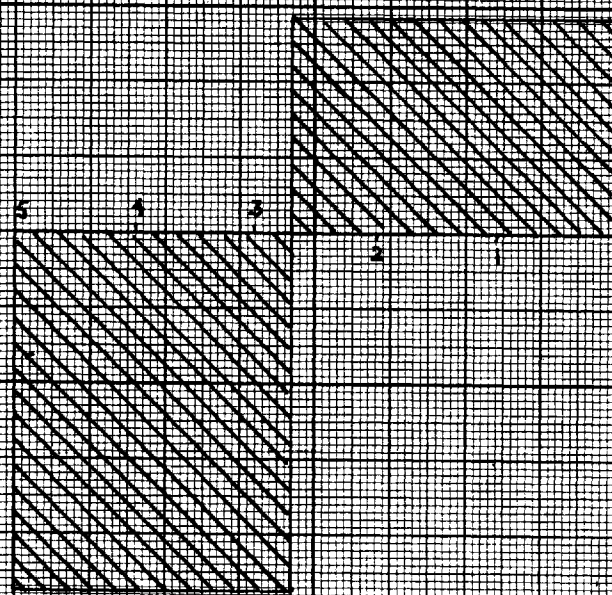
RPM 28

RPM 54

RPM 82

100
80
60
40
20
0
20
40
60
80
100

POSITIVE
NEGATIVE



WIDTH OF THE BANDS — INCHES

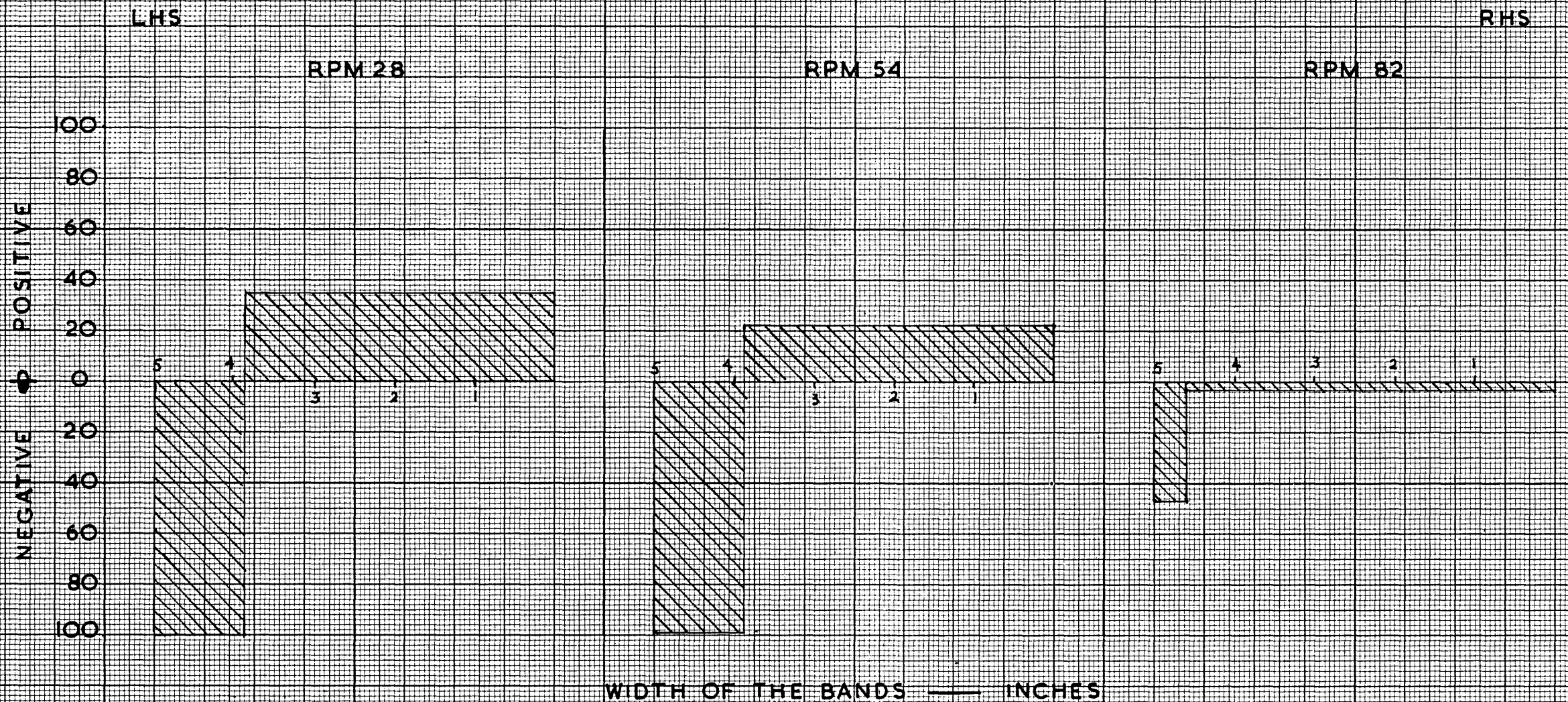
Fig(33)b

168

DEGREE OF SEGREGATION VS WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE — 75% FINE (85/100) & 25% COARSE (18/22) SAND

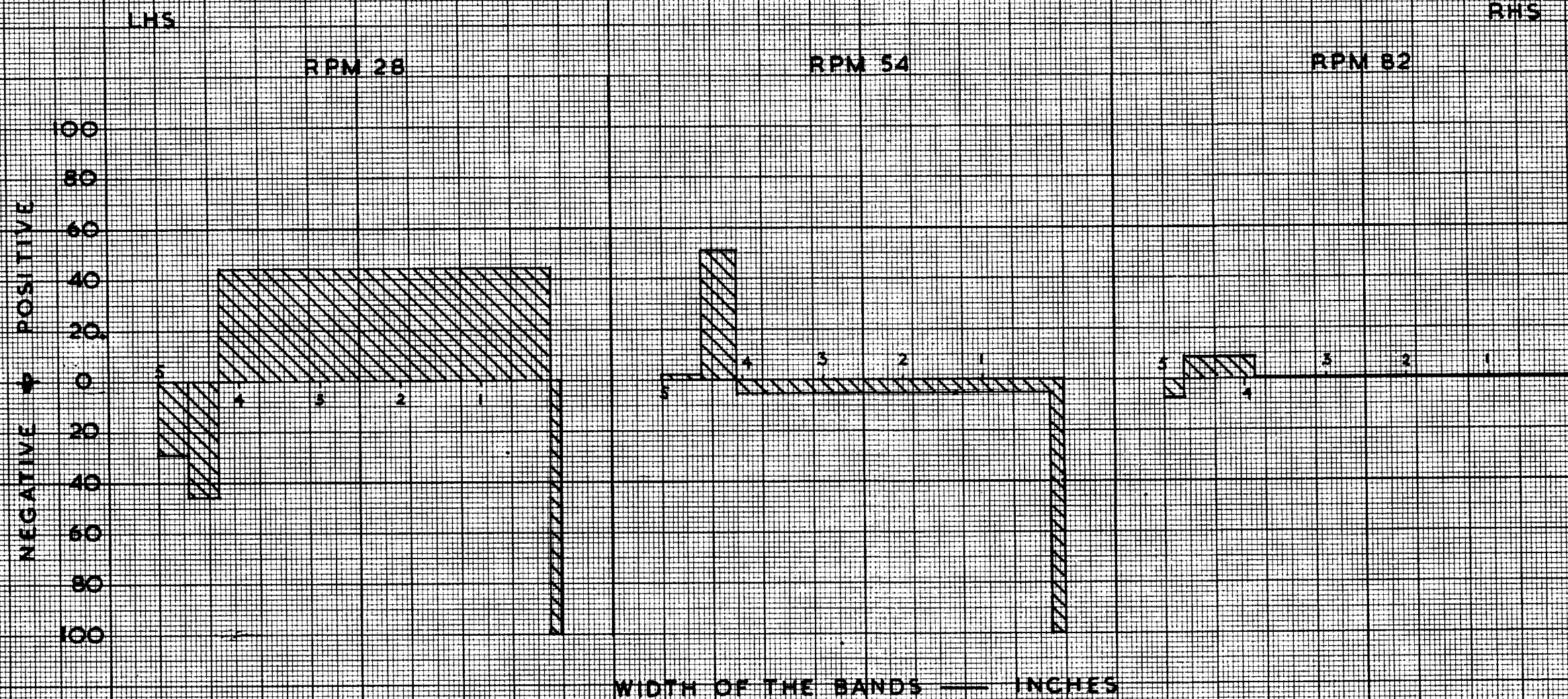
ANGLE OF INCLINATION OF THE CONE = 8°



Fig(33)c

DEGREE OF SEGREGATION VS WIDTH OF THE BANDS

ORIGINAL COMPOSITION OF THE MIXTURE 75% FINE(85/100) & 25% COARSE(18/22) SAND

ANGLE OF INCLINATION OF THE CONE = 15° 

to 54 rpm, the number of bands remains the same in^{the} case of 25 and 75 percent mixtures, while in^{the} case of^a 50 percent mixture, it increases to four. Band 3 moves slightly to the left in both the cases while the percentage of fines in the band at the extreme left increases to a new level. In the case of the 75 percent mixture some of the fines from the band near the blind end migrate to the neighbouring band on the left.

At^a still higher speed (82 rpm), the fines in the bands having a higher concentration start migrating to those on the left with a lower concentration eventually reaching a new equilibrium state (both for 25 and 50 percent mixtures). In the case of the 75 percent mixture, the composition of the band on the right hand side becomes lower than that on the left.

ANGLE OF INCLINATION:- 8°

If the axis of rotation of the cone is inclined at angle of 8 degrees with the horizontal, it can be seen that at low speeds, the number of bands formed is 3, 2 and 2 respectively for 25, 50 and 75 percent mixtures. As the speed is increased the number of bands in case of the 25 and 50 percent mixtures increase to

5 and 4 respectively, while in the case of the 75 percent mixture it remains the same.

At still higher speeds the band second from the left expands and gains more fines. There is a movement of the bands to the left which is quite considerable in the case of the 25 percent mixture; ^{the movement} ~~it~~ decreases with an increase in fines and in the case of the 75 percent fines, it is nil. In this case it is the migration of fines from one band to another which is more prominent.

ANGLE OF INCLINATION - 15° .

If the axis of rotation of the cone is inclined at 15° such that the lower side of the cone is horizontal it can be seen that at low speeds the number of bands formed is 3 in all cases (i.e. for 25, 50 and 75 percent mixtures). An increase in speed has no effect on the number of bands except that some of the fines from a band of higher concentration (on the right) move to the left to a band of lower concentration. The shift is clearer from a plot for the 25 percent mixture. At still higher speed there is a complete separation in the case of the 25 percent mixture into a band of coarse particles only and a band of fine particles

containing about 10 percent coarse. In case of the 75 percent mixture, a speed of 82 rpm produces a fairly uniform mixture.

A similar condition of complete separation is observed for mixtures of 50 percent and 75 percent fines, under different experimental conditions. A 50 percent mixture was found to separate into two bands, the one on the left hand side containing about 2 percent fines while the one on the right hand side contained about 80 percent fines; when the axis of rotation was inclined at an angle of 8° with the horizontal and the speed of rotation was 28 rpm. Under similar experimental conditions a 75 percent mixture separated into two bands, the one on the left containing no fines at all, while the one at the right contained about 82% fines.

From the above results, it may be concluded that the band formation, which will occur whenever the particles of different size (size ratio greater than 2.5) are rotated in a conical vessel, is a function of both speed of rotation and angle of inclination of the axis of rotation. An increase in the speed of rotation increases the drag on the particles, hence imparting a

larger horizontal component of the force which moves them more to the left. That the fine particles are being pushed more to the left at higher speeds is evident from the progressive decrease of fines (increasing ^{broad} negative segregation) in the band close to the ^{broad} end, and a corresponding increase in the fines in the band close to the narrow end of the cone where the degree of segregation changes sign from negative ~~value~~ to positive. An increase in the inclination reduces the tendency of the particles to slide down the inside surface of the cone; this reduction in the horizontal component of the force due to the weight of the particle down the inclined plane tends to minimise the segregation which occurs ^{due to} ~~sliding~~ sliding. When the angle of inclination of the axis of rotation of ^{the} cone is 15° , the lower ^{and} surface of the cone is horizontal ^{and} therefore the tendency of particles to change their position by sliding down the inside surface of the cone is removed.

The combined effect of increasing both the speed of rotation and the angle of inclination is to increase the drag force on the particle and minimise the tendency to slide down the surface of the cone.

The above facts will now be examined in the light of results expressed in degrees of segregation:

25% FINES.

From Figure (31)a, it can be seen that at an angle of inclination of 0° , with the horizontal, the speed of rotation has no effect on the number of bands, but it simply helps to rearrange the proportion of fines in various bands giving a new state of equilibrium.

As the angle of inclination is increased to 8° , Fig. (31)b, an increase in speed tends to increase the number of bands but at very high speed, the number is again reduced to its original value (3).

At an angle of 15° , Fig. (31)c, i.e. when the lower side of the cone is horizontal, ^{an increase in} the speed tends to reduce the number and to help in the segregation of the mixture, half of it being completely separated and the remainder having a value of $\phi \approx 70$.

50% FINES.

Fig. (32) shows the effect of speed on the degree of segregation in various bands for a mixture of 50% fines. An increase in speed at zero angle with the

horizontal Fig. (32)a increases the number of bands after which there is no change except a reorientation of the particles giving a new equilibrium state.

Fig. (32)b shows the effect of speed when the cone is inclined at an angle of 8° . The effect is similar to that described above. In Fig. (32)c, it can be seen that ^{the} speed of rotation does not alter the number of bands, but simply gives a new equilibrium condition.

75% FINES.

The speed of rotation has no effect on the number of bands when the cone is inclined at 0 and 8° with the horizontal (33) a, b and c. At an inclination of 15° , however, at a speed of 82 rpm, the mass in the cone remains more or less uniformly mixed. Therefore, it can be said that in the case of the 75 percent mixture , the combined effect of speed and higher angle of inclination is to hinder segregation.

DISCUSSION.

As already mentioned, there are a number of forces acting on a particle in a horizontal cylinder. In the case of a cone, an additional factor comes into

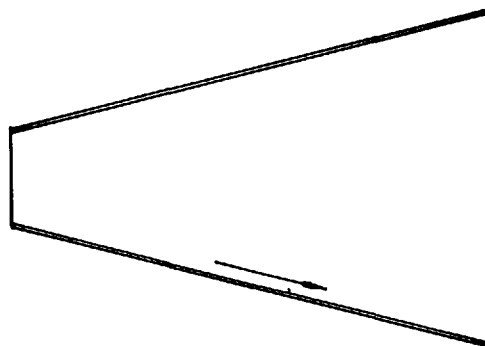
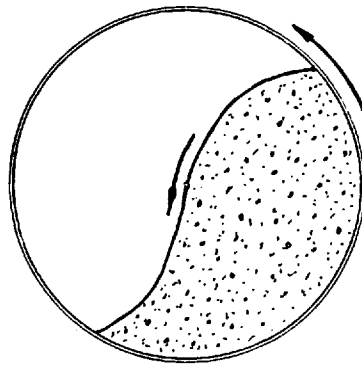
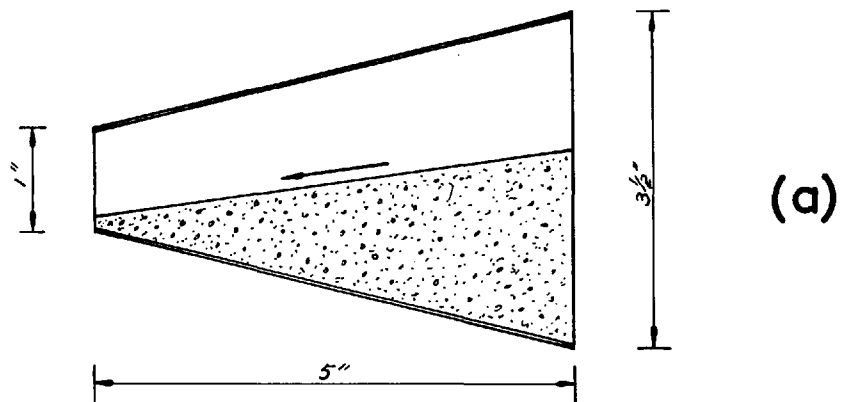
play, namely the sliding of particles along the lower inclined surface of the cone.

A particle is capable of sliding in 3 different directions.

- a) In the direction of inclination of the surface of material as shown in Fig: (34a). This inclination varied between $27-30^{\circ}$, depending on the angle of inclination of the cone with the horizontal.
- b) In the direction of inclination of the material (i.e. the dynamic angle of repose) when seen from one end. Fig. (34 b).
- c) Sliding over the inside surface of the perspex cone Fig. (34 c). The larger particles will roll further down the plane hence affecting a contributory amount of segregation, the value of which will decrease as angle of inclination of the cone is increased, the inside surface becoming horizontal at 15° .

Consider a particle at A (small or large) approaching the bottom and in contact with the end plate (Fig. 35), it is carried to a certain height to a new position A'. At that point, the horizontal component of the force due to drag pushes it to the left to point B (depending upon the size, this distance may vary) after which it

Fig(34)



Fig(35)

PATH OF A PARTICLE IN THE CONE

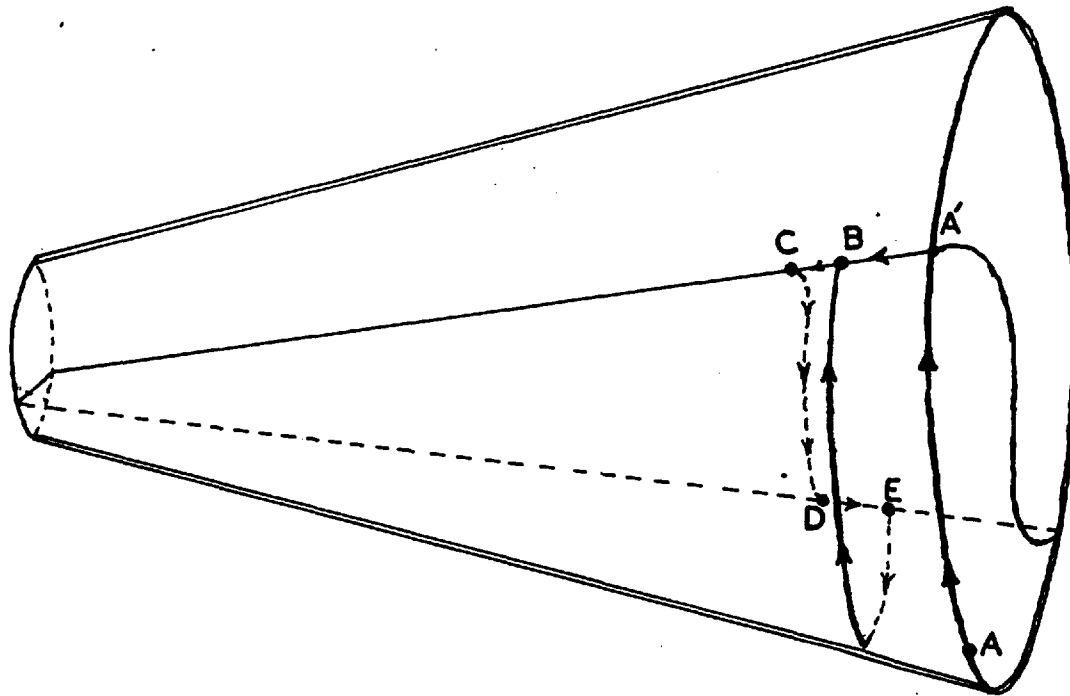
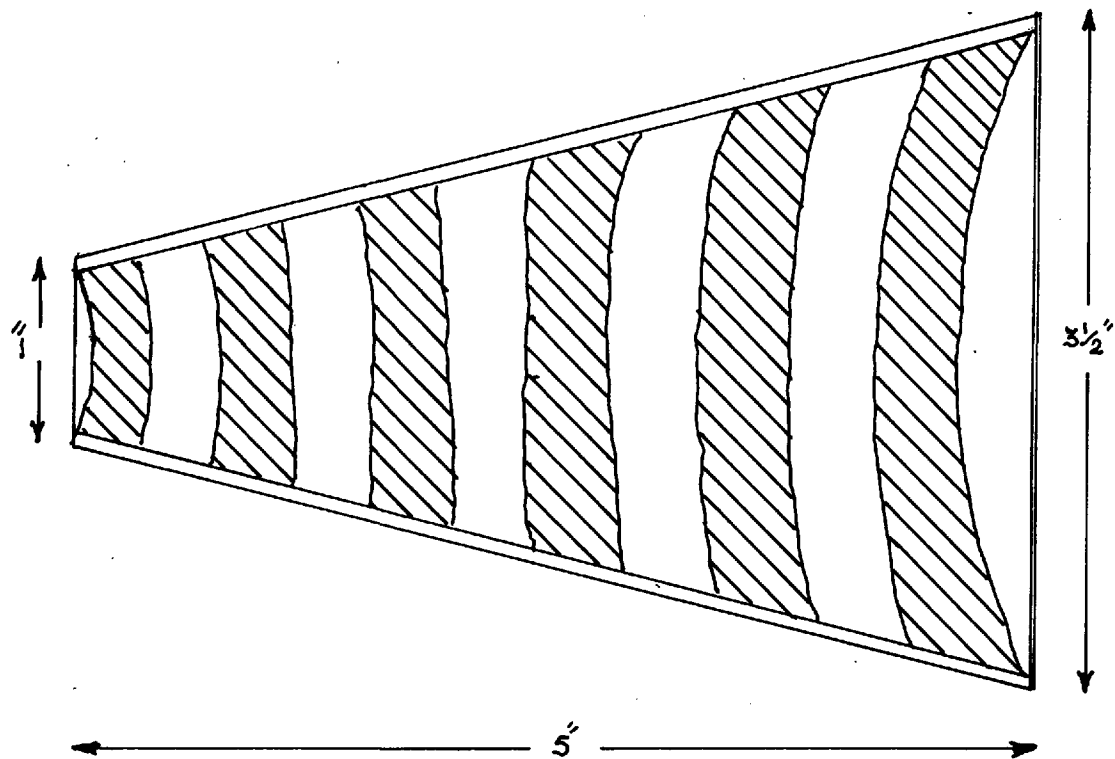


Fig (36)
BAND FORMATION IN A CONE



slides over the material slightly to the left to a position C. Then it slides down the inclined surface of the material to a position D at the bottom of the charge, where it may slide over the inside surface of the cone to a final position E, where it rejoins the circulating path with the surface of the cone. This process will go on repeating itself till an equilibrium state is reached at which all the forces acting on the particles balance; the resultant of these forces decides the position of the particle which will not change on further rotation.

The distribution of bands over the length of the cone may be explained by the drag effect, the intensity of which becomes progressively weaker in the direction of decreasing diameter. This is clear from the paths of the particles as observed from the top. These paths (Fig. 36) are curved near the ends and progressively become straighter as the end effect decreases. When 2 bands (large particles close to the end and fine particles next to them) are formed the band containing fine particles becomes thick and acting as a barrier does not allow the larger particle to return. Also the band of particles may have an end

effect of its own and may help in the formation of another two bands, the one close to it of coarse particles, followed by one of fine particles. The process repeating itself might be ^{one of the} causes of the formation of alternate bands in the cone.

In general it will be noted that whilst it is much easier to obtain a complete separation of coarse material than of fine, ~~and that~~ in nearly all cases the amount of material partly segregated exceeds that completely segregated. If, however, a method could be evolved by which material could be fed continuously to the cone and fully separated material removed at the same rate, an efficient and economic process for size or density separation might result. This problem is considered in the next section.

MATERIAL BALANCE OF A SEGREGATED MATERIAL IN A CONE:

In order to check the analytical method of determining segregation a material balance has been made as follows:

To construct the material balance, a total charge of 6 oz of mixture containing 25, 50 and 75% fines and the remainder coarse, was rotated in the cone under

pre-determined conditions. The diameter, arc length and the thickness (width) of the resultant bands were measured. The results are given in Table (XXV). The composition of these bands was found by the method already described.

From these measurements, the volume occupied by the bands was calculated (for details see Appendix II). These volumes were divided by the 'untapped' bulk density of the mixture (see Fig. (37)) to obtain the weight of material present. The total amount was found by adding the two quantities in these bands.

It will be seen from the following calculations that both the formulae proposed are valid and can be used to determine the amount of material present in a band fairly accurately. The calculated values are in reasonable agreement with the experimental values.

BULK DENSITY OF A MIXTURE OF FINE & COARSE SAND

AVE. PARTICLE SIZE — FINE, 85/100 MESH; COARSE, 18/22 MESH

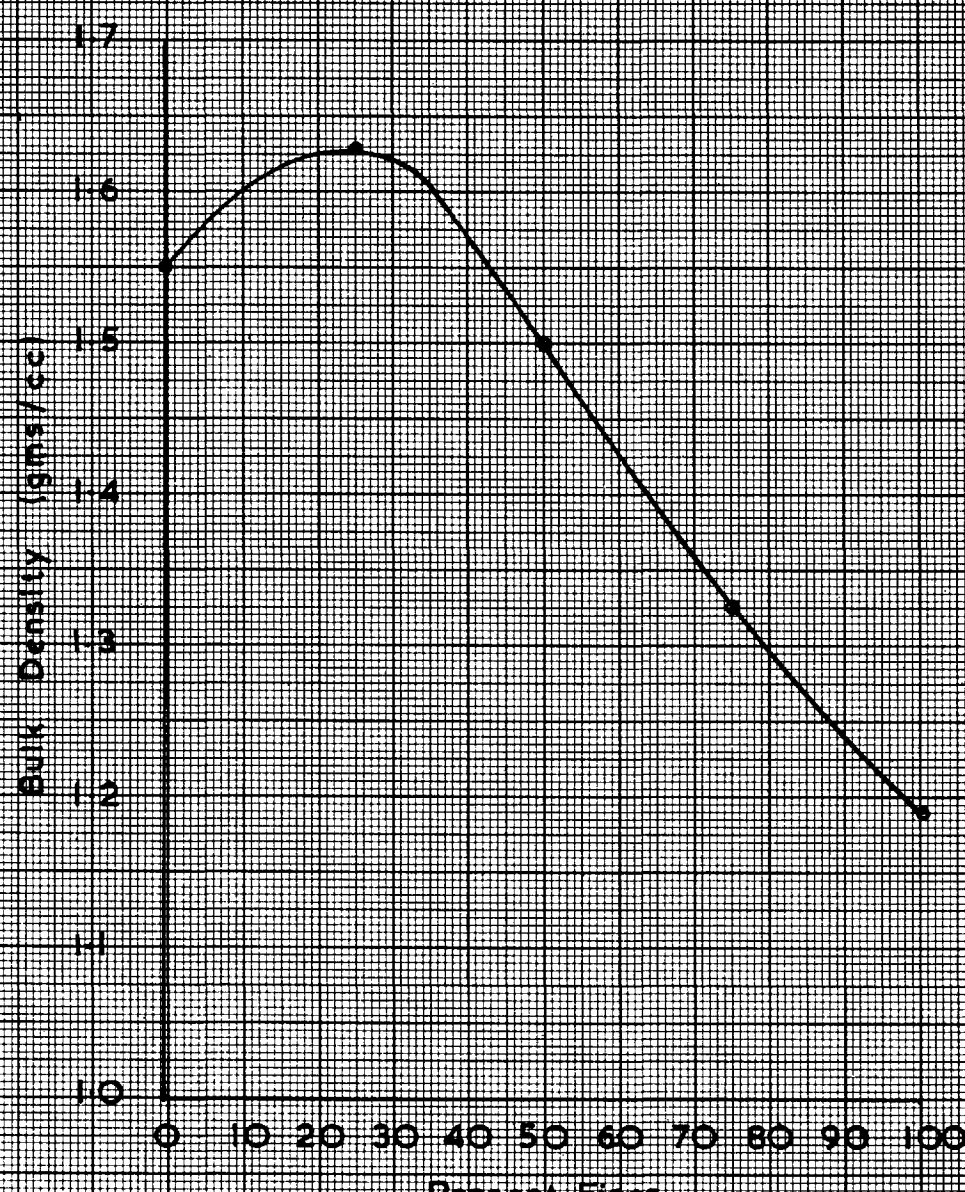


TABLE XXV

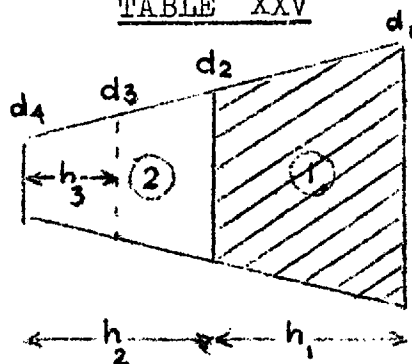


FIG (37)

TOTAL AMOUNT OF MATERIAL IN CONE IN ALL CASES : 6.0 ozs.

<u>DATA</u>	1	2	3
ORIGINAL MIX:	25% Fines, 75% Coarse	50% Fines, 50% Coarse	75% Fines, 25% Coarse
ANGLE OF IN- CLINATION	15°	8°	8°
R.P.M.	82	28	28
No. of Bands	2	2	2
COMPOSITION OF BAND (1)	Zero % Fines	76% Fines	83.8% Fines
" (2)	76.8% Fines	2.9% Fines	Zero % Fines
<u>MEASUREMENTS</u>			
diameter d_1	3½ inches	3½ inches	3½ inches
Width h_1	3 $\frac{1}{16}$ "	2 $\frac{13}{32}$ "	3 $\frac{7}{8}$ "
Arc A_{C1}	3.44	4.18	5.19

Diameter d_2	$1\frac{7}{8}$ inches	$2\frac{5}{16}$ inches	$2\frac{7}{16}$ inches
Width h_2	$1\frac{15}{16}$ "	$2\frac{19}{32}$ "	$1\frac{1}{8}$ "
A_{c_2}	3.18 "	3.17 "	2.55 "
Diameter d_3	$1\frac{9}{32}$ "	(These measurements were only obtained when angle of inclination was 15° .)	
Width h_3	$11/16$ "		
Diameter d_4	$7/8$ "	$7/8$ inches	$7/8$ inches
Arc A_{c_4}	---	1.71 "	1.71 "

CALCULATIONSDATA (1)

$$\begin{aligned}
1) \quad d_1 &= 7/2 \text{ inches} & d_2 &= 15/8 \text{ inches} \\
r_1 &= 7/4 \text{ " } \therefore r_1^2 = 2.975 & r_2 &= 15/16 \text{ " } \therefore r_2^2 = .878 \\
h_1 &= \frac{49}{16} & h_2 &= \frac{31}{16} \text{ inches} \\
Ac_1 &= 3.44 \text{ inches} & Ac_2 &= 3.18 \\
\theta_1 &= \frac{3.44}{7} \times 4 = & \theta_2 &= \frac{3.18}{15} \times 16 \\
&= 1.965 \text{ radians} & &= 3.39 \text{ radians} \\
\sin \frac{\theta_1}{2} &= \sin 0.9825 \text{ radians} & \sin \frac{\theta_2}{2} &= \sin 1.695 \text{ radians} \\
&= \sin 56^\circ .8' = 0.831 & &= -0.1253 \\
\text{Volume of band} &= \frac{\theta_1 \cdot h_1}{6} [r_1^2 + r_2^2 + r_1 r_2] - \frac{1}{4} [r_1^2 \sin \frac{\theta_1}{2} + r_2^2 \sin \frac{\theta_2}{2}] h \\
&= \frac{1.965 \times 49}{16 \times 6} [2.975 + 0.878 + 2.61] - \frac{1}{4} [2.975 \times 0.831 - \\
&\quad .878 \times 0.125] \frac{49}{16} \\
&= 1.003 (6.463) - \frac{1}{4} (2.475 - 0.11) \frac{49}{16} \\
&= 6.48 - 1.81 = 4.67 \text{ cubic inch.} \\
\text{Amount of fines in this band} &= \text{Zero \%} \\
\therefore \text{Bulk density} &= 1.55 \times 62.4 = 96.7 \text{ lb/ft}^3 \\
\therefore \text{Mass} &= \frac{4.67 \times 96.7 \times 16}{108} = \underline{\underline{4.17}}
\end{aligned}$$

$$\begin{aligned}
 2) \quad d_2 &= 15/8 \text{ inches} & d_3 &= 1 \ 9/32 \\
 r_2 &= 15/6 \text{ " } & r_3 &= \frac{41}{64} = 0.64 \\
 r_2^2 &= 0.878 & r_3^2 &= .4096 \\
 h_2 &= \frac{31}{16} \text{ inches} & h_3 &= 11/16 \\
 A_{c2} &= 3.18 \\
 \theta_2 &= \frac{3.18}{5} \times 16 = 3.39 \text{ radians}
 \end{aligned}$$

$$\sin \frac{\theta_2}{2} = -0.1253 \qquad \theta_3 = 2\pi$$

$$\sin 2\pi = 1.$$

$$\begin{aligned}
 \text{Volume of band} &= \frac{\theta_2}{6} \cdot h_2 [r_2^2 + r_3^2 + r_2 r_3] - \frac{1}{4} [r_2^2 \sin \frac{\theta_2}{2} + r_3^2 \sin \frac{\theta_3}{2}] h \\
 &= \frac{3.39}{6} \cdot \frac{31}{16} [.8784 + .41 + .36] - \frac{1}{4} [.878 \times -0.1263 - .41] \frac{31}{16} \\
 &= 1.095 (1.648) - (-.13 \times \frac{31}{16}) \\
 &= 1.87 + .252 = 2.12 \text{ cubic inch}
 \end{aligned}$$

Composition of this band = 76.8% Fines

Bulk density at this composition = $1.32 \times 62.4 = 82.4 \text{ lbs/ft}^3$

$$\therefore \text{Mass in this band} = \frac{2.12 \times 82.4 \times 16}{108} = 1.52 \text{ oz}$$

3) This is just a frustum of the cone $\therefore$ its volume will be given by

$$\begin{aligned} \text{volume} &= \frac{\pi}{3} \cdot h_2 \left[r_3^2 + r_4^2 + r_3 r_4 \right] & r_4 &= \frac{7}{86} \therefore r_4^2 = .191 \\ &= \frac{\pi}{3} \cdot \frac{11}{16} \left[.41 + .191 + .0783 \right] & & \\ &= 0.72 \left(.6793 \right) = 0.489 \end{aligned}$$

Composition in this band = 76.8 % Fines

Bulk density at this composition = $1.32 \times 62.4 = 82.4 \text{ lbs/ft}^3$

$$\therefore \text{Mass of material} = \frac{.489}{108} \times 82.4 = 0.37$$

Total Mass in 3 bands = $4.17 + 1.62 + 0.37 = 6.16 \text{ oz}$

Original amount = 6.00 oz

METHOD 1 Using equation (4), See Appendix II.

$$\begin{aligned}
 1) \quad d_1 &= \frac{7}{2} \text{ inches} & d_2 &= \frac{37}{16} \text{ inches} \\
 r_1 &= \frac{7}{4} = 1.375 \quad r_1^2 = 2.975 & r_2 &= \frac{37}{32} = 1.156, \quad r_2^2 = 1.336 \\
 h_1 &= \frac{77}{32} \text{ inches} & h_2 &= \frac{83}{22} \text{ inches} \\
 Ac_1 &= 4.18 \quad " & Ac_2 &= 3.17 \quad " \\
 \theta_1 &= 2.39 \text{ radians} & \theta_2 &= \frac{3.17 \times 32}{37} = 2.74 \text{ radians} \\
 \sin \frac{\theta_1}{2} &= 0.93 & \sin \frac{\theta_2}{2} &= 0.98
 \end{aligned}$$

$$\begin{aligned}
 \therefore \text{Vol. of band} &= \frac{\theta_1}{6} \cdot h(r_1^2 + r_2^2 + r_1 r_2) - \frac{1}{4} \left[r_1^2 \sin \frac{\theta_1}{2} + r_2^2 \sin \frac{\theta_2}{2} \right] h \\
 &= \frac{2.39}{6} \cdot \frac{77}{32} (2.975 + 1.336 + 3.98) - \frac{1}{4} \left[2.975 \times 0.93 + 1.336 \times 0.98 \right] \cdot \frac{77}{32} \\
 &= 0.96 \times 8.3 - \frac{1}{4} (2.77 + 1.31) \frac{77}{32} \\
 &= 7.97 - 2.38 = 5.6 \text{ cubic inches}
 \end{aligned}$$

Composition of this band = 76.5% Fines

Bulk density at this Composition = $1.32 \times 62.4 = 82.4 \text{ lbs/ft}^3$

$$\therefore \text{Mass of material in this band} = \frac{5.6}{1728} \times 82.4 \times 16 = 4.28 \text{ ozs}$$

108

189.

$$2) \quad d_2 = \frac{37}{16} \text{ inches} \quad d_4 = 7/8 \text{ inches}$$

$$r_2 = \frac{37}{32} = 1.156 \quad r_2^2 = 1.336 \quad r_4 = \frac{7}{16} = .4375 \quad r_4^2 = 0.191$$

$$h_2 = \frac{83}{32} \text{ inch.} \quad Ac_4 = 1.71 \text{ inch}$$

$$Ac_2 = 3.17 \quad \theta_4 = 3.91$$

$$\theta_2 = 2.74 \text{ radians} \quad \sin \frac{\theta_4}{2} = -0.3746$$

$$\sin \frac{\theta_2}{2} = 0.98$$

$$\begin{aligned} \text{Vol. of band} &= \frac{\theta_2}{6} h (r_2^2 + r_4^2 + r_2 r_4) - \frac{1}{4} \left[r_2^2 \sin \frac{\theta_2}{2} + r_4^2 \sin \frac{\theta_4}{2} \right] h \\ &= \frac{2.74}{6} \cdot \frac{83}{32} \left[1.336 + 0.191 + 0.256 \right] - \frac{1}{4} \left[1.336 \times .98 - \right. \\ &\quad \left. .1914 \times .3746 \right] \cdot \frac{83}{32} \\ &= 1.185 (1.783) - \frac{1}{4} \left[1.31 - .0716 \right] \frac{83}{32} \\ &= 2.11 - .80 = 1.31 \text{ oz} \end{aligned}$$

Composition of this band = 2.9% Fines.

$$\begin{aligned} \text{Bulk density at this composition} &= 1.564 \times 62.4 \\ &= 97.7 \text{ lbs/ft}^3 \end{aligned}$$

$$\therefore \text{Volume} = \frac{1.31}{1728} \times 97.7 \times 16 = 1.2 \text{ oz}$$

108

$$\text{TOTAL AMOUNT (CALCULATED)} = 4.28 + 1.2 = 5.48$$

$$\begin{aligned} &= 5.5 \text{ ozs} \\ \text{ORIGINAL AMOUNT} &= 6.0 \text{ "} \end{aligned}$$

METHOD 2. Using equation (7), see Appendix II

$$1) d_1 = \frac{7}{2} \text{ inches} \quad d_2 = \frac{39}{16} \text{ inches}$$

$$r_1 = \frac{7}{8} = 1.725 \quad r_2 = \frac{39}{32} = 1.22 \text{ inches}$$

$$h_1 = \frac{31}{8} \text{ inches} \quad h_2 = 1\frac{1}{8} \text{ inches}$$

$$Ac_1 = 5.19 \text{ inches} \quad Ac_2 = 2.55 \text{ inches}$$

$$r_m = \frac{r_1 + r_2}{2} = \frac{1.72 + 1.225}{2} = 1.47$$

$$r_m^2 = (1.47)^2 = 2.16 \text{ sq. in.}$$

$$Ac_m = \frac{5.19 + 2.55}{2} = \frac{7.74}{2} = 3.87 \text{ inches}$$

$$\therefore \theta_m = \frac{3.87}{117} = 2.6 \text{ radians}$$

$$\sin \frac{\theta_m}{2} = \sin 1.3 \text{ radians} = 0.9636$$

$$\begin{aligned} \text{Vol. of this band} &= \frac{\theta_m}{2} r_m^2 h_1 - \frac{1}{2} r_m^2 \sin \frac{\theta_m}{2} h_1 \\ &= 1.3 \times 2.16 \times \frac{31}{8} - \frac{1}{2} \times 2.16 \times 0.9636 \times \frac{31}{8} \\ &= \frac{31}{8} \quad 2.81 - 1.04 = 1.77 \times \frac{31}{8} \end{aligned}$$

$$= 6.85 \text{ cubic inches}$$

Composition of this band = 83.8% Fines

Bulk density at this composition = $1.28 \times 62.4 = 79.9 \text{ lbs/ft}^3$

$$\therefore \text{Mass} = \frac{6.85}{1728} \times 79.9 \times 16 = \underline{\underline{5.07 \text{ oz}}}$$

108

$$2) \quad d_2 = \frac{39}{16} \text{ inches} \quad d_4 = \frac{7}{8} \text{ inches}$$

$$r_2 = 1.22 \text{ inches} \quad r_4 = \frac{7}{16} \text{ "}$$

$$h_2 = 1\frac{1}{8} \text{ "}$$

$$Ac_2 = 2.55 \text{ "} \quad Ac_4 = 1.71$$

$$\therefore r_m = \frac{1.22 + .44}{2} = 0.83 \text{ in.}$$

$$r_m^2 = (0.83)^2 = 0.69$$

$$Ac_m = \frac{2.55 + 1.71}{2} = 2.13 \text{ "}$$

$$\therefore \theta_m = \frac{2.13}{0.83} = 2.566$$

$$\sin \frac{\theta_m}{2} = 1.283 \text{ radians}$$

$$\sin 1.283 \text{ rad} = 0.9583$$

$$\therefore \text{Volume of band} = \frac{\theta_m}{2} r_m^2 h_2 - \frac{1}{2} r_m^2 \sin \frac{\theta_m}{2} \cdot h_2$$

$$= \left(\frac{2.566}{2} \times 0.69 \times \frac{9}{8} \right) - \left(\frac{1}{2} \times 0.69 \times 0.9583 \times \frac{9}{8} \right)$$

$$= \frac{9}{8} (0.885 - .331) = \frac{9}{8} \times .554$$

$$= \underline{\underline{0.624}} \text{ oz}$$

Composition of this band = Zero % fines.

Bulk density at this composition = $1.55 \times 62.4 = 96.7 \text{ lbs/ft}^3$

$$\begin{aligned} \therefore \text{Mass of material in this band} &= \frac{.624}{108} \times 96.7 \times 16 \\ &= \underline{\underline{0.56}} \text{ oz} \end{aligned}$$

Total Amount of material = $5.07 + 0.56$

$$= \underline{\underline{5.63}} \text{ ozs}$$

SEGREGATION OF PARTICLES IN A CONTINUOUS SYSTEM.

From the experiments described in the previous section, it is concluded that the process of separation of two sizes of granular material in a conical vessel is achieved by the combined effect of speed of rotation, angle of inclination of the cone and the drag on the particles due to an end effect. Segregation, however, is seldom complete even after long periods of rotation and some modifications of the apparatus and method are necessary if continuous and complete separation is to be effected.

If we consider the mechanism of separation in a conical vessel, it is clear that it is associated with the movement of a comparatively thin layer of material. As explained previously, the larger particles tend to accumulate at the bottom of the slope and there is a sideways movement imparted to them by the inclined surface of the cone and by the end effects. The combined movement causes a segregation of small and large particles in well defined bands; but whilst the bands of large particles may contain little or no fine material, those of fine material nearly always contain an appreciable proportion of larger sizes.

If mixed material is fed to the centre of the vessel at a rate such that the residence time is sufficient to allow equilibrium to be reached and if the geometry of the vessel is such as to give an adequate 'feed back', then the discharge at one end should consist of completely separated material. In principle, it should be possible to obtain a discharge of coarse material at one end and fine at the other and a number of instances in which this has occurred will be given later.

When the vessel takes the form of a double cone with a small horizontal section between the cones, the rotation in a closed system gives rise to a separation into two bands only; that on the left hand side consisting mainly of coarse material and that on the right hand side of a mixture of coarse and fine material.

If the system is open and sufficient residence time is allowed to enable equilibrium to be reached an almost complete separation is often obtained. This is due to the changing slope of the surface of the charge and to a 'feed back' of material towards the centre of the vessel. With a double cone, the end effect merges

with a wall effect due to slope of the inside surface of the cone and ~~is~~^{is} therefore more prominent than in the case of a cylinder.

APPARATUS AND EXPERIMENTAL METHOD.

The vessel employed consists of two parts namely:

- (1) a conical section similar in all respects to that described in the previous section, and
- (2) a shorter section which could take the form of a cylinder or of cones of various angles.

The two sections were joined by a clamping ring. The assembled vessel is mounted on ball-bearings and is rotated through a gear box by an electric motor of 0.25 H.P. The general arrangement is shown in Plate (I) and as a line diagram in Fig. (38).

Three different designs of shorter sections were employed, having dimensions as shown in Fig. (39) a, b and c. It will be noted that (a) is a cylinder, (b) has an inclined surface less than the dynamic angle of repose of the material and (c) has an inclined surface greater than the dynamic angle of repose. In one series of experiments, the conical section (1) was replaced by

DOUBLE CONE SEPARATOR

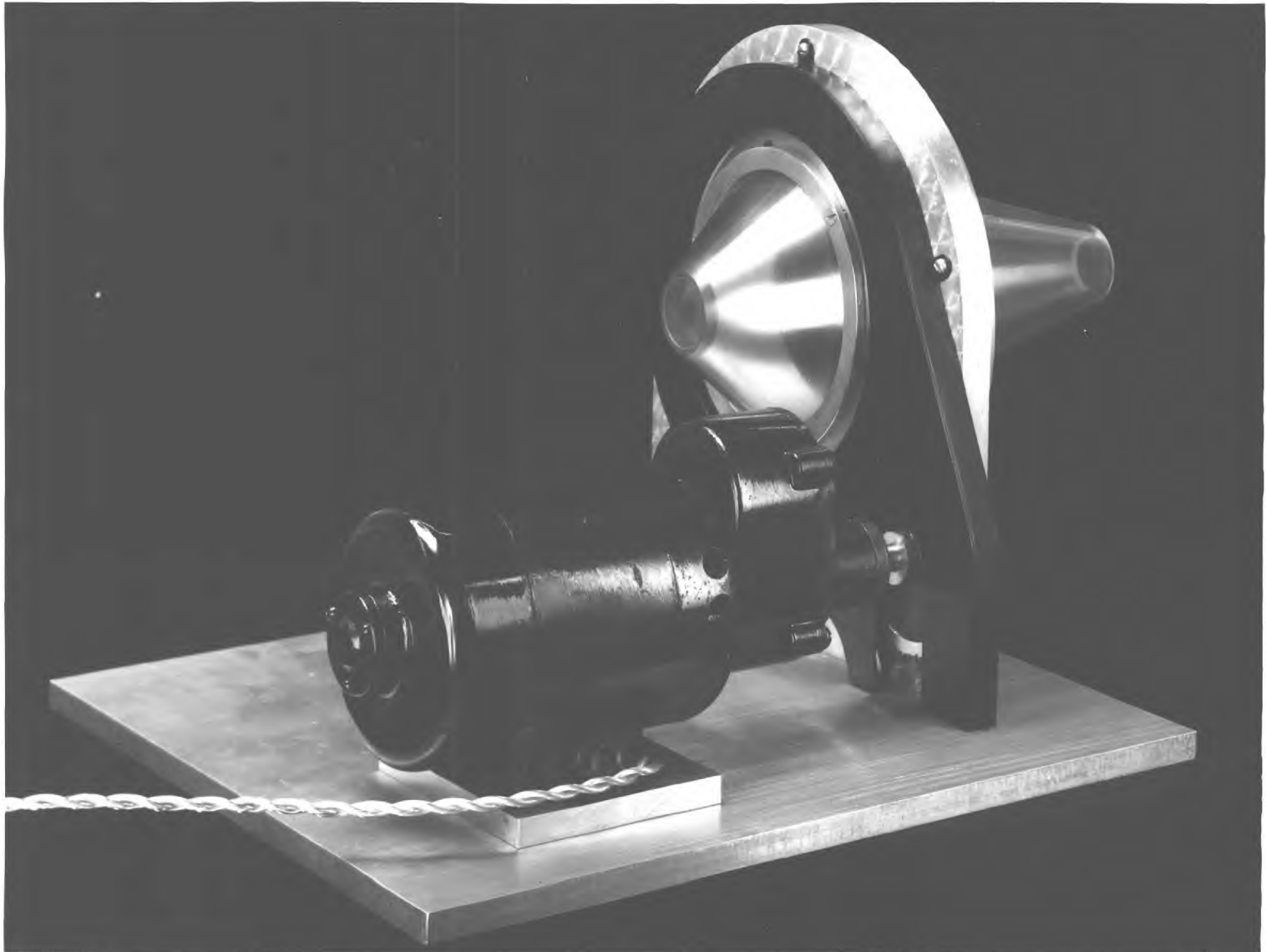


Plate I

Fig (38)
DOUBLE CONE SEPARATOR

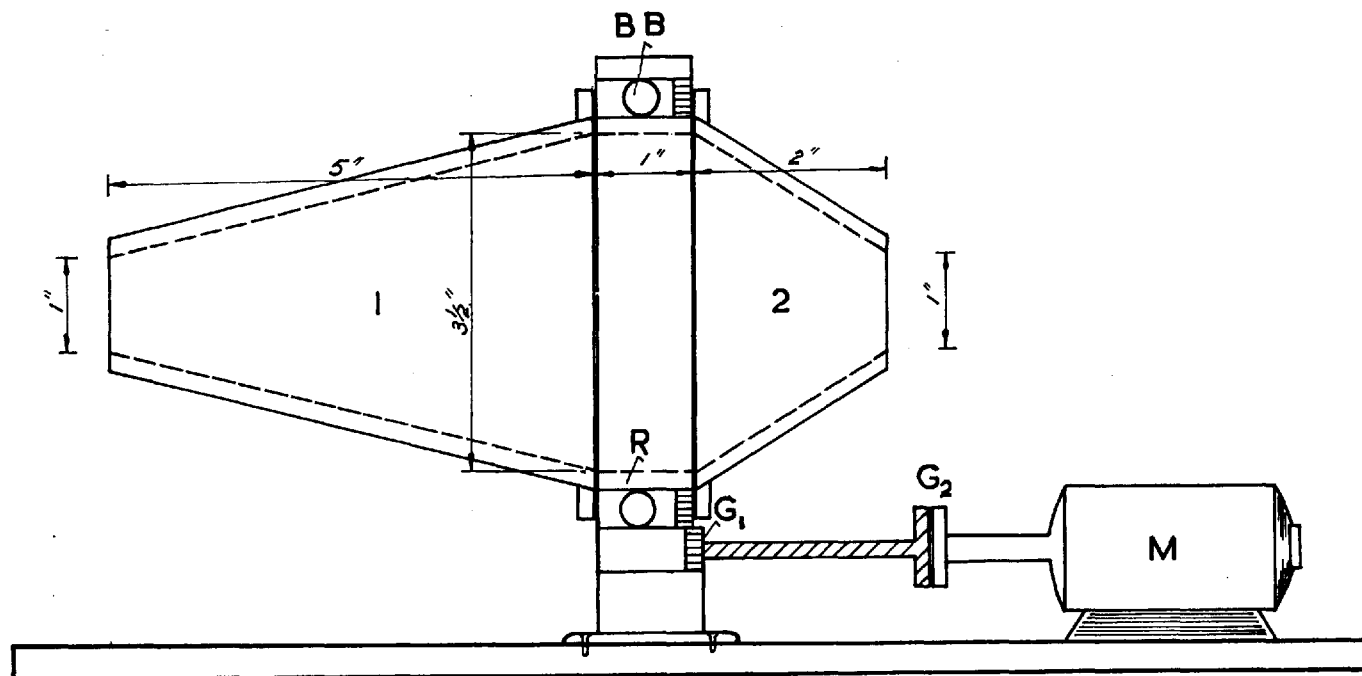
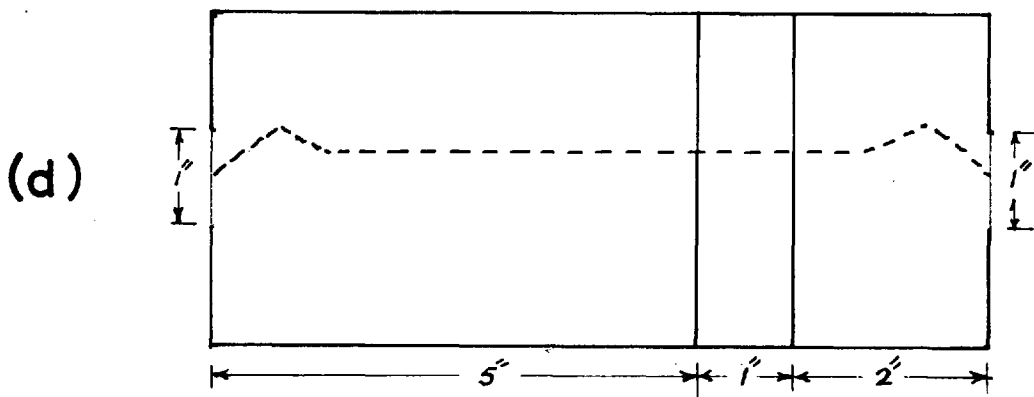
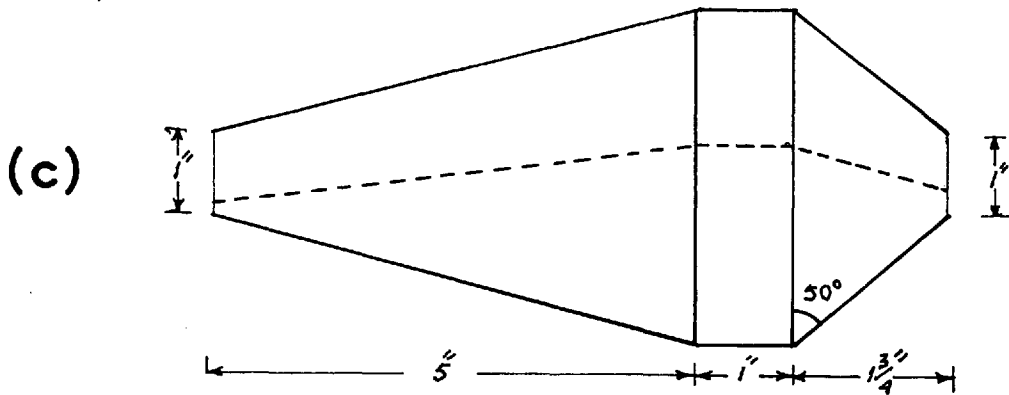
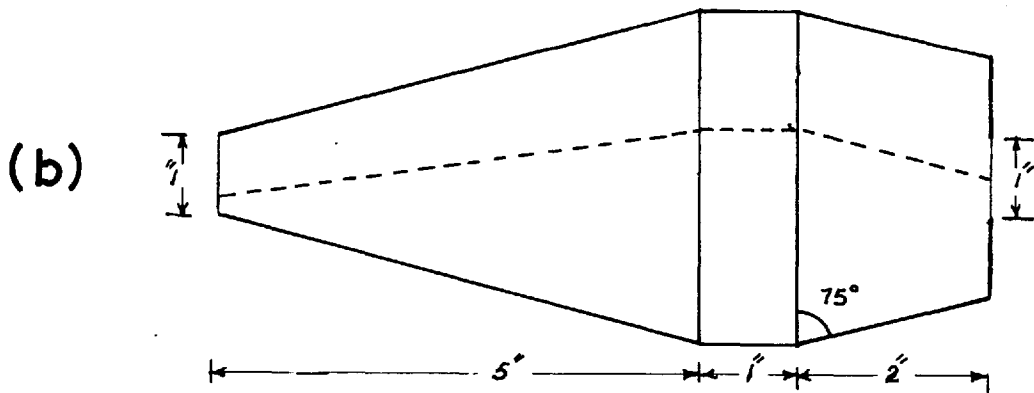
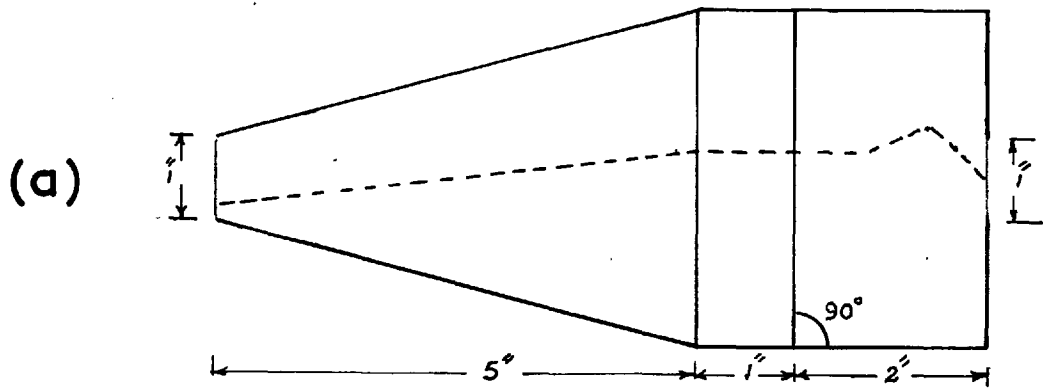


Fig (39)



a cylinder as shown in (d). Only a limited number of experiments, however, were carried out with this vessel. The thick broken lines indicate the velocity profiles in these vessels.

A mixture of constant composition was obtained by means of the distributor described in Chapter (5), the rate of feed being regulated by means of a vibrator acting on a feed pipe at its lower extremity. Typical analysis of the feed for three mixtures is given in Table (XXVI) and show the composition to be reasonably uniform with time.

Although these arrangements worked reasonably well, it was found that there were occasional unexpected variations in the feed rate and in the rate of discharge. In any future work an effort would be made to improve the feed system so as to ensure greater uniformity.

In carrying out an experiment, the rates of discharge at either end were measured at ten minutes intervals and samples taken for analysis. Each run was continued for at least two hours. Whilst for the majority of runs equilibrium was reached in less than one hour, it was found that under certain conditions a much

TABLE XXVI

ANALYSIS OF STREAM OF PARTICLES OF VARIOUS MIXTURES OF FINE AND COARSE SAND WHEN POURED THROUGH A DISTRIBUTOR PLACED ON TOP OF A GLASS FUNNEL AND VIBRATED.

SAMPLE No.	25% FINES 75% COARSE	50% FINES 50% COARSE	75% FINES 25% COARSE
1	29.7 % Fines	45.7 % fines	78.4% fines
2	25.6 "	50.1 "	78.5 "
3	28.9 "	51.0 "	78.6 "
4	24.1 "	52.4 "	75.1 "
5	24.4 "	51.5 "	75.3 "
6	20.6 "	47.3 "	72.0 "
7	24.6 "	54.0 "	76.8 "
8	27.7 "	47.6 "	74.5 "
9	25.4 "	48.2 "	75.8 "
STANDARD DEVIATION	2.757	2.698	2.39

NOTE

The above values of the standard deviation were used to calculate the value of t, which indicated that all the above results fall within a one percent significance level. The results also show that it is easier to get a uniform composition for a 75 percent mixture than for a 25 or 50 percent mixture, with this type of arrangement.

longer time was necessary; even after two hours, stable conditions had not always been reached in spite of the fact that the residence time was over one hour. In cases where equilibrium has not been reached, the runs have been omitted. The sand mixtures employed were of the same composition as those previously used and contained 25, 50 and 75 percent fines respectively. Three different speeds namely 28, 54 and 78 rpm were used.

The results for the four vessels (Fig. 39 a, b, c and d) are given in Tables XXVII - XXXV and are shown graphically in Figures 40-48). In the tables the rate of discharge from each end of the vessel and the composition of the discharged material are tabulated at 10 minutes' intervals together with other relevant data. In comparing the results it should be noted that for the conical vessels at the lower rate of rotation, the main discharge is at the left hand opening of the vessel, whilst at the higher rates, the main discharge is from the right hand opening. This result is to be expected from a consideration of the radial velocity distribution. It must also be borne in mind that when the residence time is sufficient to give equilibrium segregation will

TABLE XXVII

ORIGINAL COMPOSITION. 25% FINE, 75% COARSE SAND

END (a) ON R.H.S.

1. RPM	28
TIME OF RUN	2 HOURS
FEED RATE	3.84 g/min.
MATERIAL RETAINED	411.2 gms.
COMPOSITION OF RESIDUAL MATERIAL	38.5% FINES

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED		336.9 gms		124.3 gms.			
COMPOSITION		74.5% Fines		51.2% Fines			
DISCHARGE RATE		2.81 g/min.		1.04 g/min.			
TIME	% FINES	g/min	ϕ	%FINES	g/min	ϕ	
10 min	0.1	4.02	-99.6	40.5	0.88	20.7	
20 "	0.26	2.33	-99.1	57.4	0.33	43.7	
30 "	0.18	3.91	-99.3	41.7	1.56	22.3	
40 "	0.08	2.97	-99.7	64.7	0.51	52.8	
50 "	0.14	2.50	-99.4	58.0	0.86	44.0	
60 "	0.14	1.44	-99.4	71.7	0.51	62.3	
70 "	0.29	2.35	-99.8	59.1	0.93	45.3	
80 "	0.08	3.43	-99.7	51.1	1.82	34.8	
90 "	0.08	3.55	-99.7	65.1	1.05	53.5	
100 "	0.07	3.42	-99.8	56.3	1.86	41.7	
110 "	0.06	3.32	-99.8	49.7	1.65	32.9	
120 "	0.14	2.33	-99.4	48.7	1.06	31.6	

cont...

2. RPM	<u>54</u>
TIME OF RUN	1 HOUR 50 MIN
FEED RATE	3.62 gm/min
MATERIAL RETAINED	425.2 gms
COMPOSITION OF RESIDUAL MATERIAL	14.65 % Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED 218.3 gms.				178.0 gms			
COMPOSITION: 0.96% Fines				90.0% Fines			
DISCHARGE RATE 1.99 gm/min.				1.63 gm/min.			
TIME	% FINES	gm/min	Φ	% Fines	gm/min	Φ	
10 min	0.103	2.34	-99.6	87.7	2.14	83.6	
20 "	0.063	1.91	-99.8	89.2	1.70	85.6	
30 "	0.028	2.84	-99.9	81.9	2.19	75.9	
40 "	0.044	4.58	-99.8	82.3	2.21	76.4	
50 "	0.024	3.40	-99.9	94.9	1.70	92.1	
60 "	0.131	2.15	-99.5	95.0	1.73	93.3	
70 "	0.198	2.42	-99.2	98.0	1.43	97.3	
80 "	0.441	2.09	-98.2	96.5	1.33	95.3	
90 "	0.096	2.92	-99.6	88.4	1.78	84.5	
100 "	0.124	3.22	-99.5	93.7	1.01	91.2	
110 "	0.502	2.15	-98.0	93.9	0.83	91.9	

3. RPM	78
TIME OF RUN	2 HOURS
FEED RATE	4.34 g/min
MATERIAL RETAINED	437.7 gms
COMPOSITION OF RESIDUAL MATERIAL	11.8% Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED				151.2 gms			
COMPOSITION				369.5 gms			
DISCHARGE RATE				17.3% Fines			
				41.2% Fines			
				1.26 g/min			
				3.08 g/min.			
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ	
10 min	12.2	2.04	-51.2	89.4	2.99	81.9	
20 "	38.0	0.66	17.3	15.6	3.42	-37.6	
30 "	15.5	0.98	-38.0	100.0	3.03	66.6	
40 "	6.4	1.66	-34.4	12.8	2.53	-48.8	
50 "	26.4	0.67	1.87	16.9	2.2	-32.4	
60 "	19.4	0.91	-22.4	20.9	2.1	-16.4	
70 "	26.2	0.76	1.6	18.7	2.37	-25.2	
80 "	32.8	0.67	11.7	22.1	2.50	-11.6	
90 "	26.4	0.90	1.87	10.2	4.98	-59.2	
100 "	51.2	2.63	34.9	8.6	5.85	-65.6	
110 "	5.96	2.37	-76.2	9.3	5.69	-62.8	
120 "	38.9	0.59	18.5	16.1	2.95	-35.6	

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

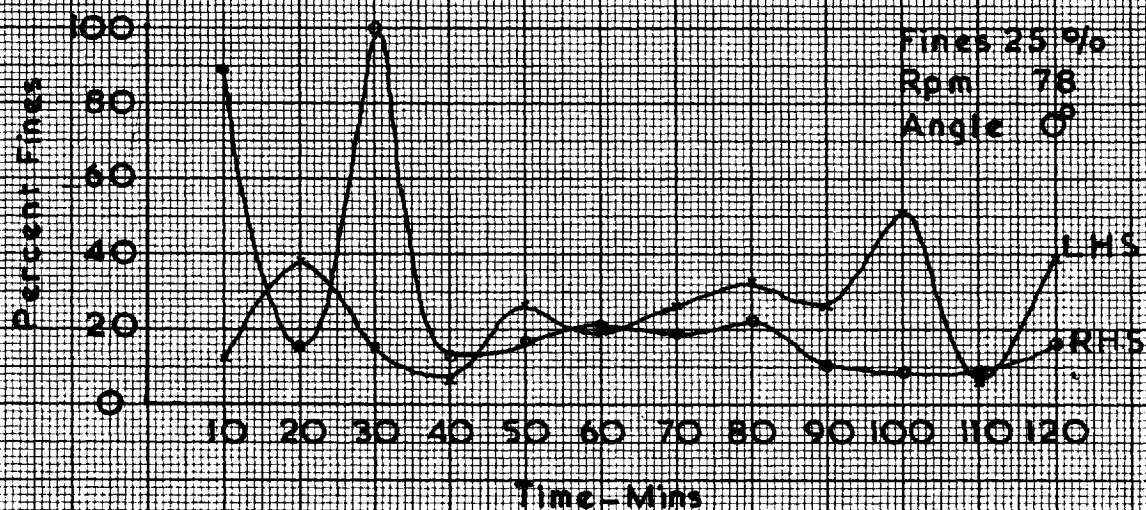
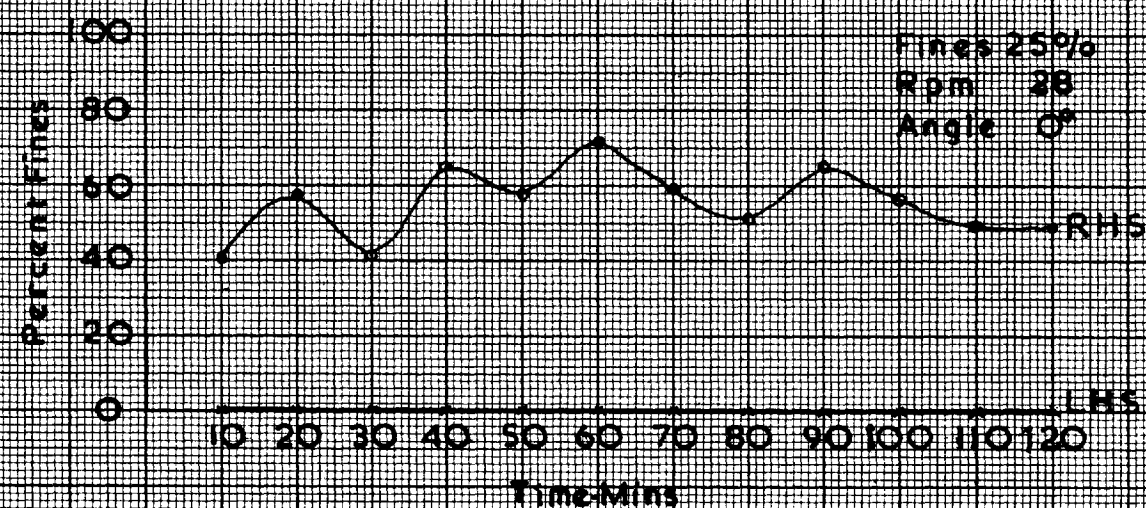
BASE ANGLE OF THE RHS END = 90° 

TABLE XXVIII

ORIGINAL COMPOSITION - 50% FINE, 50% COARSE SAND
END (a) ON R.H.S.

1. RPM.	<u>28</u>
TIME OF RUN	2 HOURS
FEED RATE	3.45 g/min.
MATERIAL RETAINED	365.3 gms
COMPOSITION OF RESIDUAL MATERIAL	83.2% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		403.2 gms		10.03 gms		
COMPOSITION		18.9% Fines		90.0% Fines		
DISCHARGE RATE		3.36 g/min		0.084 g/min.		
TIME	%Fines	g/min	φ	%Fines	g/min	φ
10 min	ZERO	4.42	-100	62.3	0.08	24.6
20 "	"	3.77	-100	100.0	0.04	100.0
30 "	"	3.31	-100	100.0	0.04	"
40 "	"	3.12	-100	96.6	0.30	93.2
50 "	0.098	2.85	-99.8	87.5	0.10	75.0
60 "	1.25	3.04	-97.5	95.2	0.10	90.4
70 "	10.7	3.25	-78.6	96.4	0.13	92.8
80 "	35.8	3.23	-28.4	97.8	0.11	95.6
90 "	57.0	2.91	14.0	98.2	0.12	96.4
100 "	52.7	3.41	5.4	100.0	0.08	100.0
110 "	53.5	3.23	7.0	95.5	0.08	91.0
120 "	58.0	3.12	16.0	93.7	0.08	87.4

Cont...

2. RPM 54
 TIME OF RUN 2 HOURS
 FEED RATE 3.9 g/min.
 MATERIAL RETAINED 425.2 gms
 COMPOSITION OF RESIDUAL MATERIAL 32.0% Fines

LEFT HAND SIDE				RIGHT HAND SIDE.		
TOTAL AMT:COLLECTED		147.3 gms.		320.3 gms		
COMPOSITION		13.5% Fines		82.9 % Fines		
DISCHARGE RATE		1.23 g/min		2.67 g/min.		
TIME	%Fines	g/min	φ	%Fines	g/min	φ
10 min	5.3	4.77	-89.4	98.4	0.6	96.8
20 "	20.6	1.72	-58.8	99.8	0.75	99.6
30 "	4.27	1.92	-91.5	95.2	1.16	90.4
40 "	6.72	2.13	-86.6	92.3	2.67	84.6
50 "	18.01	1.12	-64.0	91.0	3.47	82.0
60 "	18.5	1.18	-63.0	91.3	3.42	82.6
70 "	47.5	0.34	-5.0	91.3	3.47	82.6
80 "	18.75	0.45	-62.5	92.2	3.67	84.4
90 "	14.8	0.41	-70.4	90.3	5.91	80.6
100 "	57.14	0.01	14.3	91.9	3.05	83.8
110 "	2.2	0.73	-95.6	90.3	3.10	80.6
120 "	1.59	0.25	-96.8	90.2	2.76	80.4

3. Run at 78 rpm has been omitted because equilibrium was not attained even after 2 hours.

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

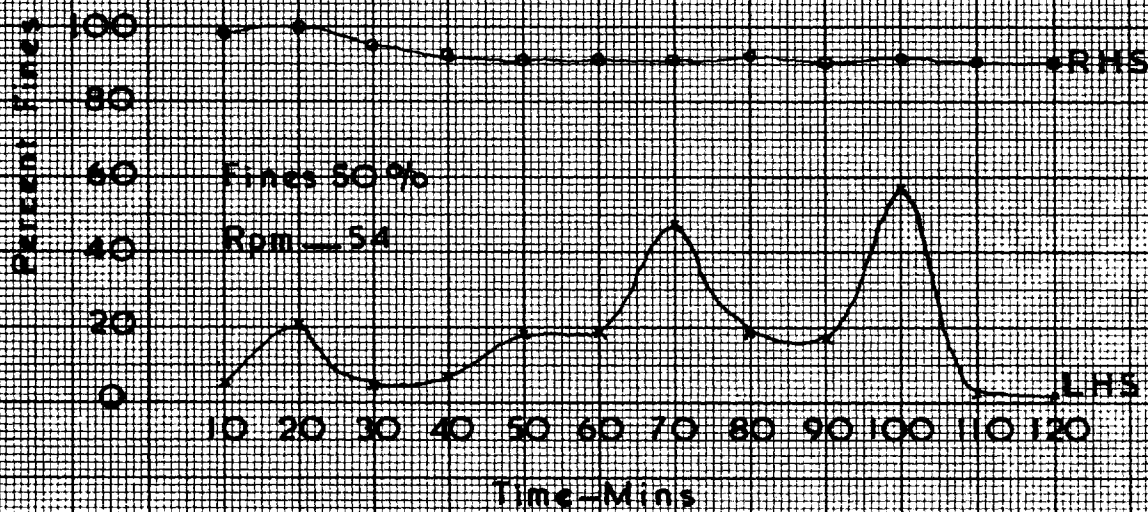
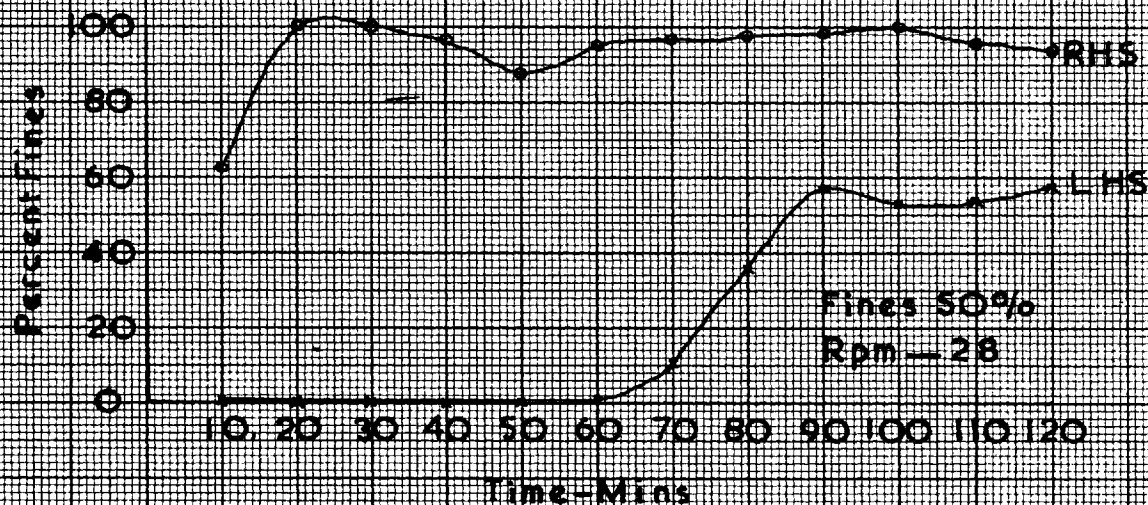
BASE ANGLE OF THE RHS END = 90° 

TABLE XXIX

ORIGINAL COMPOSITION- 75% FINES, 25% COARSE SAND
END (a) ON R.H.S.

1. RPM	<u>28</u>
TIME OF RUN	2 HOURS
FEED RATE	3.5 g/min
MATERIAL RETAINED	373.2 gms
COMPOSITION OF RESIDUAL MATERIAL	89.5% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED				243.7 gms		
COMPOSITION				175.6 gms		
DISCHARGE RATE				38.4% Fines		
				2.03 g/min.		
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ
10 min	0.06	2.78	-99.9	91.9	1.35	67.6
20 "	0.37	2.17	-99.5	95.0	1.38	80.0
30 "	1.18	2.03	-98.4	96.3	1.33	85.2
40 "	8.51	1.93	-88.7	96.7	1.34	86.8
50 "	80.0	2.12	20.0	93.9	1.23	75.6
60 "	64.3	2.29	-14.3	95.4	1.29	81.6
70 "	69.4	1.45	-7.5	96.8	1.0	87.2
80 "	65.4	2.24	-13.0	90.8	2.14	63.2
90 "	61.8	2.60	-17.6	90.9	2.57	63.6
100 "	56.1	2.43	-24.1	91.6	2.16	66.4
110 "	63.5	2.66	-15.3	93.2	2.55	72.8

Cont...

2. RPM	54
TIME OF RUN	2 HOURS
FEED RATE	4.05 g/min.
MATERIAL RETAINED	390.0 gms
COMPOSITION OF RESIDUAL MATERIAL	74.9% Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED		133.6 gms		382.5 gms			
COMPOSITION		15.4% Fines		95.0% Fines			
DISCHARGE RATE		1.114 g/min		2.93 g/min.			
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ	
10 min	100	0.47	100	98.5	3.45	94.0	
20 "	100	0.35	100	98.0	2.89	92.0	
30 "	25.0	0.78	-66.6	95.2	4.26	80.8	
40 "	43.7	0.50	-41.7	95.0	3.60	80.0	
50 "	17.3	1.21	-76.9	94.8	3.80	79.2	
60 "	13.4	1.36	-82.1	95.8	4.44	83.2	
70 "	14.6	1.10	-80.5	93.9	3.69	75.6	
80 "	9.9	2.28	-86.8	94.3	3.41	77.2	
90 "	3.9	1.23	-94.8	94.9	2.61	79.6	
100 "	7.15	1.35	-90.4	94.3	3.12	77.2	
110 "	1.95	2.1	-97.3	93.4	3.53	73.6	
120 "	5.75	1.6	-92.3	92.5	3.36	70.0	

3. Run at 78 rpm has been omitted because equilibrium was not attained even after 2 hours.

Fig(42)

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

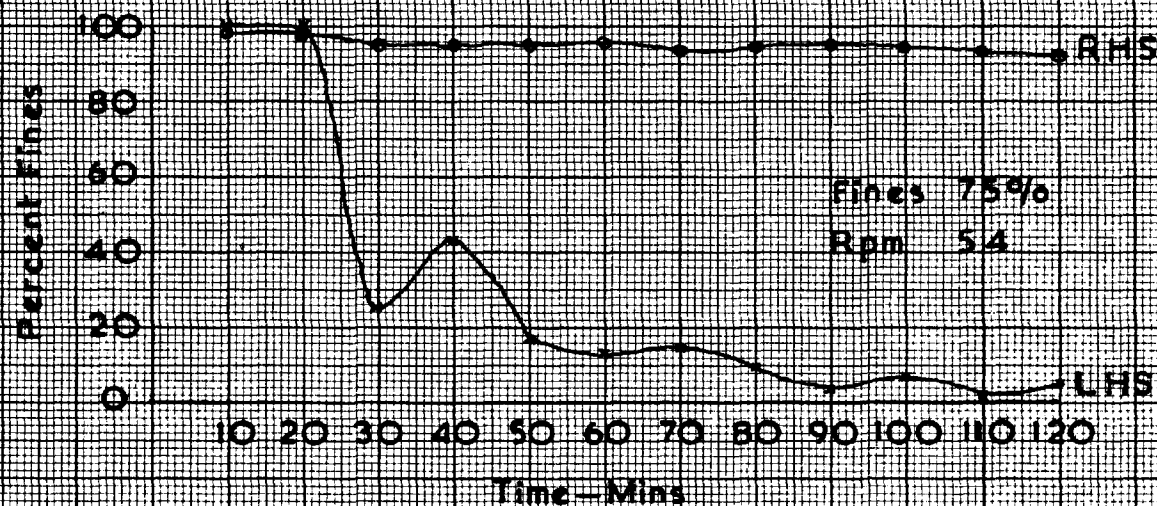
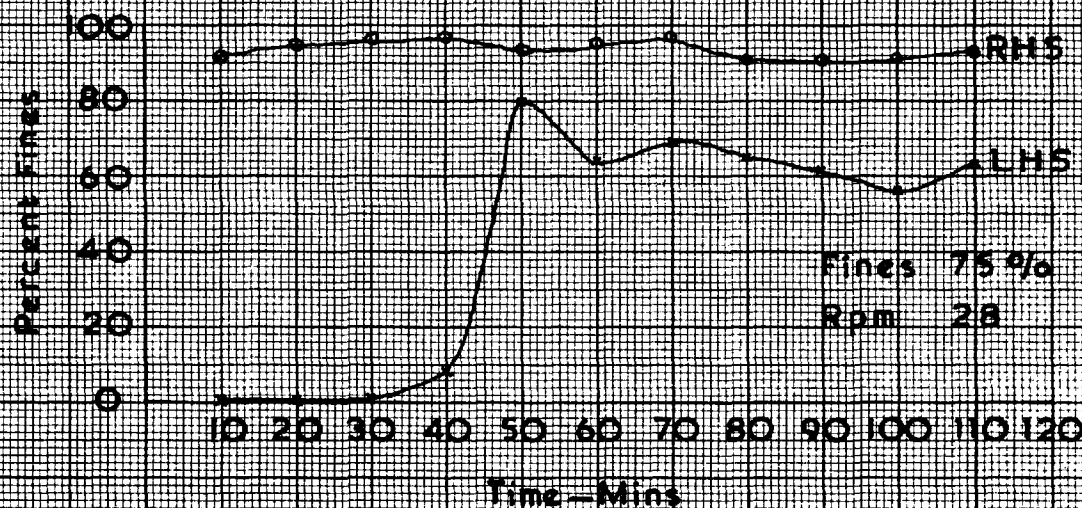
BASE ANGLE OF THE RHS END = 90° 

TABLE XXX

ORIGINAL COMPOSITION 25% FINE, 75% COARSE SAND
END (b) ON R.H.S.

1. RPM	<u>28</u>
TIME OF RUN	2 HOURS 10 MINS.
FEED RATE	4.72 ~~gm~~ /min.
MATERIAL RETAINED	330.8 gms
COMPOSITION OF RESIDUAL MATERIAL	59.2% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		340.72 gms		280.83 gms		
COMPOSITION		13.3% Fines		97.1% Fines		
DISCHARGE RATE		2.62 ~~gm~~ /min		2.1 ~~gm~~ /min.		
TIME	%Fines	~~gm~~ /min	⬇	%Fines	~~gm~~ /min	⬇
10 min.	ZERO	2.96	-100	ZERO	1.34	-100
20 "	ZERO	2.51	-100	ZERO	1.62	-100
30 "	ZERO	2.89	-100	ZERO	1.82	-100
40 "	ZERO	2.87	-100	ZERO	1.85	-100
50 "	ZERO	2.83	-100	ZERO	2.82	-100
60 "	ZERO	2.97	-100	ZERO	2.43	-100
70 "	0.39	3.12	-98.4	ZERO	2.69	-100
80 "	5.0	2.75	-80.0	ZERO	2.57	-100
90 "	50.5	2.40	34.0	ZERO	2.36	-100
100 "	38.6	2.24	18.1	ZERO	2.56	-100
110 "	43.7	1.77	24.9	ZERO	2.20	-100
120 "	33.9	2.32	14.3	ZERO	2.12	-100
130 "	59.8	2.05	46.4	ZERO	3.15	-100

Cont...

2. RPM	54
TIME OF RUN	2 HOURS 10 MINS
FEED RATE	4.13 g/min.
MATERIAL RETAINED	331.8 gms
COMPOSITION OF RESIDUAL MATERIAL	73.5% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED	272.06 gms.			264.18 gms		
COMPOSITION	15.0 % Fines			0.1. Fines		
DISCHARGE RATE	2.1 g/min.			2.03 g/min.		
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ
10 min	ZERO	1.95	-100	ZERO	2.44	-100
20 "	"	1.82	"	"	3.53	"
30 "	"	1.53	"	"	3.17	"
40 "	0.29	1.67	-98.8	"	2.43	"
50 "	0.53	1.29	-97.9	0.18	2.12	-99.3
60 "	0.76	1.63	-96.9	0.24	1.97	-99.1
70 "	1.26	3.13	-95.0	0.28	2.70	-98.9
80 "	5.9	2.28	-36.4	0.73	1.15	-97.1
90 "	19.2	2.09	-23.2	0.39	0.91	-98.4
100 "	37.8	2.31	17.1	0.47	0.84	-98.1
110 "	45.7	2.45	27.6	0.14	1.18	-99.4
120 "	45.1	2.41	26.8	0.06	1.30	-99.8
130 "	51.5	2.47	35.3	0.07	1.72	-99.7

cont....

3. RPM	<u>78</u>
TIME OF RUN	2 HOURS 10 MIN
FEED RATE	3.93 g/min
MATERIAL RETAINED	369.8 gms
COMPOSITION OF RESIDUAL MATERIAL	31.9% Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED		325.46 gms		190.7 gms			
COMPOSITION		37.5% Fines		1.34% Fines			
DISCHARGE RATE		2.5 g/min		1.43 g/min.			
TIME	%Fines	g/min	φ	%Fines	g/min	φ	
10 min	6.41	5.17	-76.4	5.08	0.83	-70.7	
20 "	18.6	2.16	-25.6	8.03	0.49	-67.9	
30 "	15.8	2.27	-36.8	6.35	0.49	-74.6	
40 "	11.6	2.90	-53.6	6.98	0.53	-72.1	
50 "	12.9	3.46	-48.6	0.73	1.60	-97.1	
60 "	27.9	2.29	3.8	0.53	1.20	-97.1	
70 "	25.5	3.46	0.7	0.79	2.02	-96.8	
80 "	99.0	1.77	98.7	0.14	1.41	-99.5	
90 "	98.0	1.74	97.3	0.20	1.63	-99.2	
100 "	62.8	2.60	50.4	0.08	2.91	-99.7	
110 "	99.4	1.62	99.2	0.80	1.30	-96.8	
120 "	75.9	1.71	67.8	0.25	2.07	-99.0	
130 "	81.9	1.52	75.8	0.51	2.33	-98.0	

Fig(43)

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR
BASE ANGLE OF THE RHS END = 75°

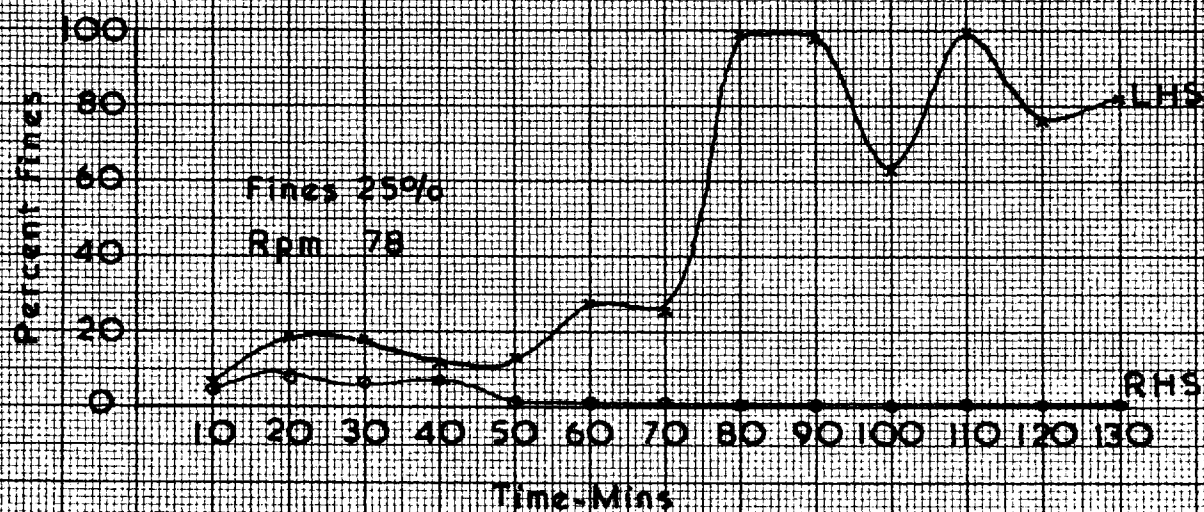
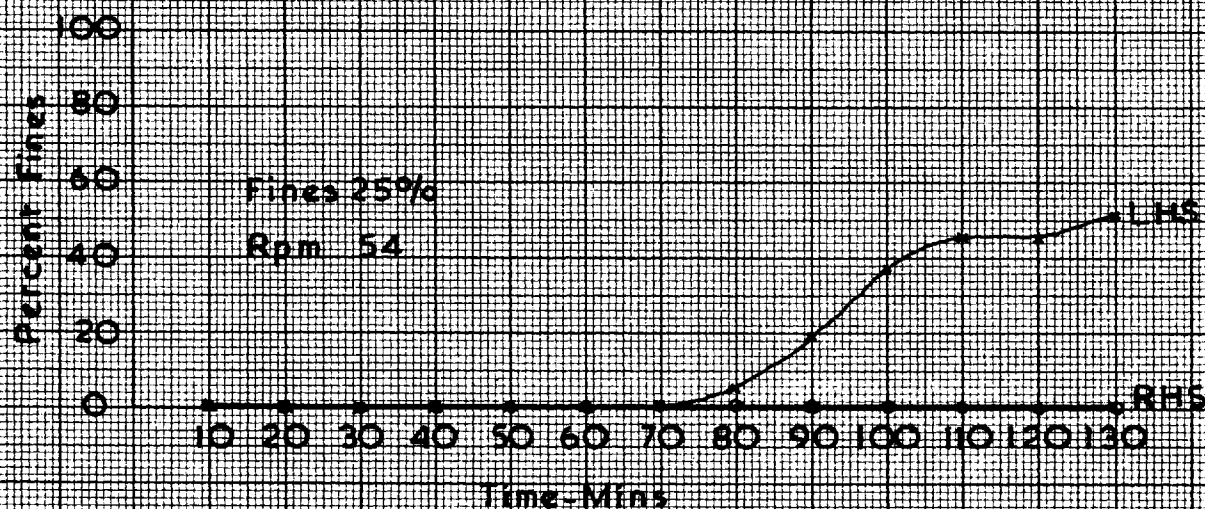
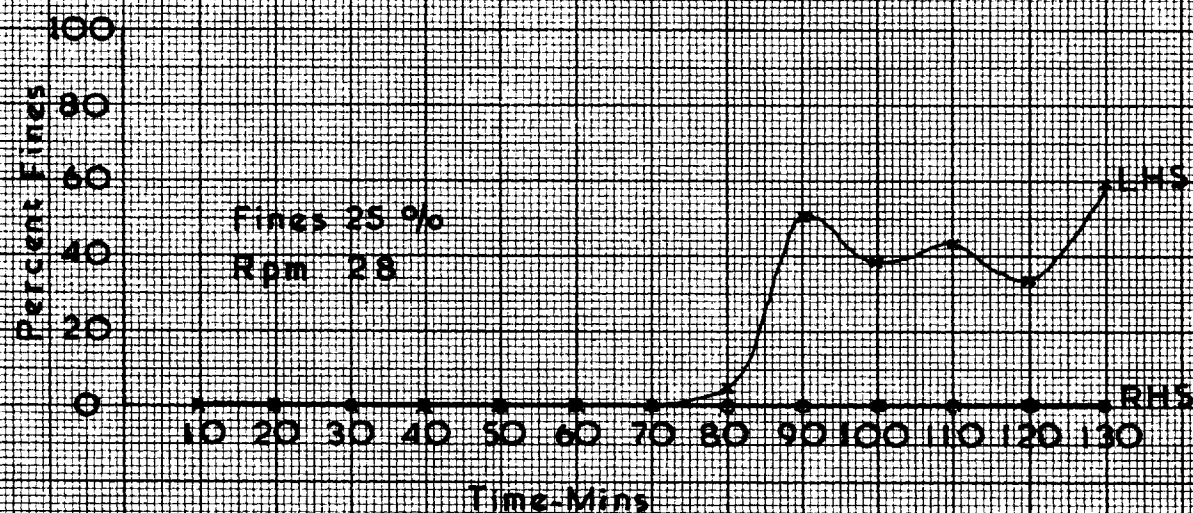


TABLE XXXI

ORIGINAL COMPOSITION 50% FINE, 50% COARSE SAND.

END (b) ON R.H.S

1. RPM	<u>28</u>
TIME OF RUN	2 HOURS 10 MIN
FEED RATE	4.3 g/min
MATERIAL RETAINED	319.8 gms
COMPOSITION OF RESIDUAL MATERIAL	86.0% Fines.

LEFT HADN SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		293.1 gms		265.1 gms		
COMPOSITION		50.0% Fines		10.0% Fines		
DISCHARGE RATE		2.26 g/min		2.04 g/min.		
TIME	%Fines	g/min	ϕ	%Fines	g/min	ϕ
10 min.	ZERO	1.04	-100	ZERO	2.09	-100
20 "	"	2.18	"	"	2.57	"
30 "	"	2.30	"	"	2.08	"
40 "	"	2.47	"	"	2.03	"
50 "	4.27	1.50	-91.5	0.2	2.18	-99.6
60 "	44.8	3.11	-10.4	0.83	2.64	-98.3
70 "	80.0	2.84	60.0	3.42	2.87	-93.2
80 "	87.4	2.63	74.8	22.85	2.06	-54.3
90 "	93.9	2.32	87.8	20.5	2.02	-59.0
100 "	81.5	2.67	63.0	10.0	2.09	-80.0
110 "	99.5	2.37	99.0	23.3	1.27	-53.4
120 "	58.5	2.37	17.0	10.7	2.25	-78.6
130 "	84.7	1.86	69.4	17.6	2.10	-65.2

cont...

2. RPM	54
TIME OF RUN	2 HOURS
FEED RATE	4.1 g/min.
MATERIAL RETAINED	336.8 gms
COMPOSITION OF RESIDUAL MATERIAL	83.2% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED				78.15 gms.		
COMPOSITION				21.0% Fines		
DISCHARGE RATE				0.65 g/min		
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ
10 min	2.35	2.52	-95.3	0.73	0.04	-98.5
20 "	3.41	2.51	-93.2	0.62	0.90	-98.8
30 "	3.96	2.21	-92.1	0.87	0.96	-98.3
40 "	2.31	3.53	-95.4	0.45	1.01	-99.1
50 "	3.77	3.73	-92.5	5.59	1.95	-88.8
60 "	17.2	3.58	-65.6	30.4	0.46	-39.2
70 "	53.7	3.11	7.4	54.6	0.18	9.2
80 "	41.7	3.43	-16.6	46.2	0.46	-7.6
90 "	52.6	4.18	5.2	42.0	0.42	-16.0
100 "	56.4	3.28	12.8	45.0	0.43	-10.0
110 "	45.8	4.94	8.4	34.4	0.88	-31.2
120 "	44.7	4.35	-10.6	37.6	0.90	-24.8

cont...

217.

3. RPM	78
TIME OF RUN	2 HOURS
FEED RATE	3.31 g/min
MATERIAL RETAINED	381.0 gms
COMPOSITION OF RESIDUAL MATERIAL	30.6% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		101.54 gms		295.35 gms		
COMPOSITION		8.2 Fines		89.4 % Fines		
DISCHARGE RATE		0.85 g/min		2.46 g/min.		
TIME	%FINES	g/min	Φ	%Fines	g/min	Φ
10 min	100	.015	100	98.5	3.94	97.0
20 "	"	0.06	"	98.3	2.68	96.6
30 "	"	0.14	"	97.9	2.72	95.8
40 "	"	0.10	"	92.2	2.70	84.4
50 "	11.65	0.914	-67.6	89.9	3.032	79.8
60 "	3.84	1.095	-92.3	82.2	2.02	64.4
70 "	5.7	1.327	-88.6	77.5	1.356	55.0
80 "	1.49	2.904	-97.0	79.7	1.793	59.4
90 "	5.09	0.935	-89.8	86.9	1.306	73.8
100 "	2.48	1.58	-95.0	76.2	2.971	52.4
110 "	3.66	1.528	-92.7	89.4	2.796	79.8
120 "	2.78	1.916	-94.4	84.7	2.884	69.4

Fig(44)

217

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

BASE ANGLE OF THE RHS END = 75°

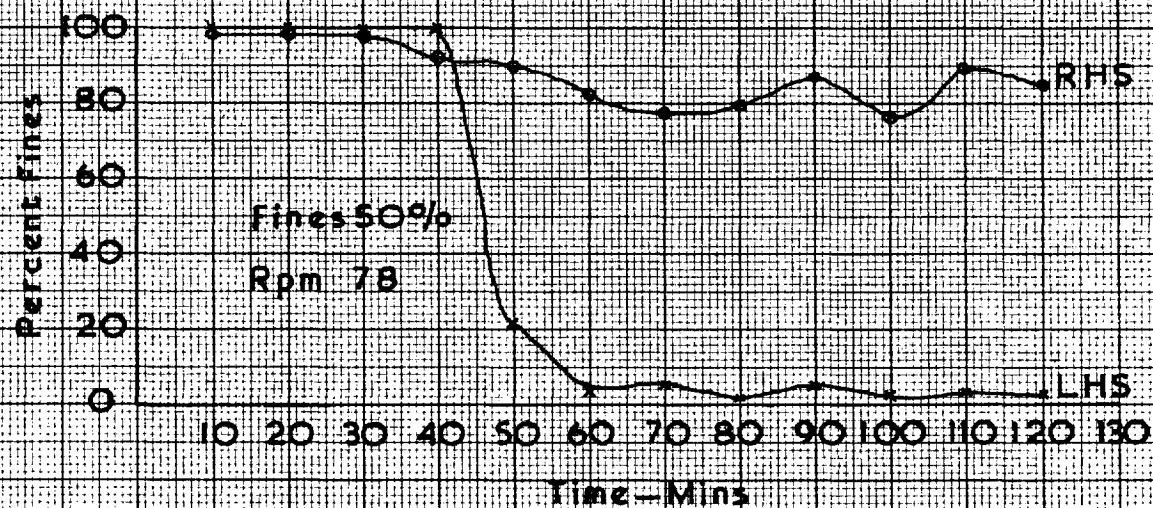
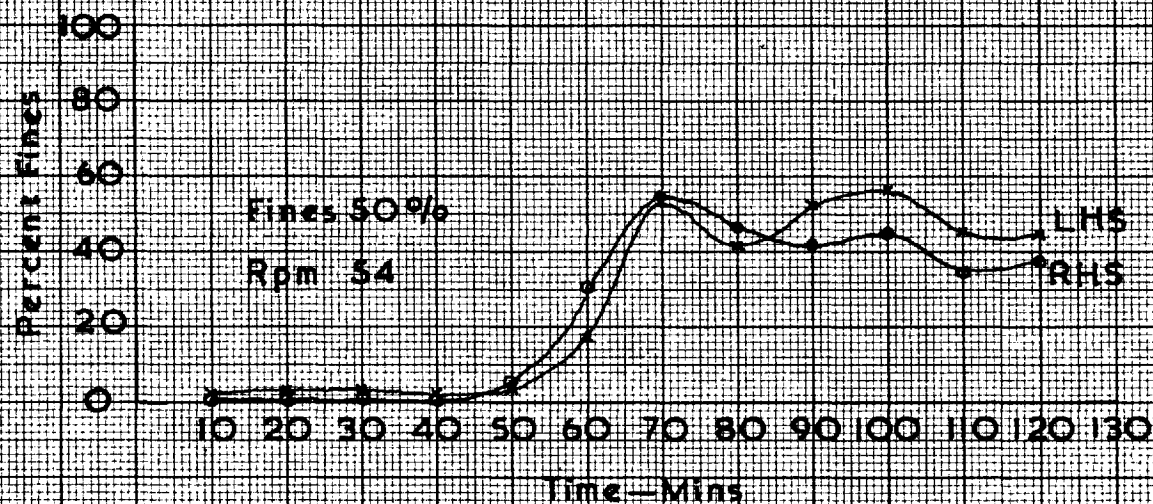
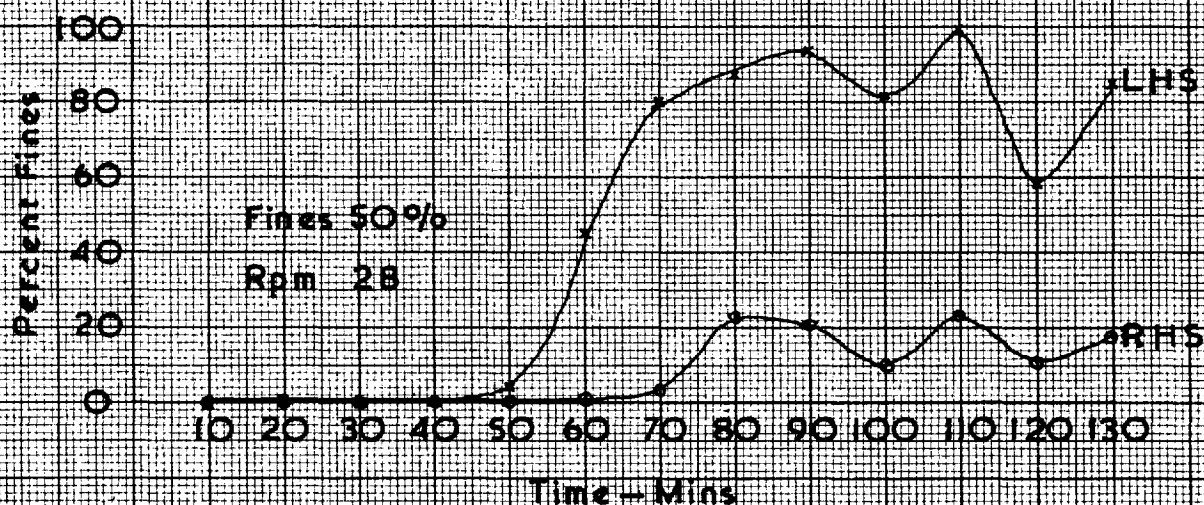


TABLE XXXII

ORIGINAL COMPOSITION. 75% FINE, 25. COARSE SAND,
END (b) ON R.H.S.

1. RPM	<u>28</u>
TIME OF RUN	2 HOURS
FEED RATE	3.63 g/min.
MATERIAL RETAINED	319.8 gms
COMPOSITION OF RESIDUAL MATERIAL	87.8% FINES.

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT: COLLECTED		222.63 gms		212.6 gms.			
COMPOSITION		77.8% Fines		52.3% Fines			
DISCHARGE RATE		1.855 g/min.		1.772 g/min.			
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ	
10 min	16.9	2.70	-77.4	0.25	0.32	-99.7	
20 "	0.18	0.89	-99.8	41.5	2.05	-49.7	
30 "	0.76	1.15	-99.0	72.0	1.81	-4.0	
40 "	5.06	1.48	-93.3	95.5	1.50	82.0	
50 "	52.3	2.19	-30.3	95.5	2.21	82.0	
60 "	62.5	2.66	-16.7	96.3	1.87	85.2	
70 "	58.4	2.19	-22.1	94.2	1.85	76.8	
80 "	66.8	2.30	-12.1	94.0	1.88	76.0	
90 "	68.5	1.47	-8.7	92.8	1.61	71.2	
100 "	65.2	1.82	-18.3	84.0	1.88	36.0	
110 "	61.3	1.88	-18.3	89.3	1.81	57.2	
120 "	63.0	1.67	-16.1	91.5	1.73	66.0	

cont..

2. RPM	<u>54</u>
TIME OF RUN	1 HOUR 10 MINS
FEED RATE	4.06 g/min
MATERIAL RETAINED	336.8 gms
COMPOSITION OF RESIDUAL MATERIAL	86.4% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED	246.64 gms			38.0 gms		
COMPOSITION	64.3%Fines			37.8% Fines		
DISCHARGE RATE	3.523 g/min.			0.543 g/min		
TIME	% FINES	g/min	Φ	%Fines	g/min	Φ
10 Min.	69.0	3.22	-8.0	54.6	0.10	-27.2
20 "	79.4	3.22	17.6	32.9	0.42	-56.1
30 "	33.4	2.84	-55.5	28.3	0.61	-62.2
40 "	61.1	3.07	-14.3	33.6	0.49	-55.2
50 "	81.0	4.51	24.0	35.1	1.38	-53.2
60 "	76.9	3.32	7.6	56.1	0.58	-25.2
70 "	75.0	3.21	ZERO	17.5	0.47	-76.6

3. Run at 78 rpm has been omitted because equilibrium was not attained even after 2 hours.

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

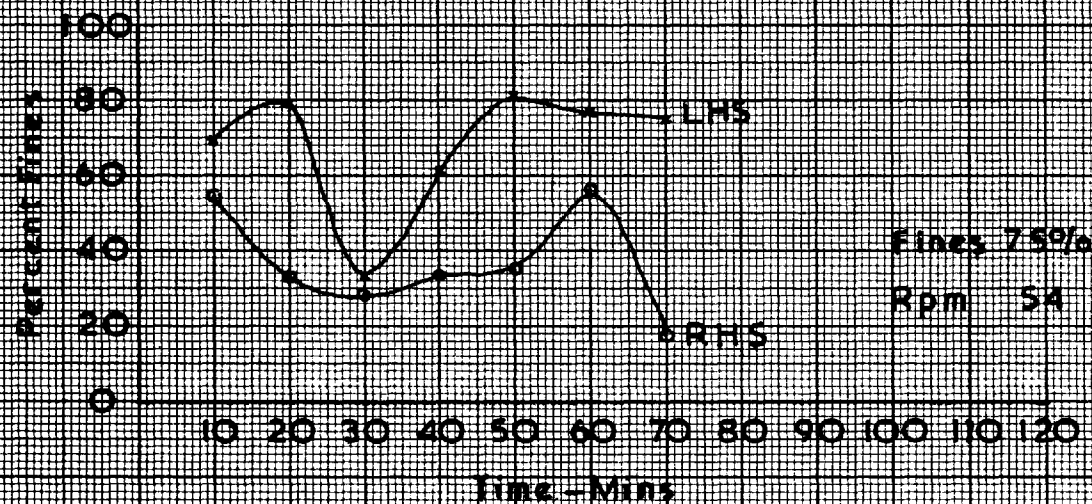
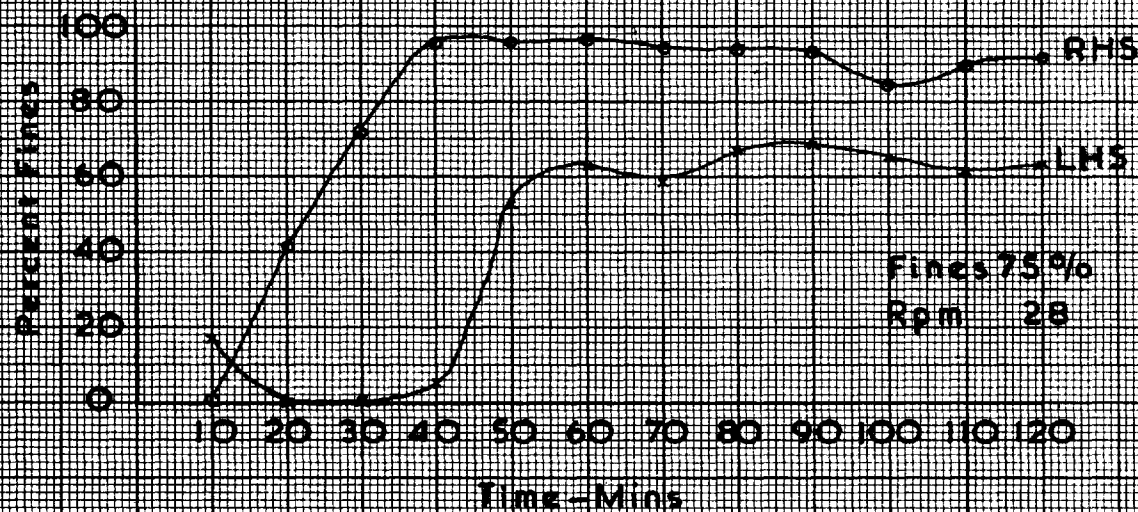
BASE ANGLE OF THE RHS END- 75° 

TABLE XXXIII

ORIGINAL COMPOSITION. 25% FINE, 75% COARSE SAND.

END (c) ON R.H.S.

1. Run at 28 rpm has been omitted because equilibrium was not attained even after two hours.

2. RPM 54
 TIME OF RUN 2 HOURS
 FEED RATE 3.3 ~~gm~~/min
 MATERIAL RETAINED 293.3 gms
 COMPOSITION OF RESIDUAL MATERIAL. 18.8% Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED		191.68 gms		204.0 gms			
COMPOSITION		5.1% Fines		56.7% Fines			
DISCHARGE RATE		1.6 ~~gm~~ /min.		1.7 ~~gm~~ /min.			
TIME	%Fines	~~gm~~ /min	Φ	%Fines	~~gm~~ /min	Φ	
10 min	4.9	1.9	-80.4	100	1.62	100	
20 "	3.6	2.29	-85.6	100	1.70	100	
30 "	2.8	1.81	-88.8	58.5	1.75	44.6	
40 "	5.3	1.04	-78.8	43.9	1.62	25.2	
50 "	0.93	2.30	-96.3	39.4	2.38	19.2	
60 "	1.7	1.43	-93.2	41.6	1.73	22.1	
70 "	1.5	1.53	-94.0	45.8	1.52	27.7	
80 "	0.84	2.06	-96.6	46.1	1.99	28.1	
90 "	0.48	1.91	-98.1	48.7	1.75	31.6	
100 "	0.94	1.28	-96.2	74.7	1.84	66.3	
110 "	0.65	1.72	-97.4	54.0	1.47	38.7	
120 "	1.2	1.39	-95.2	43.5	1.24	24.7	

cont..

3. RPM	<u>78</u>
TIME OF RUN	2 HOURS
FEED RATE	5.58 g/min.
MATERIAL RETAINED	316.8 gms
COMPOSITION OF RESIDUAL MATERIAL	18.2% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED	241.59 gms			429.56 gms		
COMPOSITION	8.3% Fines			40.0% Fines		
DISCHARGE RATE	2.01 g/min.			3.57 g/min.		
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ
10 min	26.0	1.61	1.3	100	0.67	100
20 "	19.0	2.06	-24.0	100	2.21	100
30 "	11.1	2.10	-55.6	39.2	2.65	18.9
40 "	16.0	1.16	-36.0	34.4	2.61	15.2
50 "	8.3	1.57	-66.8	40.1	3.39	20.1
60 "	7.5	1.63	-70.0	68.6	3.85	58.1
70 "	3.8	1.96	-84.8	37.8	3.88	17.1
80 "	4.9	1.75	-80.4	34.2	3.59	15.2
90 "	10.6	1.56	-57.6	35.7	3.95	14.3
100 "	1.1	2.48	-95.6	23.2	3.31	-7.2
110 "	2.5	1.83	-90.0	38.8	3.75	18.4
120 "	5.4	1.48	-78.4	35.6	3.93	14.1

Fig (46)

24

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

BASE ANGLE OF THE RHS END - 50°

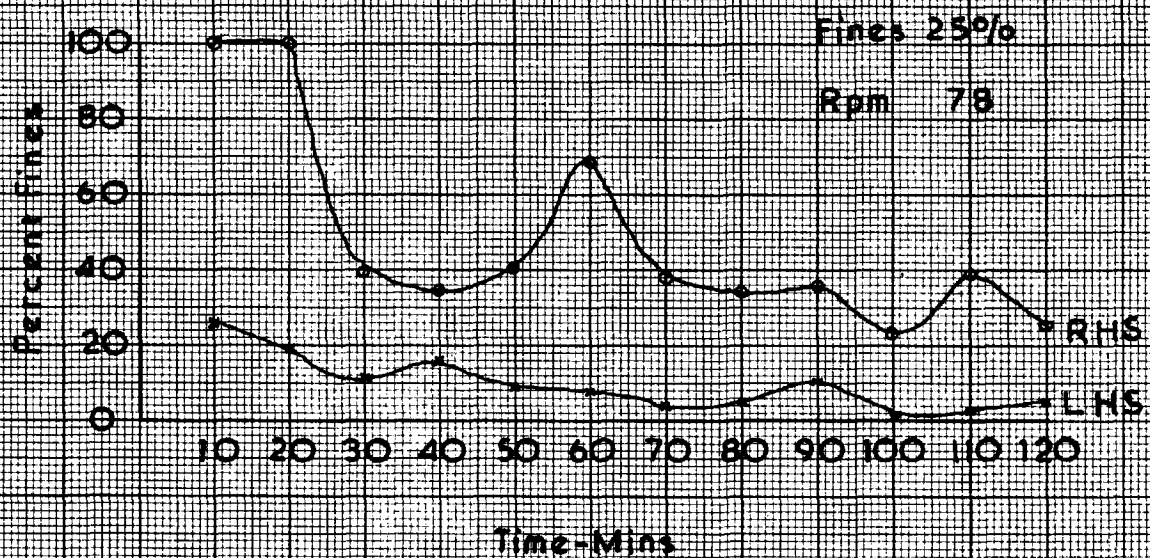
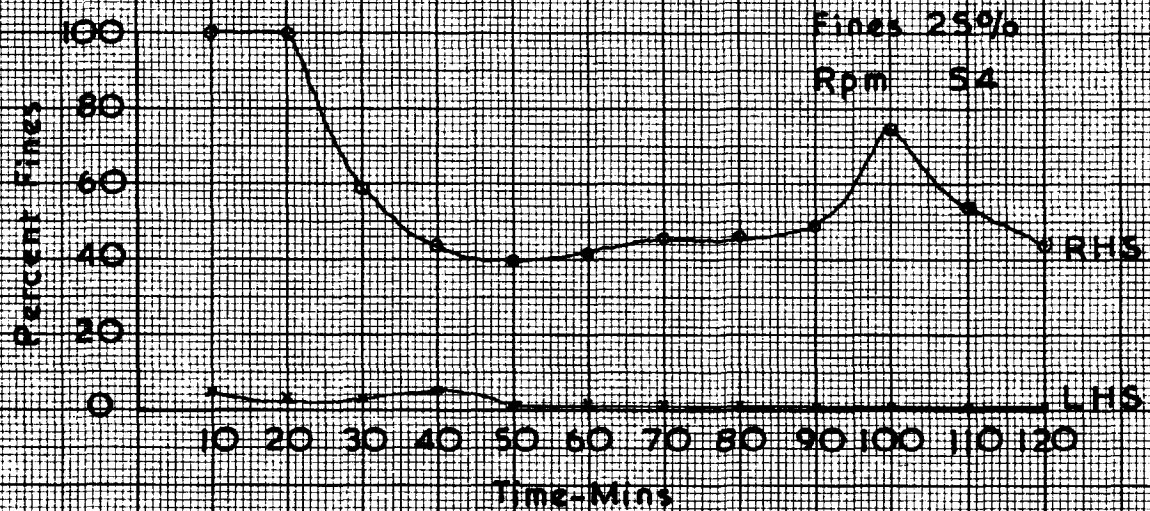


TABLE XXXIV

ORIGINAL COMPOSITION. 50% FINE, 50% COARSE SAND,
END (c) ON R.H.S.

1. RPM	<u>28</u>
TIME OF RUN	2 HOURS 5 MINS
FEED RATE	5.03 g/min.
MATERIAL RETAINED	272.0 gms.
COMPOSITION OF RESIDUAL MATERIAL.	48.5% Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED		61.89 gms		566.78 gms.			
COMPOSITION		15.6% Fines		48.6% Fines			
DISCHARGE RATE		0.495 g/min.		4.53 g/min.			
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ	
10 min	27.2	0.42	-45.6	58.5	2.43	17.0	
20 "	22.3	0.36	-55.4	69.8	4.78	39.6	
30 "	8.95	0.68	-82.0	41.7	4.39	-16.6	
40 "	13.4	0.53	-73.2	54.2	3.53	8.4	
50 "	28.1	0.23	-43.8	49.3	4.33	-3.4	
60 "	22.0	0.34	-56.0	48.1	4.68	-3.8	
70 "	35.5	0.11	-29.0	50.2	4.73	0.4	
80 "	45.4	0.11	-9.2	55.2	4.29	10.4	
90 "	27.8	0.19	-44.4	54.5	4.44	9.0	
100 "	37.8	0.13	-24.4	47.8	5.06	-4.4	
110 "	32.6	0.17	-34.8	54.1	4.59	8.2	
120 "	12.8	0.25	-74.4	40.8	5.42	-18.4	

cont...

2. RPM 54
 TIME OF RUN 1 HOUR 1 MIN
 FEED RATE 3.59 g/min
 MATERIAL RETAINED 291.8 gms
 COMPOSITION OF RESIDUAL MATERIAL 29.5% Fines.

LEFT HAND SIDE					RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		46.0 gms			172.88 gms		
COMPOSITION		5.5% Fines			96.3% Fines		
DISCHARGE RATE		0.754 g/min			2.84 gms/min.		
TIME	%Fines	g/min	Φ		%Fines	g/min	Φ
10 min	2.37	0.17	-95.3		99.7	3.252	99.4
20 "	2.33	0.395	-95.3		100	2.436	100
30 "	2.22	0.90	-95.6		"	2.889	"
40 "	2.06	1.032	-95.9		"	2.313	"
50 "	3.1	1.46	-93.8		"	2.513	"
60 "	0.32	4.11	-99.4		"	2.733	"

cont..

3. RPM	<u>78</u>
TIME OF RUN	ONE HOUR
FEED RATE	4.06 g/min
MATERIAL RETAINED	319.0 gms
COMPOSITION OF RESIDUAL MATERIAL	22.2% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		75.21 gms		168.83 gms		
COMPOSITION		16.6% Fines		100.0%Fines		
DISCHARGE RATE		1.25 g/min.		2.81 gms/min		
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ
5 min	100	0.04	100	100	3.94	100
10 "	11.9	3.04	-76.2	"	2.35	"
15 "	24.5	1.24	-51.0	"	1.63	"
20 "	34.0	0.91	-32.0	"	1.94	"
25 "	8.3	3.04	-83.4	"	3.24	"
30 "	9.4	2.13	-81.2	"	2.31	"
35 "	7.3	2.46	-85.4	"	2.66	"
40 "	8.2	1.30	-83.6	"	1.84	"
45 "	7.2	1.22	-85.6	"	2.35	"
50 "	4.7	1.65	-90.6	"	2.39	"
55 "	3.5	1.82	-93.0	"	2.67	"

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

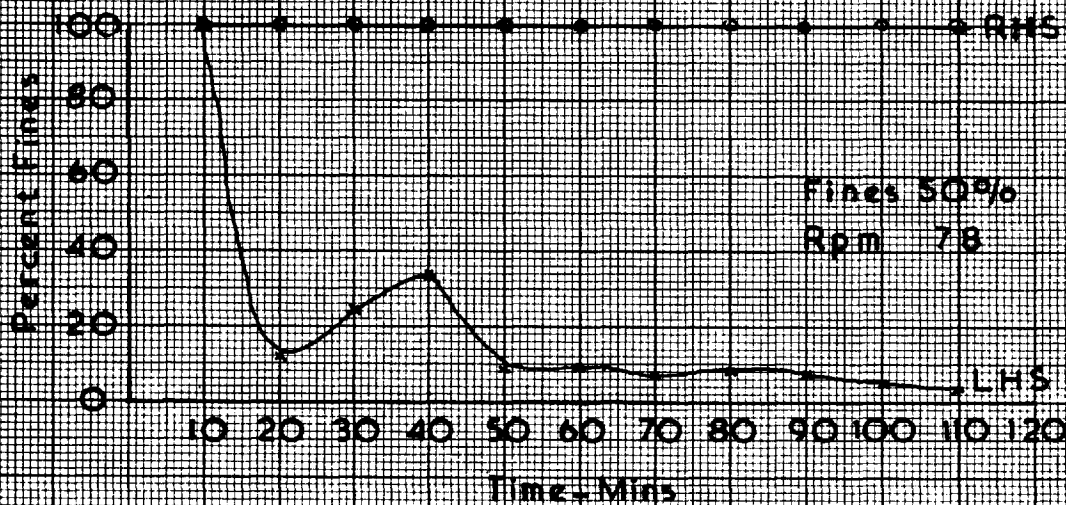
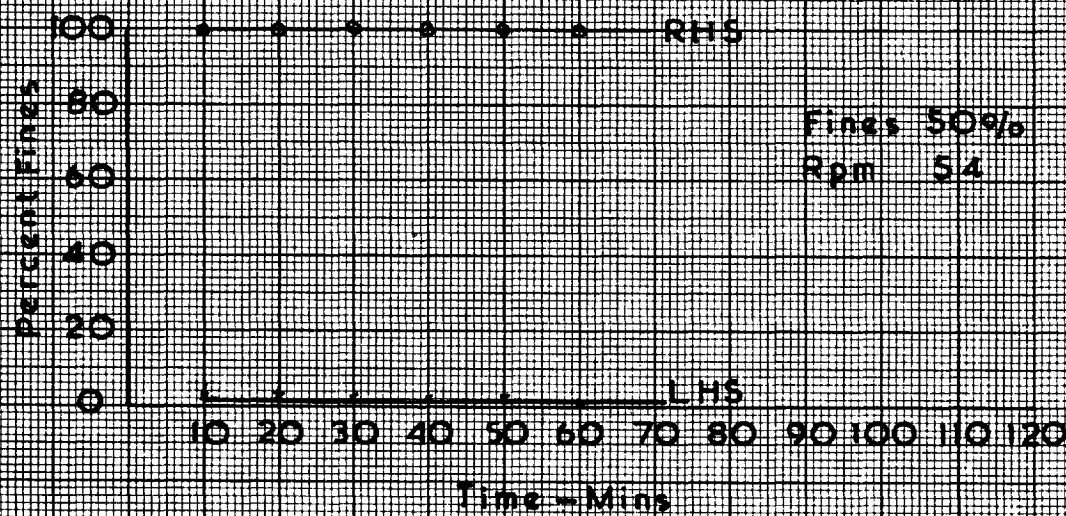
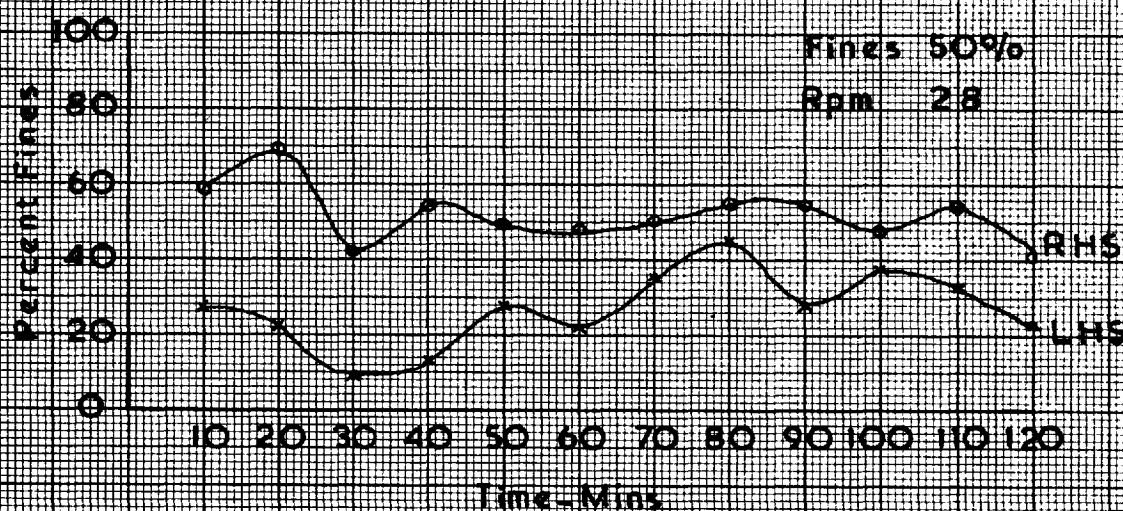
BASE ANGLE OF THE RHS END = 50° 

TABLE XXXV

ORIGINAL COMPOSITION - 75% FINE, 25% COARSE SAND,
END (c) on R.H.S

1. RPM	<u>28</u>
TIME OF RUN	2 HOURS
FEED RATE	3.14 g/min
MATERIAL RETAINED	263.8 gms
COMPOSITION OF RESIDUAL MATERIAL.	83.4% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		198.5 gms		178.32 gms		
COMPOSITION		75.4% Fines		62.2% Fines		
DISCHARGE RATE		1.654 g/min		1.486 g/min.		
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ
10 min	7.0	2.82	-90.7	36.7	2.60	-51.1
20 "	91.7	1.43	66.8	70.9	1.37	-5.5
30 "	93.0	1.57	72.0	78.9	1.52	15.6
40 "	91.5	1.47	66.0	56.9	1.57	-24.2
50 "	93.7	1.55	74.8	87.3	1.21	9.2
60 "	96.5	1.39	86.0	83.3	0.91	33.2
70 "	86.0	1.75	44.0	59.4	0.51	-20.8
80 "	98.2	1.29	92.8	91.5	0.61	66.0
90 "	89.5	1.56	58.0	79.9	1.08	19.6
100 "	83.2	1.78	32.8	60.8	1.73	-18.9
110 "	86.6	1.71	46.4	85.2	1.34	20.4
120 "	90.3	1.64	61.2	65.2	1.81	-12.2

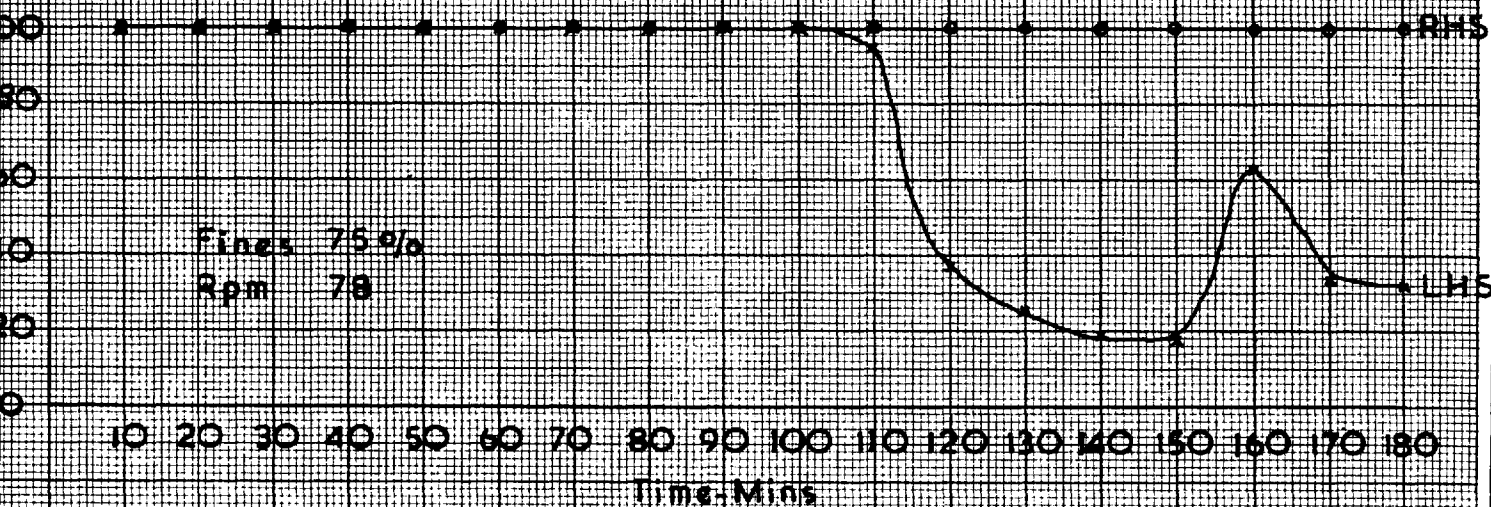
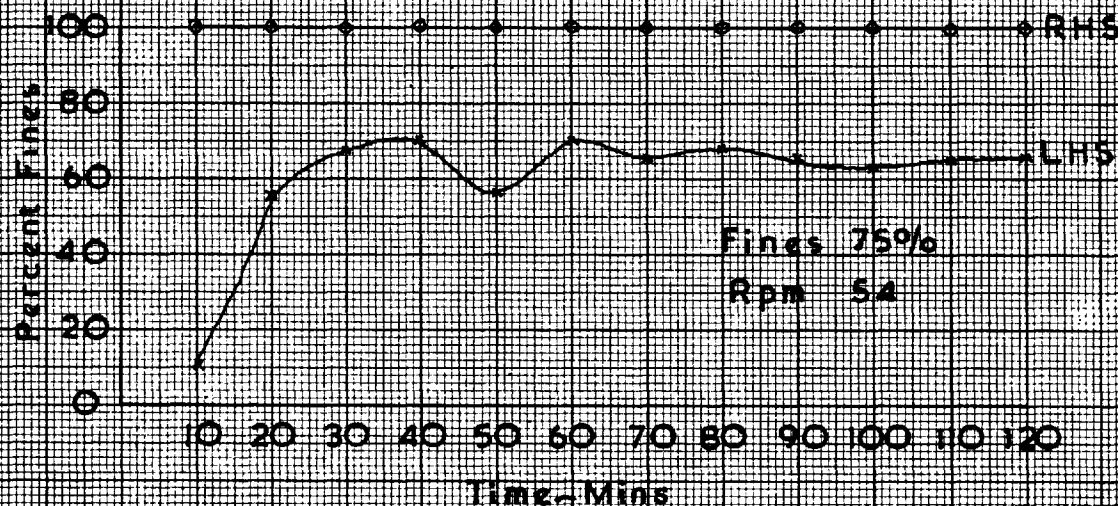
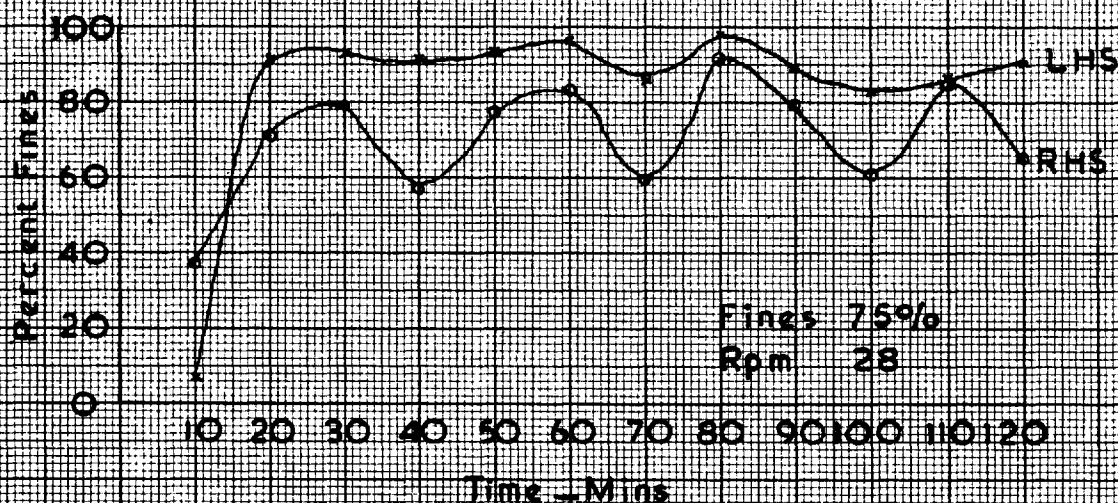
2. RPM	<u>54</u>
TIME OF RUN	2 HOURS
FEED RATE	5.83 g/min
MATERIAL RETAINED	272.8 gms
COMPOSITION OF RESIDUAL MATERIAL	81.1% Fines

LEFT HAND SIDE					RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		207.2 gms			492.2 gms		
COMPOSITION		100% Fines			56.1% Fines		
DISCHARGE RATE		1.73 g/min			4.1 g/min.		
TIME	%Fines	g/min	Φ		%Fines	g/min	Φ
10 min	100	1.98	100		10.7	5.09	-85.7
20 "	"	1.39	"		55.6	4.21	-25.9
30 "	"	1.28	"		67.5	3.69	-10.0
40 "	"	1.32	"		70.3	3.44	-6.3
50 "	"	1.86	"		56.3	4.44	-24.9
60 "	"	1.496	"		70.0	3.396	-6.7
70 "	"	1.774	"		65.4	3.928	-12.8
80 "	"	2.24	"		68.1	4.228	-9.2
90 "	"	1.946	"		65.5	4.012	-12.7
100 "	"	2.058	"		63.2	4.768	-15.7
110 "	"	1.712	"		65.2	3.764	-13.1
120 "	"	1.77	"		65.9	3.917	-12.1

3. RPM	<u>78</u>
TIME OF RUN	3 HOURS
FEED RATE	4.36 g/min
MATERIAL RETAINED	307.8 gms
COMPOSITION OF RESIDUAL MATERIAL	24.0% Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED		131.31 gms		653.69 gms.			
COMPOSITION		64.2% Fines		100% Fines			
DISCHARGE RATE		0.73 g/min		3.63 g/min.			
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ	
10 min	100	2.88	100	100	0.90	100	
20 "	"	2.61	"	"	2.06	"	
30 "	"	1.05	"	"	3.88	"	
40 "	"	0.08	"	"	3.90	"	
50 "	"	0.04	"	"	3.89	"	
60 "	"	0.01	"	"	4.75	"	
70 "	"	0.03	"	"	4.41	"	
80 "	"	0.04	"	"	4.36	"	
90 "	"	0.05	"	"	4.52	"	
100 "	"	0.10	"	"	5.04	"	
110 "	94.7	1.60	78.8	"	3.33	"	
120 "	37.0	0.56	-44.0	"	2.98	"	
130 "	25.5	1.03	-66.0	"	3.96	"	
140 "	18.7	1.14	-75.1	"	3.79	"	
150 "	17.5	1.02	-76.7	"	4.01	"	
160 "	62.7	0.46	-16.4	"	3.75	"	
170 "	33.4	0.61	-55.5	"	3.71	"	
180 "	31.9	0.56	-57.5	"	3.61	"	

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

BASE ANGLE OF THE RHS END = 50° 

occur in the form of alternate bands of fine and coarse material, the number of bands being a function of the length of the vessel and speed of rotation. It has so far not been possible to predict whether the end band will be of coarse or fine material and hence it may be expected that under one set of conditions, the discharge may be predominantly fine from one end, whilst at the other end only ^{will} partial segregation have occurred; ~~and~~ ^{set of} under another conditions, the discharge from one end will be wholly fine material and at the other end wholly coarse material. The latter condition however can only arise when the magnitude ^{and composition} of the two individual discharges ^{weight and} corresponds with the composition of the feed material. It is therefore a function of the speed of the vessel. It is not always easy to disentangle these various effects and until further work is done, there will be a degree of empiricism about the method of working.

Now we turn to Table (XXVII), in which are recorded the data for a mixture of 25 percent fines rotated in vessel (a), it will be seen that at a speed of rotation of 28 rpm coarse material only is discharged from ^{the} left hand end of the vessel, whilst from the right

hand end, the relatively small discharge consists of an approximately 50:50 mixture of coarse and fine particles. At 54 rpm, coarse material only is discharged at the left hand end, and a 9:1 fine material from the right hand end. At 78 rpm, no complete separation occurs at either end.

With a 50:50 mixture, (Table XXVIII), the time required for the attainment of stable conditions is longer than that in the previous series and a complete separation is not found at any of ^{the} three speeds. At 54 rpm, however, the right hand discharge consists predominantly of fine material, the degree of segregation ranging from 80.4 to 99.6. With a 75:25 mixture, (Table XXIX) the right hand discharge at both 28 and 54 rpm consists of almost completely separated fine material, whilst the left hand discharge is only partially separated.

The results for vessel (b) in which the two cones have equal angle are given in Tables XXX - XXXII and Fig; (43-45). The symmetry of the vessel results in a much longer time being required for the attainment of equilibrium; and it is doubtful whether even after

2 hours conditions were stable. For none of the three mixtures was a complete separation obtained but for the 25:75 and 50:50 mixtures, the right hand discharge consisted of nearly pure fines.

The results for vessel (c) in which the angle of the right hand cone exceeded the dynamic angle of repose of the feed material, are given in Tables XXXIII - XXXV and Fig. (46-48). In this series, complete separation is only obtained for a 50:50 mixture at 54 rpm. The separation of coarse material however, is nearly complete in the left hand discharge of a 25:75 mixtures at 54 and 78 rpm and of a 75:25 mixture at 54 rpm.

The results for vessel (d) are given in table XXXVI and Fig. (49) and show that a high degree of separation is only found with a 25:75 mixture at 54 rpm. The experiments with this vessel, however, are incomplete and no firm conclusions can be based upon them.

MATERIAL BALANCE

In view of variations in feed rate in the experiments described above, it was thought desirable to check a few of the results by a material balance.

TABLE XXXVI
HORIZONTAL CYLINDER.

1. ORIGINAL COMPOSITION	25% Fines, 75% Coarse
RPM	<u>54</u> Sand
TIME OF RUN	1 HOUR 40 MINS
MATERIAL RETAINED	726.4 gms
COMPOSITION OF RESIDUAL MATERIAL	14.95% Fines
FEED RATE	4.0 g/min.

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED		191.5 gms		208.0 gms			
COMPOSITION		83.0% Fines		8.7% Fines			
DISCHARGE RATE		1.915 g/min.		2.09 g/min.			
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ	
10 min	89.9	1.66	86.5	100	1.09	100	
20 "	86.5	3.40	82.0	92.8	0.91	90.4	
30 "	83.1	5.18	77.5	77.2	0.92	69.6	
40 "	59.4	2.84	45.8	2.13	3.70	-91.5	
50 "	90.0	1.67	86.7	0.52	2.10	-97.9	
60 "	90.4	1.67	87.2	0.37	2.92	-98.5	
70 "	93.5	1.25	91.3	0.32	2.73	-98.7	
80 "	92.9	1.42	90.5	0.36	3.02	-98.6	
90 "	92.0	1.53	89.3	0.25	3.03	-99.0	
100 "	91.2	1.37	90.9	0.25	2.73	-99.0	

cont...

2. ORIGINAL COMPOSITION	50% FINE, 50% COARSE SAND
RPM	<u>54</u>
TIME OF RUN	2 HOURS 40 MINS
FEED RATE	4.72 g/min
MATERIAL RETAINED	757.9 gms
COMPOSITION OF RESIDUAL MATERIAL	17.4% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		569.6 gms		185.8 gms		
COMPOSITION		82.0%Fines		80.7% Fines		
DISCHARGE RATE		3.56 g/min.		1.16 g/min		
TIME	%Fines	g/min	φ	%Fines	g/min	φ
0 Min	87.3	4.99	74.6	94.3	2.10	88.6
20 "	86.4	3.40	72.8	92.5	1.45	85.0
40 "	83.0	4.12	66.0	95.9	1.15	91.8
60 "	86.5	3.39	73.0	99.3	0.90	98.6
80 "	90.5	2.47	81.0	96.7	0.79	93.4
100 "	84.5	3.40	69.0	85.2	0.88	70.4
120 "	76.8	3.26	53.6	69.5	1.23	39.0
140 "	62.6	3.19	25.2	42.7	2.31	-14.6
160 "	55.5	3.10	11.0	37.4	2.37	-24.8

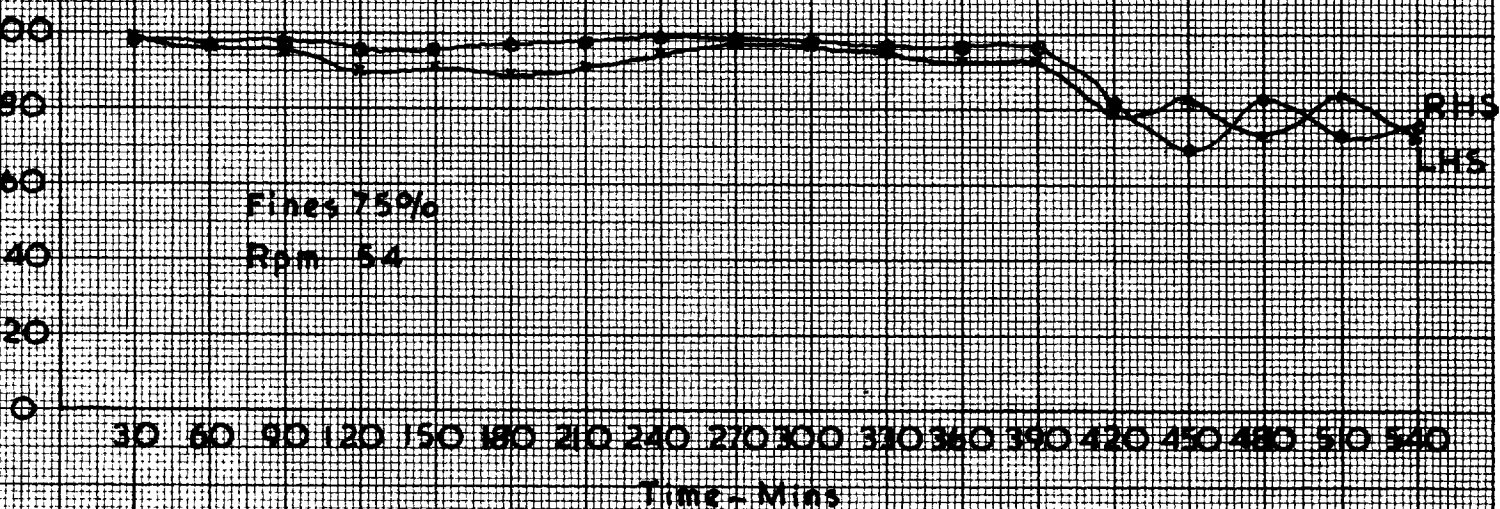
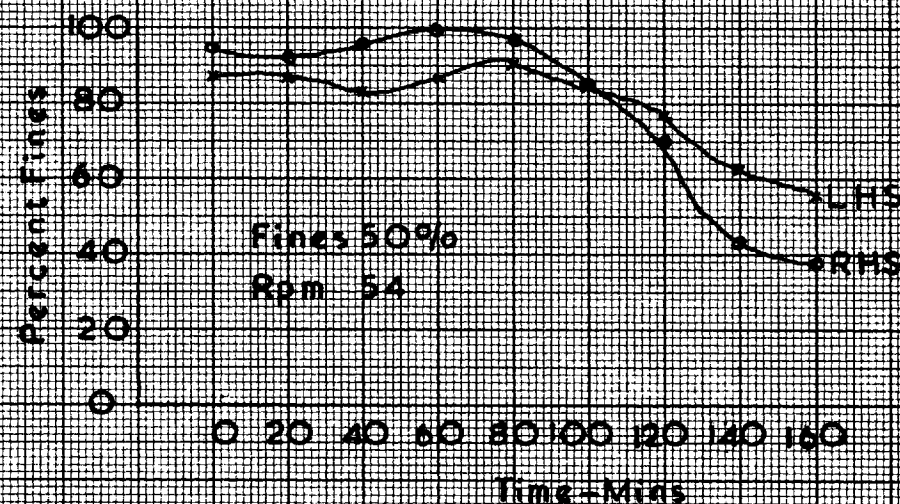
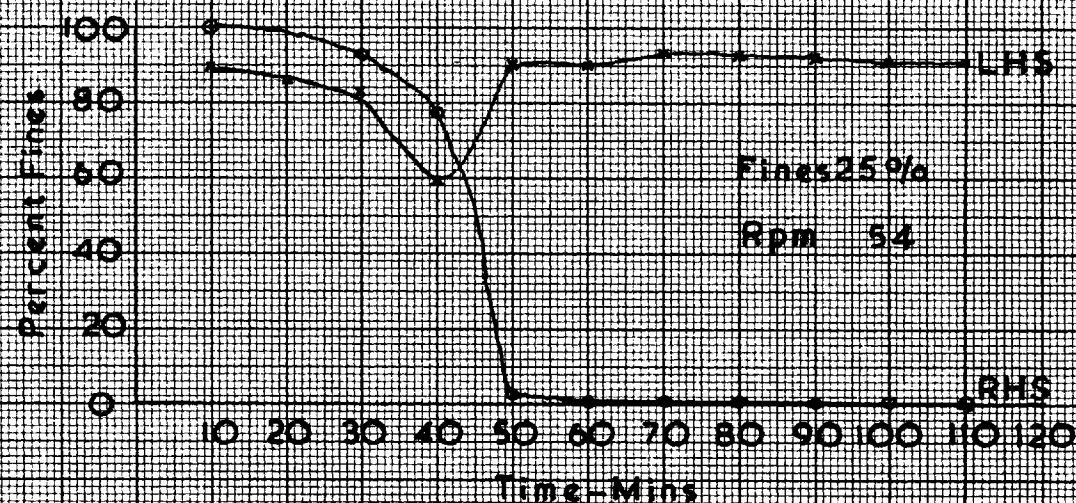
cont..

3. ORIGINAL COMPOSITION	75% FINE, 25% COARSE SAND
RPM	<u>54</u>
TIME OF RUN	9.0 HOURS
FEED RATE	4.7 g/min.
MATERIAL RETAINED	758.0 gms
COMPOSITION OF RESIDUAL MATERIAL	18.0% Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT:COLLECTED		1797.14 gms		741.4 gms.			
COMPOSITION		91.0% Fines		85% Fines			
DISCHARGE RATE		3.33 g/min		1.37 g/min			
TIME	%Fines	g/min	⊕	%Fines	g/min	⊕	
30 min	99.3	2.41	97.2	98.1	2.37	92.4	
60 "	96.0	2.85	84.0	96.9	1.53	87.6	
90 "	95.0	2.53	80.0	97.7	0.86	91.8	
120 "	90.0	3.26	60.0	95.6	1.60	82.4	
150 "	91.6	4.18	66.4	96.0	1.30	84.0	
180 "	89.4	5.47	57.6	96.9	1.42	87.6	
210 "	91.5	4.21	66.0	97.3	1.51	89.2	
240 "	95.2	3.25	80.8	99.0	0.74	96.0	
270 "	96.9	2.98	87.6	99.2	0.93	96.8	
300 "	96.5	2.79	86.0	98.2	1.02	92.8	
330 "	95.0	2.46	80.0	96.9	0.69	87.6	
360 "	93.2	2.01	72.8	96.3	0.59	85.2	
390 "	93.2	2.01	72.8	96.3	0.59	85.2	
420 "	78.7	2.38	15.0	81.9	1.78	27.6	
450 "	82.5	2.05	30.0	69.3	1.12	-7.6	
480 "	72.9	3.13	-2.8	82.2	3.46	28.8	
510 "	83.8	1.65	35.2	72.8	1.04	-2.9	
540 "	71.8	2.54	-4.3	74.7	1.74	-0.4	

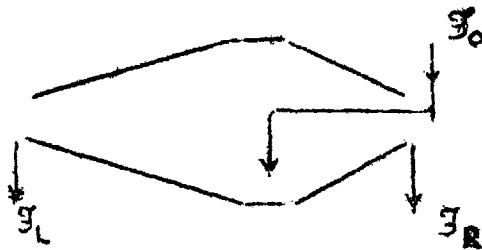
Fig (49)

HORIZONTAL CYLINDER
COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR
BASE ANGLE OF THE RHS END 90°



The continuous stream of the feed material flows out at either end of the vessel after passing through a process of separation. As there is no accumulation of material taking place, at ^{the} steady state the amount of feed per unit time should be numerically equal to the sum of the discharge rates of material at either end of the apparatus.

In other words,



$$F = W_L + W_R \quad (26)$$

where F Feed rate (gms/min)

W_L = Rate of discharge of material at L.H.S., and

W_R = Rate of discharge of material at R.H.S.

Taking into consideration the composition of ^{of the} the feed and two outflowing stream of particles, the overall material balance is given by

$$F \cdot \mathcal{F}_0 = W_L \cdot \mathcal{F}_L + W_R \cdot \mathcal{F}_R \quad (27)$$

Where $\mathcal{F}_o$, $\mathcal{F}_L$, and $\mathcal{F}_R$ is the composition in terms of percent of fines of the original mixture and of the streams coming out at LHS and R.HS of the apparatus respectively.

Substituting for F from (26) and rearranging we get

$$W_L (\mathcal{F}_o - \mathcal{F}_L) = W_R (\mathcal{F}_o - \mathcal{F}_R). \quad (28)$$

At equilibrium, this equation should hold true. In the accompanying 3 sets of calculations, it has been proved that at steady state L.H.S in equation (28) is equal to R.HS.

(1) Data taken from Table XXVII. Last 6 analysis of samples in the experiment performed at 54 rpm -
Composition 25% fines.

LHS				RHS			
W_L	$\mathcal{F}_L$	$\mathcal{F}_O - \mathcal{F}_L$	$W_L (\mathcal{F}_O - \mathcal{F}_L)$	W_R	$\mathcal{F}_R$	$\mathcal{F}_O - \mathcal{F}_R$	$W_R (\mathcal{F}_O - \mathcal{F}_R)$
1. 2.149	0.131	24.869	53.5	1.731	95.0	70.0	121.3
2. 2.424	0.198	24.802	60.2	1.431	98.0	73.0	104.4
3. 2.087	0.441	24.559	51.2	1.334	96.5	71.5	95.3
4. 2.921	0.096	24.904	87.3	1.777	88.4	63.4	113.6
5. 3.223	0.124	24.876	84.7	1.012	93.7	68.7	69.6
6. 2.154	0.502	24.498	52.7	0.827	93.9	68.9	57.0

The values of $W_L (\mathcal{F}_O - \mathcal{F}_L)$ and $W_R (\mathcal{F}_O - \mathcal{F}_R)$ approach each other eventually becoming equal at equilibrium.

(2) Data taken from Table XXXI. Last 6 analysis of samples in an experiment performed at 78 rpm. Original Composition 50% fines.

LHS				RHS			
W_L	$\mathcal{F}_L$	$\mathcal{F}_O - \mathcal{F}_L$	$W_L (\mathcal{F}_O - \mathcal{F}_L)$	W_R	$\mathcal{F}_R$	$\mathcal{F}_O - \mathcal{F}_R$	$W_R (\mathcal{F}_O - \mathcal{F}_R)$
1. 1.327	5.7	44.3	58.8	1.356	77.5	27.5	37.3
2. 2.904	1.49	48.51	141.0	1.793	79.7	29.7	53.2
3. 0.935	5.09	44.91	46.7	1.306	86.9	36.9	48.2
4. 1.58	2.48	97.52	176.0	2.971	76.2	26.2	74.8
5. 1.528	3.66	46.34	70.8	2.796	89.4	39.4	82.2
6. 1.916	2.78	47.22	90.5	2.884	84.7	34.7	170.0

The values on LHS and RHS equalise at sample No.3 in this case and subsequent slight fluctuations may be at-

(3) Data taken from Table XXXV. Last 6 analyses of samples in the experiment performed at 28 rpm - Original Composition 50% fines.

	W_L	$\mathcal{F}_L$	$\mathcal{F}_O - \mathcal{F}_L$	W_L ($\mathcal{F}_O - \mathcal{F}_L$)		W_R	$\mathcal{F}_R$	$\mathcal{F}_O - \mathcal{F}_R$	W_R ($\mathcal{F}_O - \mathcal{F}_R$)
1.	4.84	89.1	39.1	193.0		0.80	8.5	41.5	33.2
2.	3.36	95.7	45.7	153.5		1.24	3.5	46.5	57.7
3.	2.53	97.7	48.8	123.5		1.73	0.95	49.05	84.7
4.	2.25	100.0	50.0	112.5		2.41	0.6	49.4	114.1
5.	2.34	100.0	50.0	115.5		1.96	1.4	48.6	95.2
6.	1.96	100.0	50.0	98.0		8.16	0.14	49.86	105.5

The values of W_L ($\mathcal{F}_O - \mathcal{F}_L$) and W_R ($\mathcal{F}_O - \mathcal{F}_R$) become equal at sample No. 4 and the subsequent slight fluctuations may be attributed to certain unavoidable ^{such as variations in the} factors ~~like~~/flow rate of the materials.

EFFECT OF RESIDENCE TIME:-

Vessel (c) was fed with a mixture of 50 per-cent fines and 50 percent coarse particles at flow rates of 4.86, 7.15, 9.04 and 82.7 grams/ minute giving a residence time of 61.5, 39.1, 30.3 and 3.7 minutes at 54 rpm. The results, are given in Tables XXXVII and

TABLE XXXVII
EFFECT OF RESIDENCE TIME
END (c) ON R.H.S

1. ORIGINAL COMPOSITION	50% FINE, 50% COARSE
RPM	54
TIME OF RUN	2 HOURS
FEED RATE	<u>4.86 g/min</u>
MATERIAL RETAINED	293.8 gms
COMPOSITION OF RESIDUAL MATERIAL	32.1% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED	125.63 gms			457.14 gms		
COMPOSITION	37.9% Fines			73.3% Fines		
DISCHARGE RATE	1.05 g/min.			3.81 g/min.		
TIME	%Fines	g/min	φ	%Fines	g/min	φ
10 min	17.6	0.15	-64.8	56.5	4.50	13.0
20 "	86.0	0.1	72.0	58.7	4.43	17.4
30 "	93.0	0.05	86.0	58.1	4.09	16.2
40 "	99.0	0.08	98.0	62.8	4.06	25.6
50 "	34.7	0.16	-30.6	71.5	4.12	43.0
60 "	11.4	0.42	-77.2	72.7	5.51	45.4
70 "	8.5	0.80	-83.0	89.1	4.84	78.2
80 "	3.5	1.24	-93.0	95.7	3.36	91.4
90 "	0.95	1.73	-98.1	98.8	2.53	97.6
100 "	0.6	2.41	-98.8	100	2.25	100
110 "	1.4	1.96	-97.2	"	2.31	"
120 "	0.14	2.16	-97.7	"	1.96	"

Cont...

2. ORIGINAL COMPOSITION	50% FINE, 50% COARSE SAND
RPM	54
TIME OF RUN	2 HOURS
FEED RATE	7.15 g/min
MATERIAL RETAINED	279.8 gms
COMPOSITION OF RESIDUAL MATERIAL	76.8% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT: COLLECTED		527.36 gms		330.47 gms		
COMPOSITION		53.3% Fines		23.6% Fines		
DISCHARGE RATE		4.395 g/min		2.754 g/min.		
TIME	%Fines	g/min	φ	%Fines	g/min	φ
10 min	15.5	3.1	-69.0	ZERO	3.02	-100
20 "	16.7	4.31	-66.6	0.5	2.59	-99.0
30 "	37.2	4.32	-25.2	16.2	2.24	-77.6
40 "	58.1	3.58	16.2	42.1	1.48	-15.8
50 "	42.6	5.42	-14.8	36.6	2.95	-26.8
60 "	58.3	5.07	16.6	38.5	2.41	-23.0
70 "	57.9	5.87	15.8	24.2	3.39	-51.6
80 "	66.4	5.42	32.8	25.5	3.57	-49.0
90 "	66.4	5.28	32.8	27.7	3.72	-44.6
100 "	64.0	5.41	28.0	15.7	3.38	-68.6
110 "	63.8	4.89	27.6	32.4	2.63	-35.2
120 "	65.0	4.82	30.0	19.2	2.50	-61.6

cont..

3. ORIGINAL COMPOSITION	50% FINE, 50% COARSE
RPM	54 SAND
TIME OF RUN	1 HOUR 15 MINS.
FEED RATE	<u>9.04 g/min</u>
MATERIAL RETAINED	274.3 gms
COMPOSITION OF RESIDUAL MATERIAL	82.5% Fines

LEFT HAND SIDE				RIGHT HAND SIDE			
TOTAL AMT: COLLECTED		337.5 gms		340.5 gms			
COMPOSITION		33.6% Fines		39.2 Fines			
DISCHARGE RATE		4.5 g/min.		4.54 g/min.			
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ	
10 min	0.63	3.81	-98.7	29.4	5.72	-41.2	
20 "	2.1	2.82	-95.8	72.5	3.94	45.0	
30 "	2.9	4.15	-94.2	38.9	4.60	-22.2	
40 "	17.1	4.92	-65.8	37.7	3.44	-24.6	
50 "	70.1	4.73	40.2	27.2	2.73	-45.6	
60 "	72.8	4.84	45.6	19.4	2.72	-61.2	
70 "	56.9	5.72	13.8	23.6	3.73	-52.8	

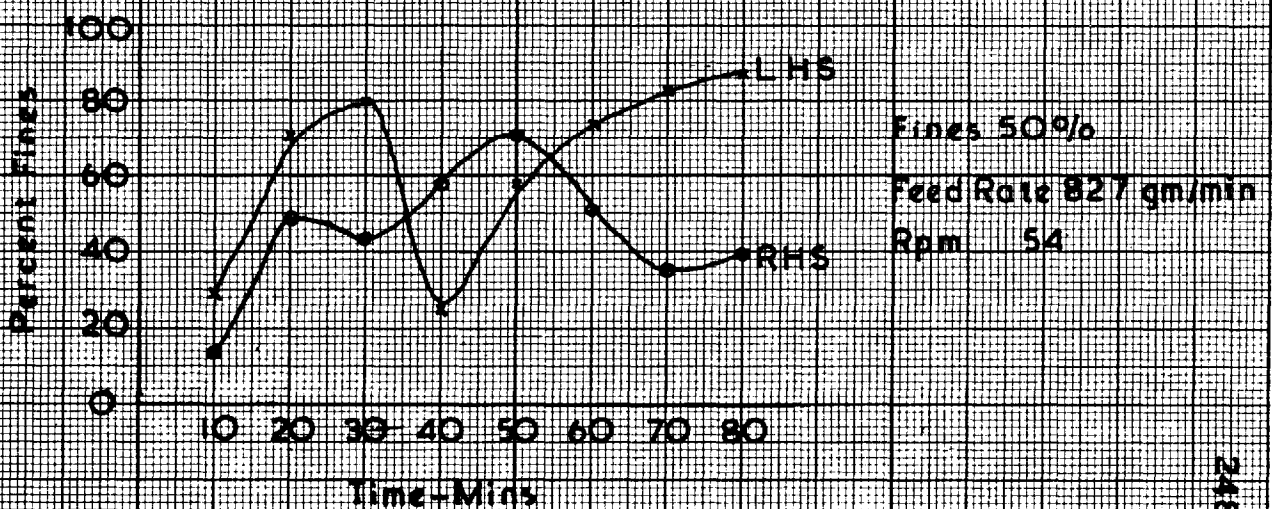
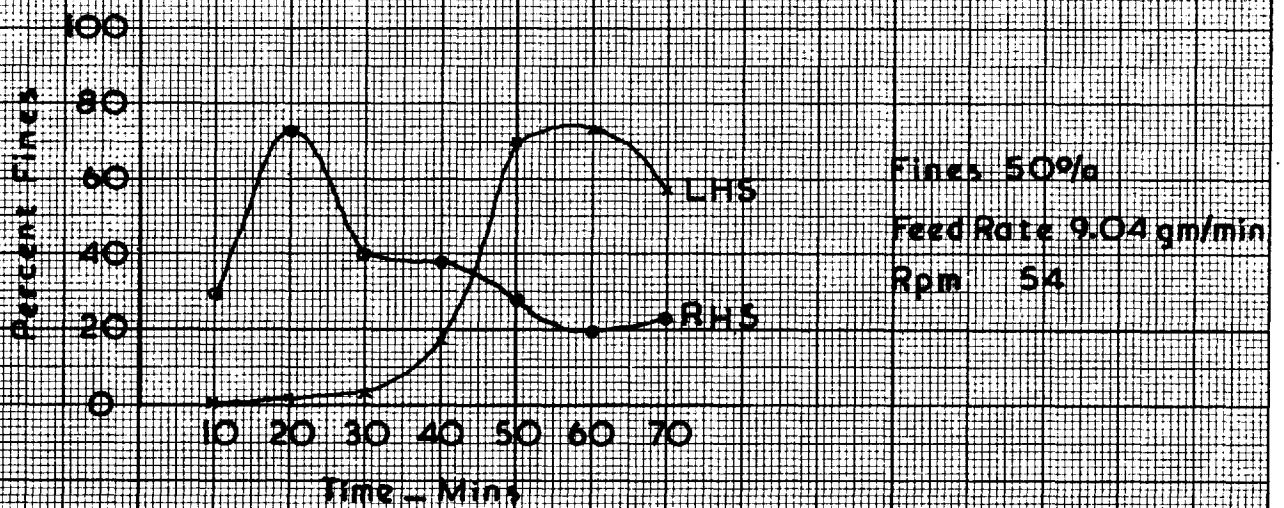
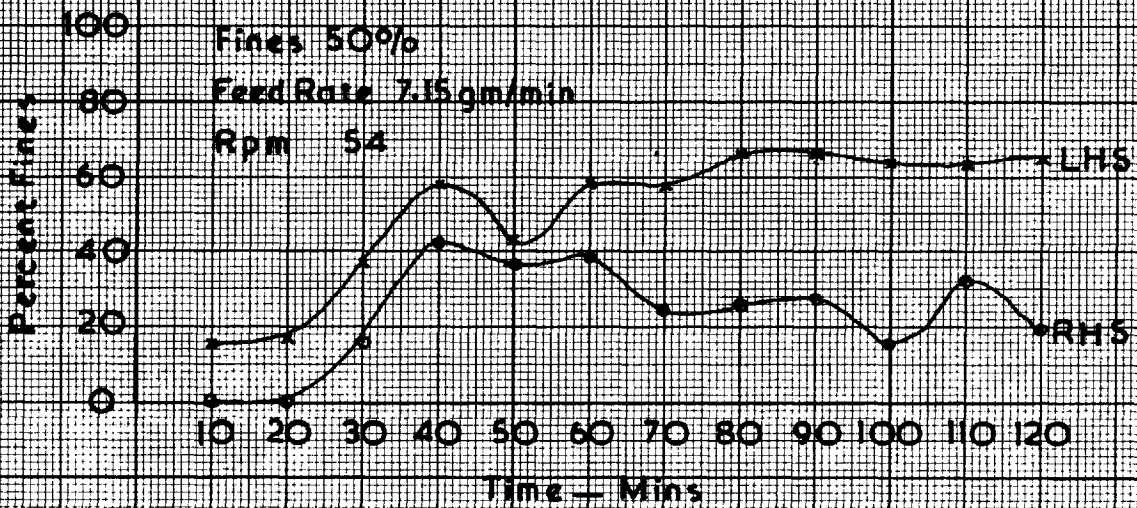
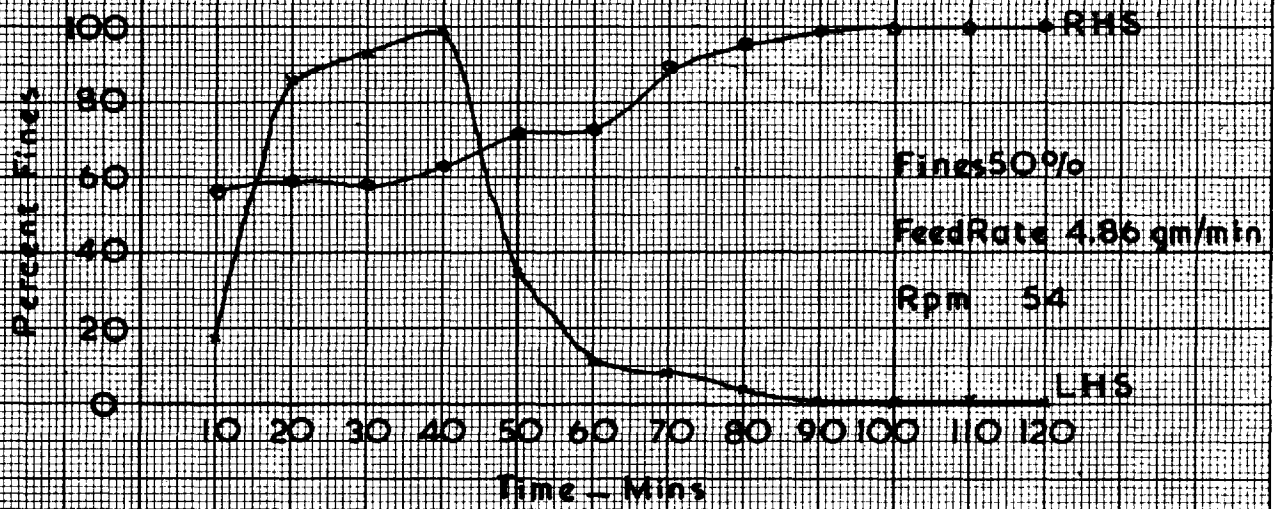
con ...

4. ORIGINAL COMPOSITION	50% FINE, 50% COARSE
RPM	54 SAND
TIME OF RUN	21 MIN 30 SEC.
FEED RATE	<u>82.7 g/min</u>
MATERIAL RETAINED	305.0 gms
COMPOSITION OF RESIDUAL MATERIAL	74.7% Fines

LEFT HAND SIDE				RIGHT HAND SIDE		
TOTAL AMT:COLLECTED		541.5 gms		1236.0 gms		
COMPOSITION		57.5% Fines		49.9 % Fines		
DISCHARGE RATE		25.2 g/min		57.5 g/min		
TIME	%Fines	g/min	Φ	%Fines	g/min	Φ
2 Min.	28.8	24.61	-42.2	13.95	52.88	-72.7
4 "	70.4	17.47	40.8	48.7	43.44	-2.6
6 "	79.7	13.92	59.4	43.4	49.0	-13.2
8 "	24.6	21.7	-50.8	58.0	32.45	16.0
10 "	57.8	30.28	15.6	71.0	76.73	42.0
12 "	73.5	42.79	47.0	50.7	89.27	1.4
14 "	82.4	40.42	64.8	35.1	99.67	-29.8
16 "	87.0	27.15	74.0	39.7	63.56	-20.6

Fig(50)

EFFECT OF RESIDENCE TIME ON
COMPOSITION OF STREAM ON BOTH SIDES OF THE SEPARATOR
BASE ANGLE OF THE RHS END-50°



plotted in Fig. (50). When these are compared with these ~~data~~ given in Table XXVII and Fig. (40) for a 50% mixture at flow rate of 3.6 g/min. (residence time 81.0 minutes) it can be seen that it is of great importance to give the material sufficient residence time (which in this case is found to be at least one hour) to go through a process of complete separation.

DISCUSSION:-

Considering the results for the three conical vessels as a whole, it would appear that certain conditions (and in especial feed rate and speed of rotation) exist under which any one of them can act as an efficient separator. These conditions, however, cannot yet be predicted and have to be determined by trial. The essential factor for determining separation is the existence of stable segregation bands at the extreme ends of the vessel. An extension of the work might lead to a method of prediction which would enable this condition to be achieved in all cases.

A comparison of the maximum degree of segregation obtained with the three vessels (See Table XXXVIII) suggests the best overall efficiency of separation for any mixture is obtained with vessel (a).

TABLE XXXVIII

AVE: DEGREE OF SEGREGATION

SHAPES WITH (a) ON RHS			WITH (b) ON RHS		WITH (c) ON RHS	
BASE ANGLE 90°			75°		50°	
SPEED 54 rpm			78 rpm		54 rpm	
MIXTURE	LHS	RHS	LHS	RHS	LHS	RHS
25%	-99.0	+90	-80	+99.0	-96.7	+38
50%	-96.0	+80	-94	+97.0	-99.0	+100
75%	-95.0	+75	--	--	+100	-13.5

SEPARATION OF A MIXTURE OF SIMILAR SIZED PARTICLES
HAVING DIFFERENT DENSITIES:

From earlier experiments with a cylindrical vessel, it is to be expected that a continuous separation of particles of different densities could be affected in any one of the conical vessels (39 a, b or c).

The experiments done in the present work showed that this was possible under certain experimental conditions. The number of experiments performed were however not sufficient to help in forming any firm conclusions. The results of one experiment performed with vessel (c) using a mixture of 50:50 magnetite and coal (density ratio 3.38:1) at 54 rpm show that a partial separation of these two materials is possible (Table XXXIX Fig. (51)).

TABLE (XXXIX)
SEGREGATION OF 50/50 MIXTURES OF COAL AND
MAGNETITE

PARTICLE SIZE - 18/22 of both Components. Density Ratio =
 1:3.38 BASE ANGLE OF RHS CONE = 50° RPM 54

Amount of material collected 243.5 gms LHS 480.5 RHS

Rate of discharge: 1.22 gm/min. 2.4

Composition : $\frac{117}{243} \times 100 = 48.2\% \text{ Mag.}$ $\frac{67.5}{480.5} \times 100 =$
 14.0% Mag.

Total time of runs = 200 minutes

AVE: FEED RATE = 3.62 gm/min.

Time	COMPO- SITION	RATE gm/min	ϕ	COMPO- SITION	RATE gm/min.	ϕ
10min.	0%Magne- tite	0.883	-100	0% Magne- tite	2.963	-100
20 "	0% "	0.859	-100	0% "	2.069	-100
30 "	0% "	0.872	-100	0% "	2.192	-100
40 "	0% "	0.762	-100	0% "	2.085	-100
50 "	0% "	0.746	-100	0.72 "	2.012	-98.56
60 "	0% "	1.102	-100	4.1 "	2.946	-91.8
70 "	0% "	1.627	-100	6.4 "	4.596	-87.2
80 "	0% "	0.767	-100	6.8 "	2.177	-86.4
90 "	0% "	1.28	-100	3.5 "	2.20	-93.0
100 "	45.8 "	1.140	-8.4	4.93 "	1.994	-90.14

253.

TIME	COMPO- SITION	RATE g/min	ϕ	COMPO- SITION	RATE g/min.	ϕ
110	59.8 Magne- tite	0.982	17.6	10.2 Mag- netite	1.803	-79.6
120	54.4 "	1.504	8.8	24.8 "	1.297	-50.4
130	63.5 "	1.936	27.0	19.6 "	2.652	-60.8
140	67.3 "	1.828	34.6	29.5 "	2.081	-41.0
150	62.4 "	1.325	24.8	21.9 "	1.735	-56.2
160	55.0 "	1.064	10.0	23.3 "	1.479	-53.4
170	68.6 "	1.688	37.2	23.9 "	1.672	-52.2
180	66.5 "	2.166	33.0	27.5 "	3.4	-45.0
190	77.8 "	2.819	54.6	34.4 "	4.551	-31.2
200	68.3 "	1.568	36.6	30.4 "	3.4	-39.2

Amount retained = 440.4 gms

% age composition= 88.0% Magnetite.

Fig (51)

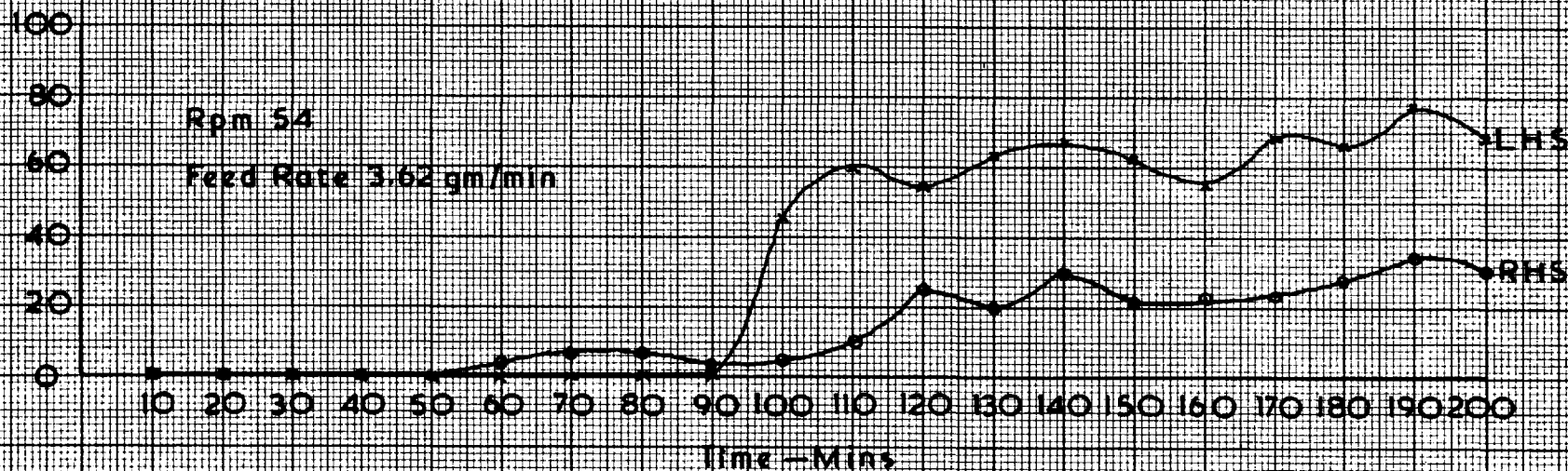
254

COMPOSITION OF STREAM AT BOTH ENDS OF THE SEPARATOR

Original Composition - 50% Magnetite, 50% Coal

Particle size of both components 18/22, Density Ratio 3.38:1

BASE ANGLE OF THE RHS END = 50°



CHAPTER 8SUMMARY AND CONCLUSIONS

1. The object of the work described in this thesis was to develop a method of separating continuously granular mixtures of particles of different sizes or densities.
2. To this end, a preliminary study was made of the variations in the angle of repose and bulk density with variation in composition of mixtures (of different sizes or densities). Whilst data on these properties is to be found in the literature, it is in many instances conflicting or incomplete. A careful re-determination was therefore made of angles of repose and bulk densities by refined methods which gave reasonably reproducible results. It was found that
 - a) when a mixture consisted of coarse material admixed with fines of such a size that cohesive forces were negligible, there was a linear relationship between the composition and angle of repose.
 - b) when the fine material was of such size that cohesive forces were appreciable, then the first additions of fines (upto 50 percent) increased the angle of repose of the coarse material; further additions resulted in a lowering of the angle.

3. In the case of bulk densities of mixtures of fine and coarse particles, it was found that a maximum occurred for a mixture containing about 75 percent of coarse material.

4. It is known that when a mixture of particles of different sizes or of the same size but different densities is poured into a heap, there is a tendency for segregation to occur according to size or density. The phenomenon has frequently been described in the literature although few qualitative results have been presented.

A careful analysis has been made of the composition of a cone of material formed by pouring a mixture of particles of different sizes and densities onto a horizontal plate and diagrams are given showing the extent and nature of the segregation so produced. The mechanism of segregation is discussed.

5. A series of experiments was next carried out to determine the extent and nature of the segregation produced in a ^{rotating} ~~rotary~~ cylinder and a ^{rotating} ~~rotary~~ cone. From these results a continuous method of separation in vessels consisting of a combination of cylinder and cone and double cone was worked out.

6. Extensive data are given for the segregation produced in four different shaped rotary vessels and the effect of such variables as composition, rate of rotation, angle of inclination and residence time. The results are discussed critically and explanation of the mechanisms involved is attempted.

A P P E N D I X (I)STATISTICAL ANALYSIS.COMPARISON OF MEANS:

In the case of all the measurements of the angle of repose, the maximum variation was found to be 2.5° in each set of experiments. An average of 12 readings was taken as giving a sufficiently accurate value of the angle. To find whether it was advisable to take the mean as a standard value, a statistical analysis was carried out on two sets of 12 readings obtained under similar experimental conditions.

We obtained two sets of readings and wish to test whether the mean of one set is significantly different from the mean of the other set, or whether the two sets can be regarded as drawn from the same population.

Let $X_1, X_2 \dots X_{n_1}$ and $X'_1, X'_2 \dots X'_{n_2}$ be two samples

Then

$$\bar{x} = \frac{\sum(x)}{n_1} \quad \text{and} \quad \bar{x}' = \frac{\sum(x')}{n_2}$$

$$s^2 = \left\{ \sum(x)^2 - \frac{[\sum(x)]^2}{n_1} + \sum(x')^2 - \frac{[\sum(x')]^2}{n_2} \right\} / n_1 + n_2 - 2$$

(1)

$$t = \frac{\bar{x} - \bar{x}'}{s} \sqrt{\frac{n_1 \cdot n_2}{n_1 + n_2}}$$

If $n_1 = n_2 = n$, the above formula reduces to

$$t = \frac{\bar{x} - \bar{x}'}{s} \sqrt{\frac{n}{2}} \quad (2)$$

Let us consider this particular case of two sets of 12 readings for the angle of repose of a sample of sand (mesh size 85/100) obtained under similar experimental conditions, where the difference between their means is a maximum, and see whether it is significantly different from zero.

Having found out t by formula (2), we refer to ~~about~~ the table of t (or from a graph) with $(n_1 + n_2 - 2)$ degrees of freedom. If our value of t exceeds that

for the 5% level, we may take it that the populations are different.

(A)		(B)	
X_A	X_A^2	X_B	X_B^2
33.0	1089	34.0	1156
33.5	1122.25	33.5	1122.25
34.0	1156	33.5	1122.25
33.5	1122.25	33.0	1089
34.0	1156	32.5	1056.25
33.0	1089	33.5	1122.25
34.0	1156	34.0	1156
33.0	1089	33.5	1122.25
34.0	1156	32.5	1056.25
34.0	1156	33.0	1089
33.0	1089	34.0	1156
33.0	1156	33.0	1089
ΣX_A	402.0	ΣX_B	400.0
$\bar{X}_A$	33.5	$\bar{X}_B$	33.34
$\bar{X}_A - \bar{X}_B = 33.5 - 33.34 = 0.16$			

261.

$$s^2 = \left\{ \left[33^2 + 33.5^2 + \dots - \frac{(402)^2}{12} \right] + \left[34^2 + 0 + 33.5^2 + \dots - \frac{(400)^2}{12} \right] \right\} / (12 + 12 - 2)$$

$$= \left[(13526.5 - 13467) + (13329.5 - 13333.4) \right] / 22$$

$$= \frac{59.5 - 3.9}{22} = \frac{55.6}{22} = 2.52$$

$$s = \sqrt{2.52} = 1.587$$

$$t = \frac{\bar{x}_A - \bar{x}_B}{s} \sqrt{\frac{n}{2}}$$

$$= \frac{0.16}{1.587} \times \sqrt{6} = \frac{0.16}{1.587} \times 2.45$$

$$= .247$$

Consulting the table of t , we find that for 22 degrees of freedom, t must be not less than 2.07 to be significant at the 5% level. Accordingly there is no evidence that here the populations are different.

SIGNIFICANCE OF TWO MEANS:

In the above example, we have 12 members in each of rows A and B. We should expect the difference between these 2 sets of readings to average zero because there is no systematic difference between two operations. We wish to test whether their mean differs significantly from zero.

A	33.0	33.5	34.0	33.5	34.0	33.0	34.0	33.0	34.0	34.0	
										33.0	33.0
B	34.0	33.5	33.5	33.0	32.5	33.5	34.0	33.5	32.5	33.0	
										34.0	33.0
~~x=A-B~~	-1.0	0	0.5	0.5	1.5	-0.5	0	-0.5	1.5	1.0	
										-1.0	0

$\bar{x} = 2/12 = 0.167 = \text{average value for A - B}$

We calculate the standard deviation of these individuals as

$$\begin{aligned}
 s &= \frac{(-1.0)^2 + (0)^2 + \dots - (-1.0 + 0 + \dots)^2}{12 - 1} \\
 &= \frac{8.5 - 0.334}{11} = \frac{8.166}{11} = 0.742
 \end{aligned}$$

$$\text{Standard deviation of mean } \bar{x} = \frac{s}{\sqrt{n}} = \frac{0.742}{12}$$

$$\begin{aligned} &= \frac{0.742}{3.464} = 0.214 \\ \therefore t &= \frac{\bar{x} - E}{s/\sqrt{n}} \quad (E = 0) \\ &= \frac{0.167}{0.214} = 0.78 \end{aligned}$$

Now the value we used for s is of course only an estimate of the population value. Being based on 12 individuals, it is not as accurate as if it were based on 100 or 1000 individuals. The table of significant values of t takes it into account. The degree of freedom is 11 in this case. From the table

against 11 degrees of freedom at 5% levels, the value of $t = 2.2$. Our present value is 0.78 and is less than the value for the 5% level i.e. our assumption that there is no difference between the two sets of readings is in reasonable accord with the data. If our value of t had been larger, however, we could have had to regard the assumption as incorrect.

CONFIDENCE LIMIT OF A MEAN:

To determine the limits between which we are reasonably confident that the true value of ^{the} mean lies, we assume that 95% accuracy is 'reasonably confident'. From the table the value of t for 5% level against 11 degrees of freedom is 2.2 $\therefore$ The limits $\pm L$ on either side of sample mean is

$$\begin{aligned}\pm L &= \pm t (s/\sqrt{n}) \\ &= \pm 2.2 \times .214 = \pm 0.47 = \pm 0.5\end{aligned}$$

where s = standard deviation,

n = number of individuals in a sample.

APPENDIX II
CALCULATION OF VOLUME OF A BAND

METHOD 1.

Consider a band of granular material in the cone as shown in Fig. (1). This will be a section of a frustum ~~of the cone~~ of thickness h (Fig. 2)
 d_1 and d_2 are the diameters of the cone at either sides, and r_1 and r_2 are the corresponding radii.

The shaded area in Fig. (2) is the band under consideration, θ_1 and θ_2 are the angles subtended at the centre ^{of circles} of radii r_1 and r_2 by their arcs (~~of the circles~~).
Total volume of this frustum

$$= \frac{\pi h}{3} (A_1 + A_2 + \sqrt{A_1 A_2}) \quad \text{where} \quad (1)$$

$$A_1 = r_1^2 \quad \text{and}$$

$$A_2 = r_2^2$$

This can also be written as

$$\text{Volume} = \frac{\pi h}{3} \cdot (r_1^2 + r_2^2 + r_1 r_2) \quad (2)$$

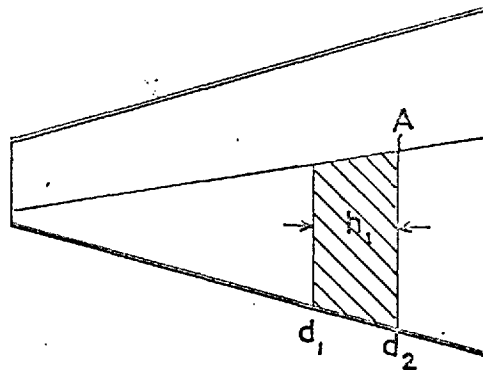
Volume of a segment of this frustum is in the ratio of areas or ratio of arc length to circumference

$$\therefore \text{Volume of the segment} = \frac{r_1 \theta_1}{2\pi r_1} \left[\frac{\pi h}{3} (r_1^2 + r_2^2 + r_1 r_2) \right]$$

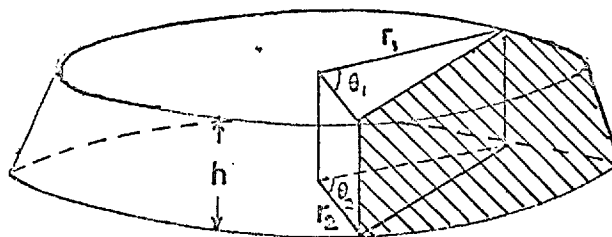
$$= \frac{\theta_1}{2\pi} \left[\frac{\pi h}{3} (r_1^2 + r_2^2 + r_1 r_2) \right] \quad (3)$$

VOLUME OF A BAND IN A CONE

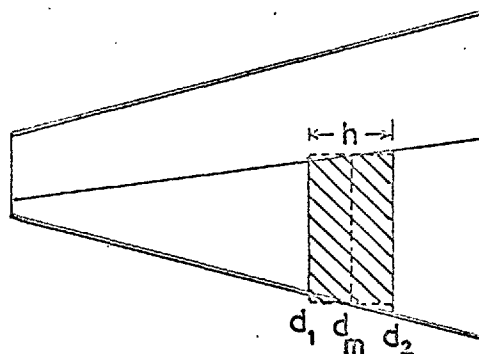
Fig(1)



(2)



Fig(3)



Volume of the circular section of this segment (band)

= Volume of the segment - volume of triangular prism

$$\text{Volume of triangular prism} = \frac{1}{4} \left[r_1^2 \sin \frac{\theta_1}{2} + r_2^2 \sin \frac{\theta_2}{2} \right] h$$

∴ Volume of the band =

$$\begin{aligned} &= \frac{\theta_1}{2\pi} \cdot \frac{\pi h}{3} (r_1^2 + r_2^2 + r_1 r_2) - \frac{1}{4} \left[r_1^2 \sin \frac{\theta_1}{2} + r_2^2 \sin \frac{\theta_2}{2} \right] h \\ &= \frac{\theta_1 \cdot h}{6} (r_1^2 + r_2^2 + r_1 r_2) - \frac{1}{4} \left[r_1^2 \sin \frac{\theta_1}{2} + r_2^2 \sin \frac{\theta_2}{2} \right] h \end{aligned} \quad (4)$$

METHOD 2.

Consider the band of material to be a section of a cylinder of diameter d_m where $d_m = \frac{d_1 + d_2}{2}$ and r_m is the corresponding radius. Fig.(3)

$$\text{Volume of the section} = \pi r_m^2 \cdot h \quad (5)$$

$$\text{Volume of a segment} = \frac{\theta_m}{2\pi} \cdot \pi r_m^2 \cdot h \quad (6)$$

$$\therefore \text{Volume of the band} = \frac{\theta_m}{2} r_m^2 - \frac{1}{2} r_m^2 \cdot \sin \frac{\theta_m}{2} \cdot h \quad (7)$$

TABLE (XXXX)

RELATIONSHIP BETWEEN MESH SIZE AND AVERAGE LINEAR

		<u>DIMENSIONS</u>		
No.	MESH SIZE	AVERAGE	LINEAR	DIMENSIONS
		MICRONS	INCHES	-FEET
1	10/12	1524	.06065	50.54 x 10 ⁻⁴
2	12/14	1282	.05135	42.8 "
3	14/16	1080	.04345	36.2 "
4	16/18	912	.03655	30.46 "
5	18/22	767	.03055	25.46 "
6	22/25	645	.02555	21.3 "
7	25/30	542	.02165	18.04 "
8	30/36	456	.01815	15.13 "
9	36/44	384	.01525	12.71 "
10	44/52	323	.01275	10.63 "
11	52/60	270	.01075	8.96 "
12	60/72	227	.0091	7.59 "
13	72/85	192	.00765	6.37 "
14	85/100	161	.0065	5.42 "
15	100/120	135	.00545	4.54 "
16	120/150	114	.0045	3.75 "
17	150/170	96	.0038	3.17 "
18	180/200	81	.00325	2.71 "

BIBLIOGRAPHY

1. Rankine, W.J.M. Trans: Roy: Soc. (Lond.),
1857, 147.
2. Darwin, G.H. Proc: Inst: Civil: Engrs.
1883, 71, 350.
3. Wilson, G. Proc: Inst: Civil: Engrs.
1902, 49, 210.
4. Crosthwaite P.M. Proc. Inst: Civil: Engrs.
1916, 203, 124.
5. Ketchum, M.S. "The design of Walls, Bins
and Grain Elevators"
McGraw Hill & Co., N.Y.(1919).
6. Goodrich, E.P. Trans: Am: Soc: C.E.,
Vol. LIII, p.272.
7. Jamieson, J.A. Trans: Can: Soc: C.E.
Vol. XVII, 1903.
8. Richter, D.W. Agric: Engr: 1954, 35, 411.
9. Holbrook & Fraser H.J. U.S. Bureau of Mines,
No.234, 1925
10. Lanza Notes on Friction 1903,
128, 115.
11. Train, D.J. Pharm: & Pharmacology,
1958, 10, 127T.
12. Pratap, R. Ph.D Thesis London University,
1964.
13. Zenz Petroleum Refiner.
1953, 36, 173.
14. Fowler R.T. and Chem: Eng: Sci:
Chowdziesner J.C. 1959, 10, 157.

15. Krishna Ph.D Thesis, I.I.T.,
Kharagpur, 1961.
16. Pilpel, N. J. Pharm: & Pharmacology,
1964, 16, 705.

Chem: & Proc: Eng: 1965,
April, 52.
17. Qureshi, S.A. Ph.D Thesis, London University,
1957.
18. Brown, R.L. Soc: Chem: Ind: Monograph
14, 1960, 151.
19. Rose H.E. & Tanaka, J. Engineer, 1959, 208, 465.
20. Brown, R.L. & Richards J.C. Trans: Inst: Chem: Engrs.
1959, 37, 108.
21. Dawes, J.G. S.M.R.E. Research Report
No. 36, 46, 49, 1952.
22. Nelson, E. J: Am: Pharm: Assoc: Sci: Ed:
1955, 44, 435.
23. Fowler R.T. and Aust: J: Chem: Engrs.
Wyatt F.A. 1960, 1, 5.
24. Wolf E.F. and A.S.M.E., 1945, 67, 585.
Hohenleiten H.L. Von.
25. Bulsara, Zenz & Eckert Ind: & Eng: Chem: Proc:
Des: & Dev: 1964, Oct 3, 348.
26. Newmann, B.S. "Flow properties of disperse
systems" Chap.10, J.J. Hermans,
North Holland Publishing Co.,
Amsterdam (1953).
27. Craik J.D. and J. Pharm: & Pharmacology
Miller, B.F. 1958, 10, 136 T.
28. Davis A.E. J. Pharmacy 1943, 150, 118.

29. Shotton & Simons J. Pharm: & Pharmacology
1950, 2, 231.
30. Craik, J.D. Ibid. 1958, 10, 73.
31. Irani & Cullis Ind: & Eng: Chem: 1959, 51, 1285.
32. Stairmand, C.J. Paper presented to Fert:
Soc: (Lond), Nov, 62.
33. Williams, J.C. Chemical Processing, 1965,
April, S6; Sheffield Univer-
sity, J. Fuel Soc: 1963, 14,
29.
34. Brown, R.L. J: Inst: Fuel. 1939, 13, 15.
35. Richards, J.C. B.C.U.R.A monthly bulletin
27, no.2, Feb. 1963.
36. Holmes, C.W.H. Colliery Engr. 1934, 11, 40
and 188.
37. Brown, R.L. B.C.U.R.A. Bulletin 145,
April, 1955.
- " & Richards B.C.U.R.A. Information Cir-
cular 156, July, 1956.
- " Fuel - 1949-26-159; 1950, 29,
220; 1960, 38, 245.
- " Nature - 1961, 191, 458.
38. Colley, C. Mechanical Engr: 1963, May, 52.
39. Oyama, Y. Bull: Inst: Phys : Chem: Res:
(Tokyo) Rept 2, 1935, 7, 570.
Sci. Paper No.951, 1940, 37, 17.
40. Donald M.B. and Brit: Chem: Engr: 1962, 7, 749,
823 and 922.
41. Coulson J.M. and Ind: Chemist. 1950, 26, 55.
Maitra N.K.

42. Bonilla, C.F. and Weidenbaum, S.S. Chem: Eng: Prog. 1955, 51, 27.J
43. Rose, H.E. Inst: Chem: Engrs. - 1959, 37, 47.
44. White H.E. & Walton S.F. J. Amer: Cer: Soc. 1937, 20, 155.
45. Furnas, C. U.S. Bureau of Mines Bull: No.307, 1931, 47.
Ind: & Eng: Chem: 1931, 23, 1052.
46. Dallavalle, J.M. Micromeritics. Pitman Publishing Corp. N.Y., 1948.
47. Weidenbaum S.S. Chapter on Mixing of Solids in "Advances in Chemical Engg:" Academic Press, N.Y., 1958.
48. Rose H.E. & Sullivan R.M.E "A treatise on internal mechanics of Ball Tube and Rod mills" Constable, London, 1958.
49. Handbook of Phys: & Chem:, 39th ed., Chemical Rubber Publishing Co. Cleveland Ohio, 1957.
50. Parry, J. Handbook of Chem: Engrs. McGraw Hill, 3rd Ed., 1950.