A STUDY TO FIND AN ECONOMIC METHOD FOR GRAVEL PLACEMENT IN WATER WELLS WITH THE LEAST AMOUNT OF SEGREGATION

By

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A STUDY TO FIND AN ECONOMIC METHOD FOR GRAVEL PLACEMENT

IN WATER WELLS WITH THE LEAST AMOUNT OF SEGREGATION

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The writer likes to acknowledge the help offered from Edward E. Johnson, Inc. He wants also to thank Mr. C. F. Briggs, Mr. R. S. Schrues, and Mr. Grant for their co-operation.

PREFACE

In March 13, 1957 the writer contacted Mr. Joe L. Mogg, Edward E. Johnson, Inc. St. Paul, Minnesota, seeking his advice for a thesis subject at the level of the Master's Degree.

Later on Mr. Mogg replied suggesting that the writer could work on investigating a method for gravel placement in water wells with the least amount of segregation. He showed that segregation is a problem facing the water wells industry in the Southwest, of the United States, and The Sahara. He offered to provide the material, and the equipment, proposing building a model well and conducting the experimental work at their plant in St. Paul.

On May 23, Mr. Bently approved the offer, and on the 27th of the same month the writer left to St. Paul, Minnesota. By the second week of June the rate of fall measuring apparatus (Plate 2), was completed. In a two weeks period the ten experiments of the rate of fall of the gravel particles and other eight experiments, that are not included in this paper, were conducted.

By the first week of July the model well was built. The three experiments on the rate of fall of the gravel particles took about a week. The gravel placement experiments required the rest of the summer. It took more than a week to dismantel the model well for extracting the gravel sections after each test and then reassemble it again for the next test. Working over the roof was dangerous. Transfering all the materials plus instauling a pump and its connections over there took a considerale amount of time.

By the end of the summer all the experimental data was collected. The writing and discussing the results were made during the fall of 1957. More tweleve experiments were not required in this paper so they were mailed back to Mr. Mogg, Edward E. Johnson, Inc, St. Paul, Minnesota.

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CHAPTER I

INTRODUCTION

Objective

"The objective of this study is to find an economical method for gravel placement in water wells with the least amount of segregation"

What is a gravel pack, and why is it used ?

The main function of a water well is to give the required amounts of water for irrigation, domestic use, or whatever its purpose may be. This requires the use of large screen openings. Large screen openings are possible to have whenever the formation is of coarse structure, but if the formation material was fine large screen openings cannot be done; and it presents a problem. As a solution to this problem the idea of having another screen of coarse gravel particles adjacent to the screen was adopted. Using this screen of gravel large screen openings were possible, and ample quantities of water were pumped.

This idea started fifty years ago in Kansas and Arkansas, where large quantities of water were needed for the rice industry, and it proved to be successful.

This screen of gravel is called gravel pack, and sometimes is referred to as "gravel envelope", "gravel treatment", "gravel filter" or similar terms. Its main function is to increase the specific yield of the well by allowing the use of large screen openings.

After this introduction about the gravel pack and its use, the reader should know about its design as an aid to the gravel placement study.

The Design of a Gravel Pack

To design a gravel pack the following points should be cosidered:

(A) The type of the gravel pack

There are two types of gravel packs: the uniform grain-size pack, and the graded grain-size pack. The uniform grain-size pack is composed of a uniform grain size, and the graded grain-size pack is composed of different sizes graded according to a designed curve or certain ratios of each size.

Each of these packs has its advantages and disadvantages. The Bureau of Reclamation in its laboratory tests on protective filters for hydraulic structures found that the major differences between the uniform grain-size pack and the graded grain-size pack are:

(1) The uniform grain-size pack has practically no segregation during its placement while the graded grain-size pack gives a segregated pack.

(2) There is practically no settlement, or a very negligible amount, during operations using the uniform grain-size pack.

(3) Under the same conditions the capacity of the uniform grain-size pack is greater than the graded grain-size pack.

These points show that the uniform grain-size pack has many advantages, but its lack of availability is its great disadvantage, meanwhile, segregation is the drawback for using the graded grain-size pack.

(B) The strucrure of the gravel pack

Several studies have been made concerning the structure of the gravel pack and the actual conditions of the formation in which it will be placed.

The studies made by the Bureau of Reclamation recommended that the grain size (ratio of 50% size of the pack to 50% size of the formation material) must be between 5 and 10.

The Soil Conservation Service of the U. S. Department of Agriculture found a very little sand movements with the ratios of 3.6 to 8.75 for the coarse formation material, and ratios of 3.8 to 6.4 for the fine formation material.

The U. S. Waterways Experiment Station concluded that a fine material will not wash through a filter material if the 15% size of the filter material is less than five times as large as the 85% of the base material. They reaffirmed this conclusion in their field laboratory investigations of the design criteria of water wells.

(C) <u>The thickness of the gravel pack</u>

About 15 years ago K. E. Hill of College of Mining, University of California investigated the thickness of the gravel envelope that is required to produce a successful screen. Assuming that the gravel of the proper grain size is used, a uniform thickness of as little as $\frac{1}{2}$ an inch around the screen proved to be sufficient. Obviously the placement of a gravel envelope only $\frac{1}{2}$ an inch thick is not practical in the construction of a well. However, it can be concluded that a pack can be as thin as it is practical to put in place under job conditions. More often job conditions recommended a minimum pack thickness of about three inches.

Studies made by Mr. Garton,* School of Agricultural Engineering, Oklahoma State University, indicated that increasing the pack thickness from 3" to 6" will increase the yield by 9% only, while it will cost about three times more.

Hence the idea of using a thick gravel pack should be abandoned forever.

(*) Unpublished paper.

(D) The permeability of the gravel pack

The pack should have a higher permeability than the formation. Studies proved that if the pack was 20 times more permeable than the formation then the resistance to flow would be negligible.

The criteria used by Edward E. Johnson, Inc. result in gradings that are 50 to 100 times more permeable than the formation. High permeability is made by using a low uniformity coefficient.

(E) Terms used in describing sand and gravel

Correct descriptions of sand and gravel sizes are important. The following gradings cover most sands and gravels, and describe their sizes in terms ordinarily used by engineers, well drillers, and others interested in these things.

			Slot size in inches
Coarse gravel, average diameter			0.187.5 and up.
Medium gravel,	"	"	0.187.5 to 0.080
Fine gravel,	"	"	0.080 to 0.040
Coarse sand,	"	"	0.040 to 0.020
Medium sand,	"	"	0.020 to 0.010
Fine sand,	"	"	0.010 to 0.004
Very fine sand,	"	"	0.004 to 0.002
Silt,	"	"	0.002 and finer

Methods of Placement of a Gravel Pack.

It was noticed that many gravel packed wells failed, due to sand pumping or being clogged, although the pack was well designed. Analysis of the pack after settlement showed that the coarse particles were accumulated at the bottom while fine ones remained at the top, which means that the pack was segregated as shown in Figure (1).

Pack segregation was referred to the method of placement, and research was needed to find a proper method for gravel placement that gives the least amount of segregation.

The objective of this study is now understandable, it is to find a method for gravel placement that gives a pack with the least amount of segregation, which should be inexpensive or economical at the same time.

Four methods were selected to be tried experimentally and to find which one will give the least amount of segregation. They are:

(1) The bailing method

(2) The tremie method

(3) The pump method

(4) The package method

Plate (1)

A segregated pack with the coarse particles at the bottom and the fine ones at the top.

CHAPTER II

REVIEW OF LITERATURE

A study of gravel placement is not a study of settlement. It is true that settlement is closley related to gravel placement but each one forms a separate subject. It is quite enough for the study of gravel placement to know how a particle will behave while settling and the factors affecting its rate of fall.

It should be understood that it is out of the scope of this paper to do experiments or derive relationships or equations for settlement. But due to the relation between settlement and gravel placement this chapter has been written to review the work done on settlement.

Laws of Settlement

(A) Stokes' Law

The classic formula for settling velocities is that made by Stokes which he developed in 1851. He considered the particle to be falling under its weight and to be resisted by the force of viscosity of the liquid. Equating these two forces he derived his formula that follows:

$$6 \pi s r v = 4/3 \pi r^3 g (D - d)$$

or $$v = 2/9 (D - d) g r^2/s$$

where v = rate of fall in cm/sec.

D = density of falling sphere

d = density of the medium

g = acceleration of gravity (980 cm/sec^2)

r = radius of falling sphere

s = viscosity of the medium.

Several assumptions underlie Stokes' Law, and it is important to consider them. These assumptions are:

(1) The particle must be spherical, smooth and rigid, and there should be no slipping between it and the medium.

(2) The medium should be considered homogenous in comparison to the size of the paricle.

(3) The particle should fall as it would in a medium of unlimited extent.

(4) A constant rate of fall must have been reached.

(5) The settling velocity must not be too great.

Assumption (1) is satisfied to the extent that the particles are wetted by the liquids commonly used, and no slip between any of them happens. But the condition that the particle be a sphere is the least satisfied and it introduces several difficulties since no gravel particle is a perfect sphere.

Experiments made by Schone, Hilgard, Owens, Atterberg, Boswell and Richard showed a fairly close agreement between the values computed by Stokes' Law and their experimental data until a diameter of 0.05 mm. Hence Stokes' Law was practically limited to particles of 0.05 mm. diameter or less.

Assumption (2) merely states that the distance between the molecules of the fluid must be small compared with the size of the particle, which is fully satisfied in general.

Assumption (3) is concerned with the change in rate of fall due to the nearness of the liquid container wall to the particle. Lorentz studied the case of a particle falling parallel to a plain wall. His studies furnished the following facts:

(1) The effect of wall nearness is to reduce the rate of fall. This reduction is greater the nearer the particle is to the wall, until it reaches at a certain distance after which there will be no effect.

(2) The effect of the wall nearness varies with the size of the particle.

Ludenburg approached the problem from the point of a sphere of radius (r) settling in a cylinder of radius (R). Experiments made by Arnold according to Ludenburg idea showed that the rate of fall is not affected unless when the radius of the particle equals 1/10 the radius of the cylinder.

Assumption (4) states that the constant rate of fall must be reached. Weyssenhoff computed an equation that proved that for a particle of 0.05 mm. only a distance of 0.003 mm. is required to achieve constant velocity. Hence this assumption needs no consideration.

Assumption (5) provides that the motion should be slow. This restriction is made on Stokes' law because he did not consider the drag forces that affect particles falling at high speeds. These forces are considered in the formula made by Rubey in 1933, that follows.

(B) Rubey's Formula

In 1933 Rubey derived a general formula that agreed with the observed rates of fall over a wider range than Stokes' law. He considered the forces acting on the particle to be the sum of the viscous resistance and the impact of the fluid. Equating this sum to the weight of the particle he derived the formula known by his name and that follows:

$$4/3\, \pi r^3 (D - d)\, g = 6 \pi r\, s\, v + r^2 v^2 d$$

$$\text{or} \quad v = (4/3\, g\, d\, (D - d)\, r^3 + 9\, s^2 + 3\, s)^{1/2} / d\, r$$

(Symbols have the same significance as in Stokes' law)

Figure (1) adopted from Rubey's papers shows the gradual transmition between the range of viscous resistance and the fluid impact. The heavy line agrees with the settling velocities for quartz and galena as were observed and Rubey's calculated figures.

(C) Wadell's Work

The most recent work on settling velocities has been made by Wadell. He opened a new approach to the problem, by examining the functional relationship between the coefficient of resistance (C) and Reynold's number (R). The coefficient of resistance is defined by equating the force producing motion to a sphere to the force resisting its motion expressed as a coefficient of resistance times the dynamic preasure acting on the cross-sectional area of the sphere, i.e. $4/3 \pi r^3 (D - d) g = C \pi r^2 v^2 d/2$

$$\text{or} \quad C = 8/3\, g\, (D - d)\, r/d\, v^2$$

Reynold's number is defined in terms of the sphere radius, its velocity, its density, and the viscosity of the liquid, or. $R = 2\, r\, D/s$ it is a dimensionless figure.

Wadell plotted a number of settling velocities and the radii of the settling particles in terms of R and C with R as abcissa & C as ordinate on log-log paper. From these graphs he developed an emperical formula for settling velocities, which not only extended the rate of settling velocities to much larger diameters but also enabled him to elucidate the influence of the shape of the particle. Wadell wrote his formula in terms of a correction to be applied to Stokes' law, which is:

$$R = r\,(1 + 0.08\,(2\, r\, v \cdot d\, /s)^{0.69897}$$

where R = the actual radius

r = the radius according to Stokes' law

v = actual settling velocity.

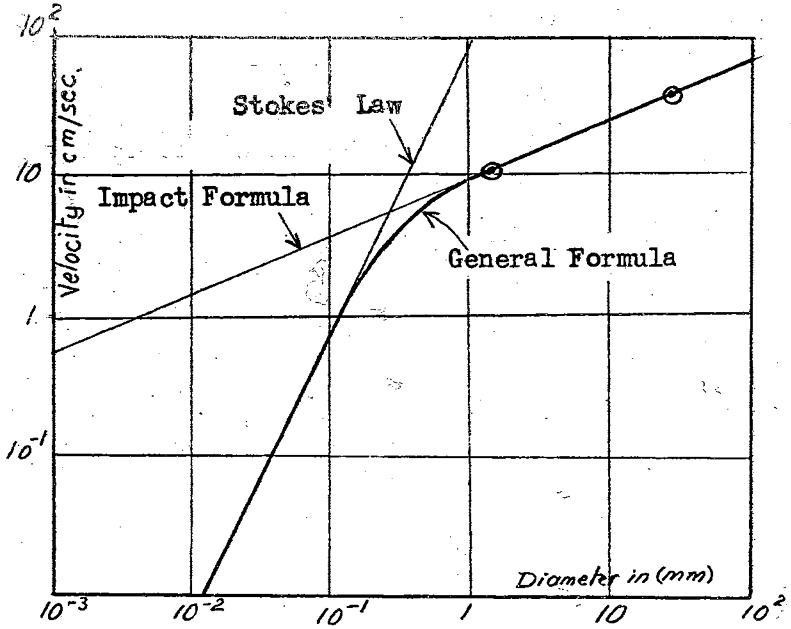


Fig.(1) Rate of fall against particle diameter. The thick line agrees with observed data. The two dots give the range of sizes referred to in Chapter III.

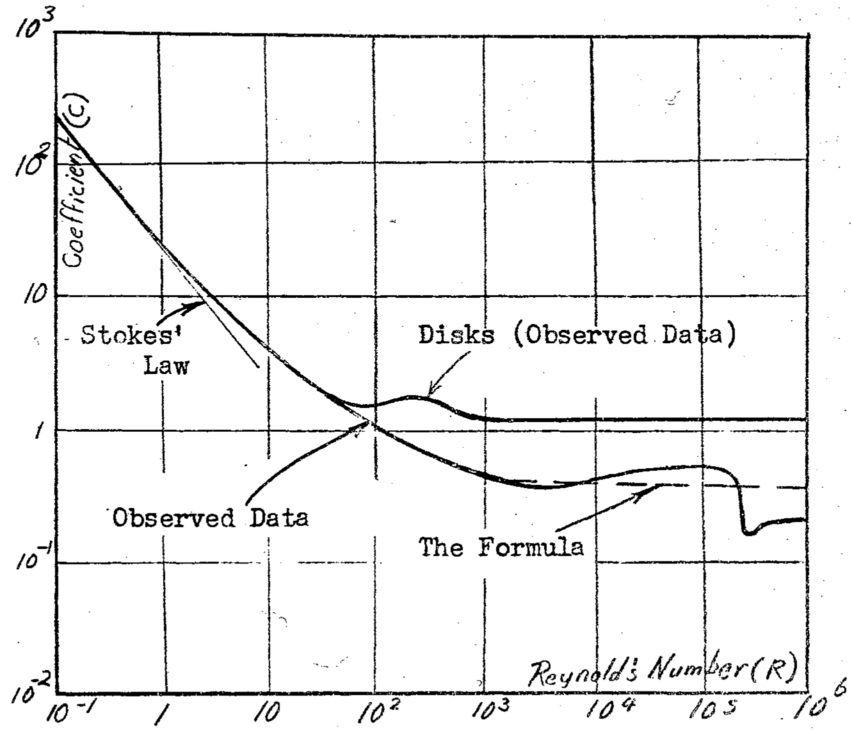


Fig. (2)
Reyonld's Number (R) against Drag Coefficient (C).

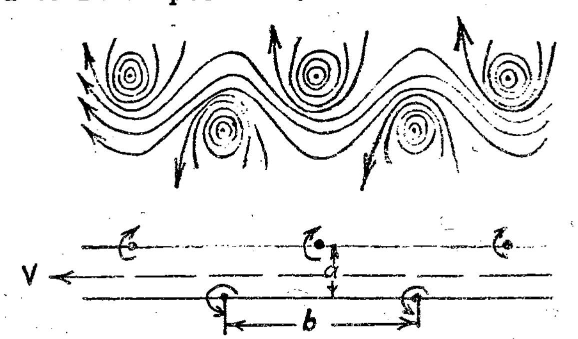


Fig. (3)

van Karman Vortices Analysis

Plotting Stokes' law, Rubey's formula, and Wadell's emperical formula on the R - C curve shown in Figure (2) we notice:

(1) Stokes' law agrees with the emperical formula only till the values of $R = 0.2$ which is a very low value.

(2) Rubey's formula agrees with the same formula till the values of $R = 10^3$.

(3) Beyond 10^5 the curve shows an abrupt change in shape due to the attack of the turbulence flow in the boundary layer at the front of the sphere.

Shape Factor

The shape of the gravel particles make them not applicable to the previous laws. To find the effect of a particle shape on its rate of fall the following shape factor form has been developed:

Shape Factor (S. F.) = c/a b

where c = longest axis of the particle

b = intermediate axis

c = shortest axis of the mutually perpendicular axes of the particle.

It should be understood that this shape factor relates only three of the multitude number of dimensions of the particle. There may be rounded, rough, smooth, or angular particles of the same shape factor.

There are other shape factors based on roundness, spherity, or other phsical characteristices of the particle but they do not adequately define its shape for hydraulic studies. This shape factor is the best for the studies of rate of fall since a & b are the most important dimensions that form the projected area of the particle which affects the drag force. Curves are available for Reynold's number (R) against the drag coeffecient (C) for the different shape factors.

The Behavior of the Settling Particles and the Mechanics of the Fluid

If a body moves through a fluid or a particle falls in it, the fluid will be accelerated from places of higher pressure to places of lower pressure. This acceleration is such that where the pressure is high the velocity is low and vice versa. The mathematical equation for this relation is:

$$P + 1/2\ d\ v^2 = H$$

where P = static pressure

v = liquid velocity

d = liquid density

H = total head

If the velocity of the particle is high enough it will cause much pressure reduction forming a vortex around it's zone. In case of a group of particles settling at the same time each one will have a vortex tail for itself. The interference of these vorticis will change their rate of fall.

This pattern of motion has been analyzed by van Karman. He made a conclusion that the relative spacing in two directions (shown in Figure 3) is related by the relationship $a/b = 1/\pi \cosh^{-1} \sqrt{2} = 0.2801$. He also obtained an equation for the system velocity V, which is $V = I/b \sqrt{8}$ where V = the velocity of the vortex, I = vortex intensity, and b = the longtudinal spacing between the particle and its neighboring one. The values of V were found to be smaller than the particle velocity, hence the vortex velocity is smaller than the particle velocity.

This analysis explains how a particle will fall in case of a batch of gravel being placed at a time and how the rate of fall of each particle will be reduced if their vortices interfered. This is more evidenced in the case of a very deep well.

CHAPTER III

SETTLEMENT OF GRAVEL PARTICLES BEING PLACED INDIVIDUALLY

Objective

Gravel particles are not spherical in shape. Their size is defined by the size of the sieve opening, e.g., a particle of 0.525" size means that it can be retained on a sieve of 0.525" opening. But this size is not the only dimension of the particle.

Moreover the particle may be smooth, rough, or of any surface condition, angular round or of any irregular shape. Also a batch defined by one sieve size will contain particles that are larger than this size, and smaller than the preceding sieve size. These particles will have different specific weights.

This shows that gravel particles vary from spheres in nominal dimension, shape, surface condition, and specific weight.

The best approach to study the settlement of the gravel particles is to find a coefficient that covers all these variations. This coefficient can be found by two ways, either having a special coefficient for each particular particle or having an average coefficient for each group of particles of one avergae size. The first way is impossible; but the second can be achieved by finding the average rate of fall of a group of particles of one average size. This coefficient will be called the particle coefficient (P. C.).

The objective of this chapter is to study the settlement of the gravel particles and relate the results to the settlement of the spheres through the particle coefficient.

Procedures & Apparatus

The apparatus used consisted of a plastic tube 5 3/4" diameter and 50' long as shown in Plate (2). At the top of the tube there was fixed a hopper-like mechanism that could be opened and closed by a string at the level of the tube bottom. This arrangment was made for accurate vision of the particle at its final settling point, as well as dropping the particle at the same time of starting the stop watch. The apparatus was kept perpendicular by a water balance (Plate 3); it was also well set up such that it does not shake and cause turbulence to the fluid.

Procedures for running the experiment were :

(1) The sample was obtained from different parts all over the country, thus it included all kinds of rocks, shapes, and surface conditions. To limit the variation in size the average size between each two successive sieves was considered as follows:

Sieve Size (inches)		Average Size (inches)
Passing	Retaining	
0.750	0.525	0.637
0.525	0.371	0.448
0.371	0.263	0.317
0.263	0.185	0.224
0.185	0.131	0.158
0.131	0.093	0.112
0.093	0.065	0.079
0.065	0.046	0.055
0.046	0.033	0.040
0.033	0.023	0.028

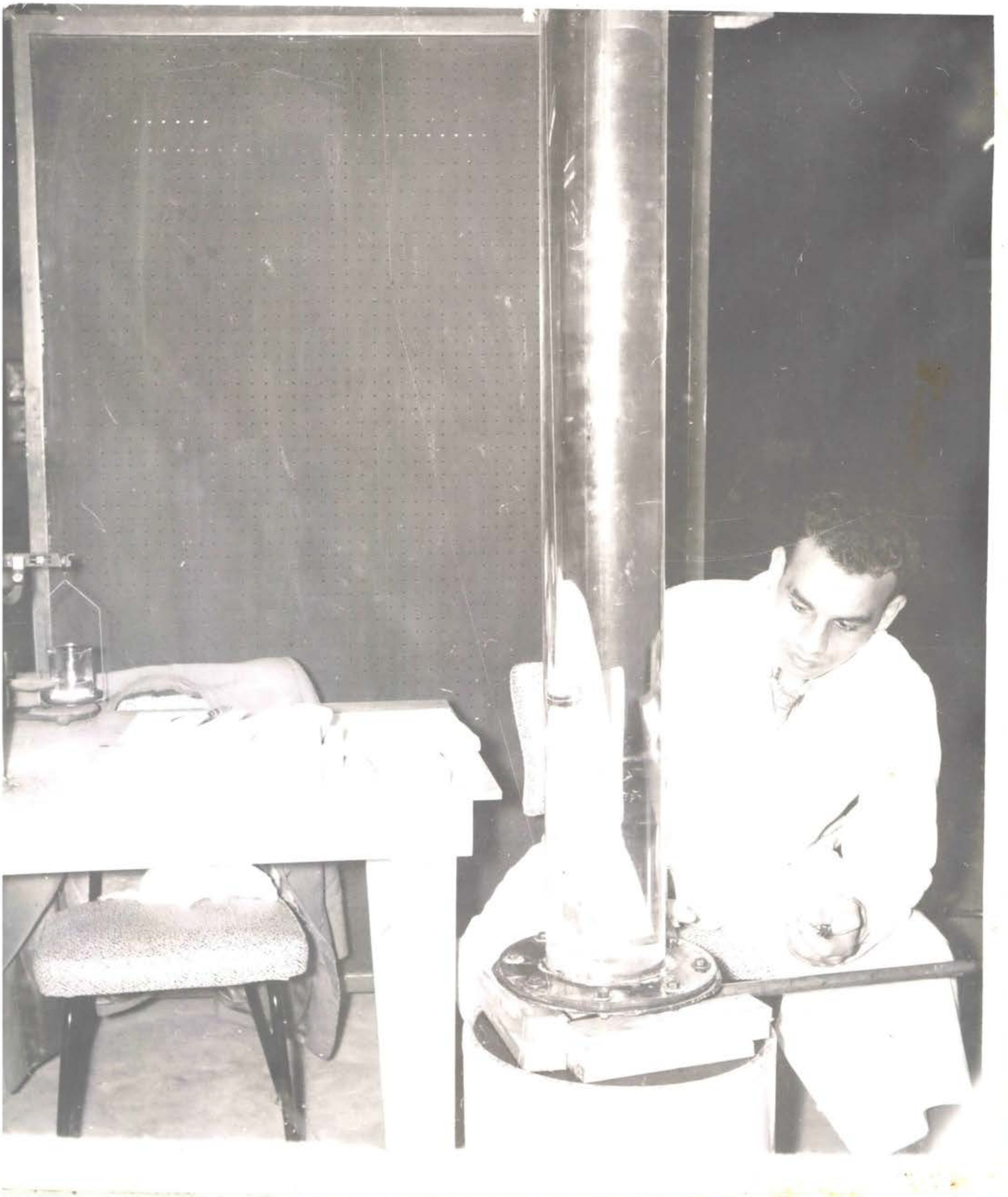


Plate (2): Rate of fall measuring apparatus

Plate (3)

Leveling the settling apparatus

before conducting the test

(2) Ten particles of each size were placed through the hopper-like mechanism. In case of large particles one was placed at a time, but in case of small or fine ones a group was placed at a time.

(3) Time taken by each particle until it reached the bottom of the tube was measured by the stop watch. In case of fine particles, when a group was placed at a time, an average reading was taken.

(4) From the time taken by each particle of the ten particles of each size the average time taken by a particle of this size was found.

(5) The average rate of fall was found by dividing the tube length by the average time.

(6) A curve was made between the average rate of fall and the average particle size. Also a table was made giving the maximum and the minimum values of the rate of fall.

Experimental Data

	Average Size (inches) 0.637	Particle Description	Average Size (inches) 0.448	Particle Description
Time in seconds	3.00	rough & white	3.20	round, small granite
" " "	4.00	smooth, gray & white	4.20	yellow porous sand stone
" " "	3.80	porous and red	3.70	flat, rough & gray
" " "	3.60	gray and flat	3.20	small, rough & black
" " "	4.00	flat and white	3.00	rough quartz
" " "	2.80	group of particles	2.80	round & black
" " "	2.40	granite stone	3.20	black & flat
" " "	2.40	gray and round	3.20	black & flat
" " "	2.20	smooth and round	3.40	flat, round & red
" " "	2.20	smooth, red, & round	3.00	group of particles
Total time	30.40	seconds	32.90	seconds
Average time	3.04	seconds	3.29	seconds
Average rate of fall	16.50	inches/sec.	15.20	inches/sec.

Experimental Data (cont.)

	Average Size (inches) 0.317	Particle Description	Average Size (inches) 0.224	Particle Description
Time in seconds	4.00	small & round	4.40	rough granite
" " "	3.40	yellow stone	3.80	round & black
" " "	4.40	red & round	3.60	group of particles.
" " "	6.00	flat & black	3.20	round granite
" " "	4.00	round & black	4.80	flat & smooth
" " "	3.40	rough granite	4.40	rough & black
" " "	2.70	round granite	4.00	rough & white
" " "	2.70	small round & black	3.40	group of particles.
" " "	3.40	round & black	3.20	" " "
" " "	3.60	group of particles	4.00	" " "
Total time	38.00	seconds	38.80	seconds
Average time	3.80	seconds	3.88	seconds
Average rate of fall	13.20	inches/sec.	12.80	inches/sec.

Experimental Data (cont)

	Average Size (inches) 0.158	Particle Description	Average Size (inches) 0.112	Particle Description
Time in seconds	4.20	arbitrary group	5.60	arbitrary group
" " "	4.70	" "	5.60	" "
" " "	5.00	" "	5.00	" "
" " "	4.40	" "	5.80	" "
" " "	4.50	" "	5.60	" "
" " "	4.80	" "	5.40	" "
" " "	4. 20	" "	5.50	" "
" " "	4.50	" "	4.70	" "
" " "	4.50	" "	5.80	" "
" " "	5.00	" "	5.50	
Total time	45.00	seconds	54.50	seconds
Average time	4.50	seconds	5.45	seconds
Average rate of fall	11.20	inches/sec.	9.30	inches/sec.

Experimental Data (cont.)

	Average Size (inches) 0.079	Particle Description	Average Size (inches) 0.055	Particle Description
Time in seconds	6.20	arbitrary group	6.60	arbitrary group
" " "	6.00	" "	7.00	" "
" " "	6.00	" "	7.40	" "
" " "	5.80	" "	6.60	" "
" " "	6.00	" "	7.00	" "
" " "	6.60	" "	7.20	" "
" " "	5.20	" "	7.80	" "
" " "	5.50	" "	8.00	" "
" " "	6.00	" "	6.00	" "
" " "	6.00	" "	5.50	" "
Total time	59.30	seconds	69.10	seconds
Average time	5.93	seconds	6.91	seconds
Average rate of fall	8.40	inches/sec.	7.30	inches/sec.

Experimental Data (cont.)

	Average Size (inches) 0.040	Particle Description	Average Size (inches) 0.028	Particle Description
Time in seconds	10.00	arbitrary group	12.70	arbitrary group
" " "	10.00	" "	13.00	" "
" " "	10.70	" "	13.20	" "
" " "	9.70	" "	14.60	" "
" " "	9.70	" "	12.60	" "
" " "	9.40	" "	13.00	" "
" " "	10.00	" "	12.20	" "
" " "	10.00	" "	12.80	" "
" " "	9.80	" "	12.60	" "
" " "	9.40	" "	12.60	" "
Total time	98.50	seconds	124.30	seconds
Average time	9.85	seconds	12.43	seconds
Average rate of fall	5.10	inches/sec.	4.00	inches/sec.

Results & Conclusion

The following table gives the maximum and the minimum values of the rate of fall of each gravel particle used.

Aver. Size (inches)	Size Range Max. Min. Difference	Aver. Rate of fall.	Rate of Fall Range Max. Min. Difference
(A) 0.637	0.725 - 0.525 = 0.175	16.5	22.7 - 12.5 = 10.2
0.448	0.525 - 0.371 = 0.154	15.2	18.0 - 11.9 = 6.1
0.317	0.371 - 0.263 = 0.108	13.2	18.6 - 8.35 = 9.25
0.224	0.263 - 0.185 = 0.078	12.8	16.0 - 10.7 = 5.3
(B) 0.158	0.185 - 0.131 = 0.054	11.8	11.9 - 10.0 = 1.9
0.112	0.131 - 0.093 = 0.038	9.3	10.6 - 8.6 = 2.0
0.079	0.093 - 0.065 = 0.028	8.4	9.6 - 7.6 = 2.0
0.055	0.065 - 0.046 = 0.019	7.3	9.1 - 6.25 = 2.85
(C) 0.040	0.046 - 0.033 = 0.013	5.1	5.3 - 4.65 = 0.65
0.028	0.033 - 0.023 = 0.010	4.0	4.1 - 3.42 = 0.88

From the above table we find:

(1) The difference between the maximum and the minimum values of the rate of fall increases as the difference between the maximum and the minimum values of the particle size increases and vice versa.

(2) The rate of fall of the particle increases by increasing its diameter. The relation between them is a log relation as shown on the semi-log curve Figure (4) which is drawn to the exact equation of a straight line as follows:

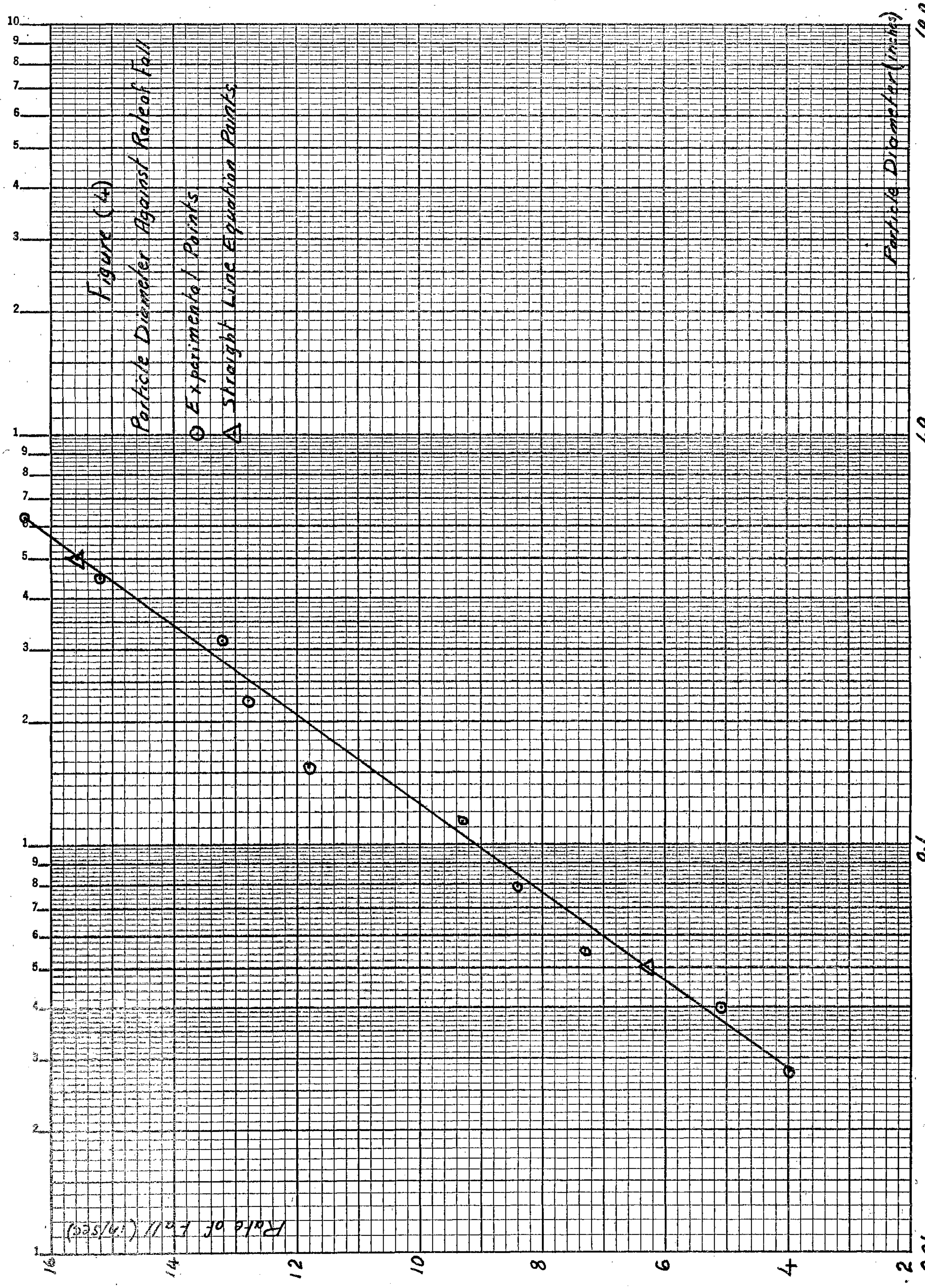


Figure (4)
Particle Diameter Against Rate of Fall
Experimental Points
Straight Line Equation Points
Particle Diameter (inches)
Rate of Fall (in/sec)
10.0
1.0
0.1
0.01
16
14
12
10
8
6
4
2

The equation for a straight line is $Y = m x + B$. Assuming the velocity (V) to be represented on the Y-axis and the diameter (D) on the X-axis; hence the equation can be written $V = \log D\ m + B$.

Substituting for V and log D by the values given in the previous table; hence

(D)	V = log D m + B ;	(D)	V = log D m + B.
(0.637)	16.5 = (9.804 - 10) m + B ;	(0.112)	9.3 = (9.048 - 10) m + B.
(0.448)	15.2 = (9.652 - 10) m + B ;	(0.079)	8.4 = (8.897 - 10) m + B.
(0.317)	13.2 = (9.501 - 10) m + B ;	(0.055)	7.3 = (8.740 - 10) m + B.
(0.224)	12.8 = (9.350 - 10) m + B ;	(0.040)	5.1 = (8.602 - 10) m + B.
(0.158)	11.8 = (9.198 - 10) m + B ;	(0.028)	4.0 = (8.447 - 10) m + B.
Adding	69.5 = (47.505 - 50) m + B:		34.1 = (43.734 - 50)m + B.

Hence we have the two equations:

$$69.50 = (47.505 - 50)\ m + B \quad \ldots\ldots. \ (1)$$

$$\text{and} \quad 34.10 = (43.734 - 50)\ m + B \quad \ldots\ldots. \ (1)$$

Subtracting (2) from (1) hence: $35.4 = (3.771)\ m$

or $m = (35.40/3.771) = 9.387$

Substituting in (1) hence: $69.50 = (47.505 - 50) \times 9.387 + 5\ B$

$= (23.4206) + 5\ B$

or $B = 18.584$

Substituting in equation (1) by the values of m and B for $D = 0.5$ and $D = 0.05$ where $\log 0.5 = (8.699 - 10) = -1.301$ and $\log 0.05 = (9.699 - 10) = -0.301$

hence $V_1 = -1.301 \times 9.387 + 18.584 = 15.664$

and $V_2 = -0.301 \times 9.387 + 18.584 = 6.364$

Drawing the straight line joining V_1 & V_2 we find that it passes through the points already plotted for the values of V & D, Figure (4), which represent the results taken from the experiment made. Hence this straight line represents the relation between the particle diameter and its rate of fall.

Since the rate of fall considered was the average for a wide variety of particles, its values cover the different shapes, surface conditions, specific weights, and sizes variations. It shows that the rate of fall of a gravel particle increases by increasing its size.

Plotting the same ralation between V & D on log-log paper we get the curve shown in Figure(5).

Comparing Figure (5) with Figure (1) which gives the relation between the sphere diameter (D) and its rate of fall (V) we find that for the same range of sizes 0.637" to 0.028" - shown by two circled dots in Figure (1)- this relation is represented by a straight line in Figure (1) and by a curve in Figure (5). This curvature of Figure (5) is expected due to the variation of the gravel particles from the spheres. But it indicates that the gravel particles do not obey settling laws for spheres, although the rate of fall of a gravel particle increases by increasing its size.

Since the shape factor covers the variation in the shape of the particle only another factor is needed to cover all the variations together. Using the values of the rate of fall of a gravel particle and a sphere both of the same size another factor can be developed that relates and covers all the variations. This factor will be called the particle factor, it is defined as the ratio of the rate of fall of the gravel particle (V) to the rate of fall of a sphere of the same size (V') i.e Particle Factor (P. F.) = V/V'. Both values of V and V' should be taken under the same conditions of temperature and liquid specifications.

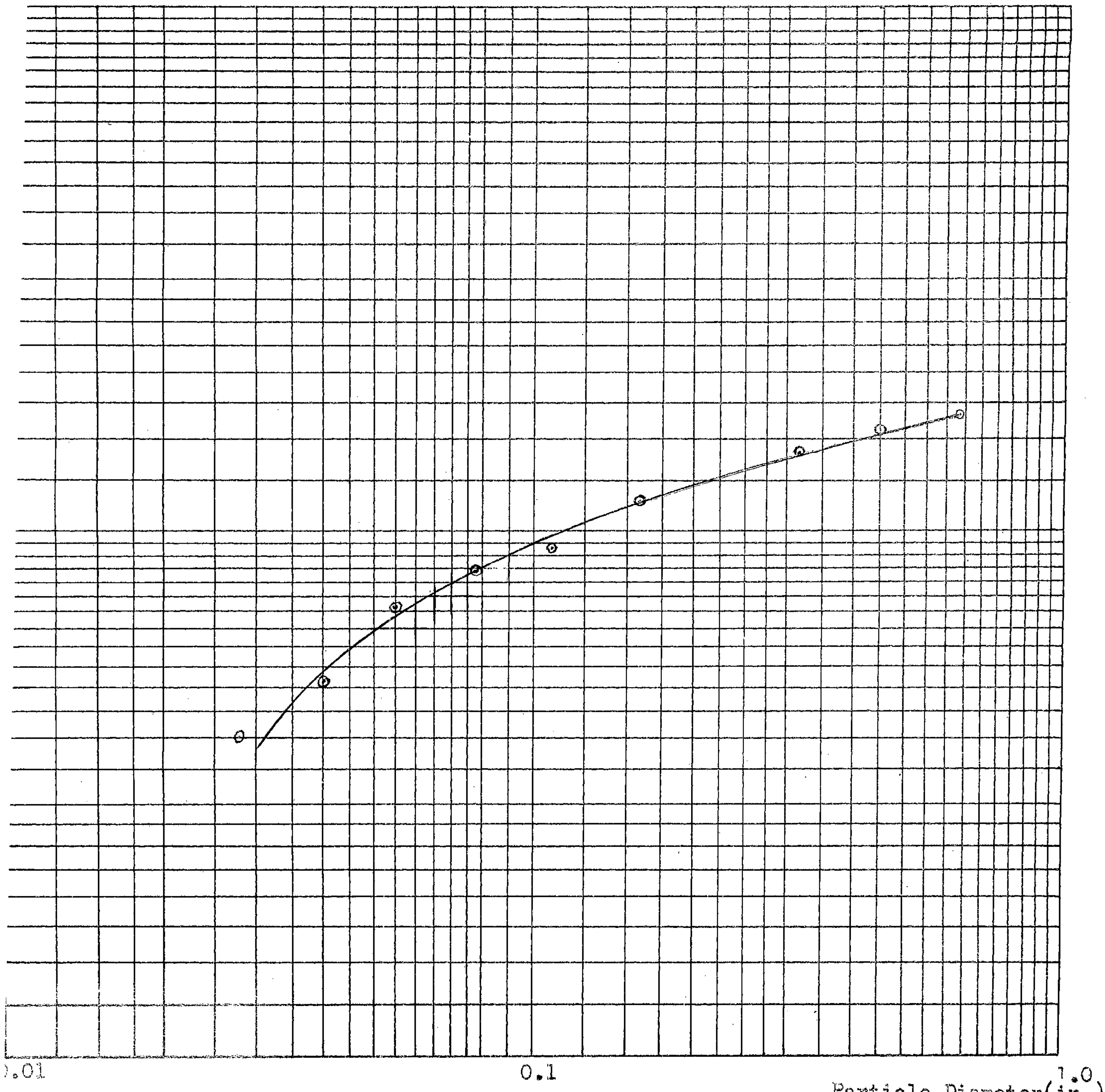


Figure (5): Particle Diameter Against Rate of Fall.

The particle factor can give the rate of fall of any gravel particle if the rate of fall of a sphere of the same size was known. An attempt was made to find the numerical values of the particle factor of the particles used in this experiment but the actual values of the rate of fall of spheres of the same size were not available.

Conclusion

"Gravel paricles do not obey the settling laws of spheres, but the rate of fall of a gravel particle increases by increasing its diameter and vice versa. The relation between the rate of fall of the gravel particle and its diameter is a log relation."

CHAPTER IV

SETTLEMENT OF A SYSTEM OF GRAVEL PARTICLES

Objective

In Chapter III the behavior of individual particles while settling was discussed, but when a system of particles settle at a time their behavior will be different. From the analysis made by Karman (page 13) we find that the particles have to be apart by a certain distance given by the ratio $a/b = 0.2801$ in order that no interference will happen between them. This ratio can not be maintained during settling of gravel particles. Moreover, the graded pack is composed of different sizes, and not only that each size has a different rate of fall; but also for the same size there is a wide range of rates as shown in Chapter III, page 24.

For these differences of the settlement of a group of particles from the settlement of a single particle this chapter has been made to show the effect of certain factors on the rate of fall of a system of particles. At the same time it will give a full picture of the settlement of the system.

Procedures & Apparatus

The model well shown in Plate 4 was used. It consisted of a tube 6" internal diameter and 20' high, with a transperant plastic tube 5 3/4" diameter in its middle for vision and taking pictures. The bottom consisted of a steel tube with a piston inside that was operated upwards by a hand pump for extracting the sample in sections in case of gravel placement tests discribed in the next chapter. For measuring the rate of fall in these experiments the stop watch was used. The fall distance was the end of the plastic tube.

Three experiments were conducted each for a different purpose as follows:

Experiment No. (1)

The purpose of this experiment is to find the effect of the particle size on the rate of fall of a system of particles.

Experiment No. (2)

This experiment was made to find the effect of the batch size on the rate of fall.

Experiment No. (3)

In order to find how a batch will settle if its particles were held together by an adhering fluid.

Experiment No. (1)

Sample Preparing

A batch was prepared with minimum weight of large size particles and maximum of the small size ones according to the following table:

Particle Size (inches)	Weight (lbs)	Cumulative Weight (lbs)	Retained Weight (%)
0.525	0.25	0.25	1.50
0.371	0.50	0.75	4.55
0.263	0.75	1.50	9.00
0.158	1.00	2.50	15.00
0.131	1.25	3.75	22.60
0.093	1.50	5.25	31.80
0.650	1.75	7.00	42.50
0.046	2.00	9.00	54.50
0.033	2.25	11.25	68.50
0.230	2.50	13.75	83.50
0.016	2.75	16.50	100.00

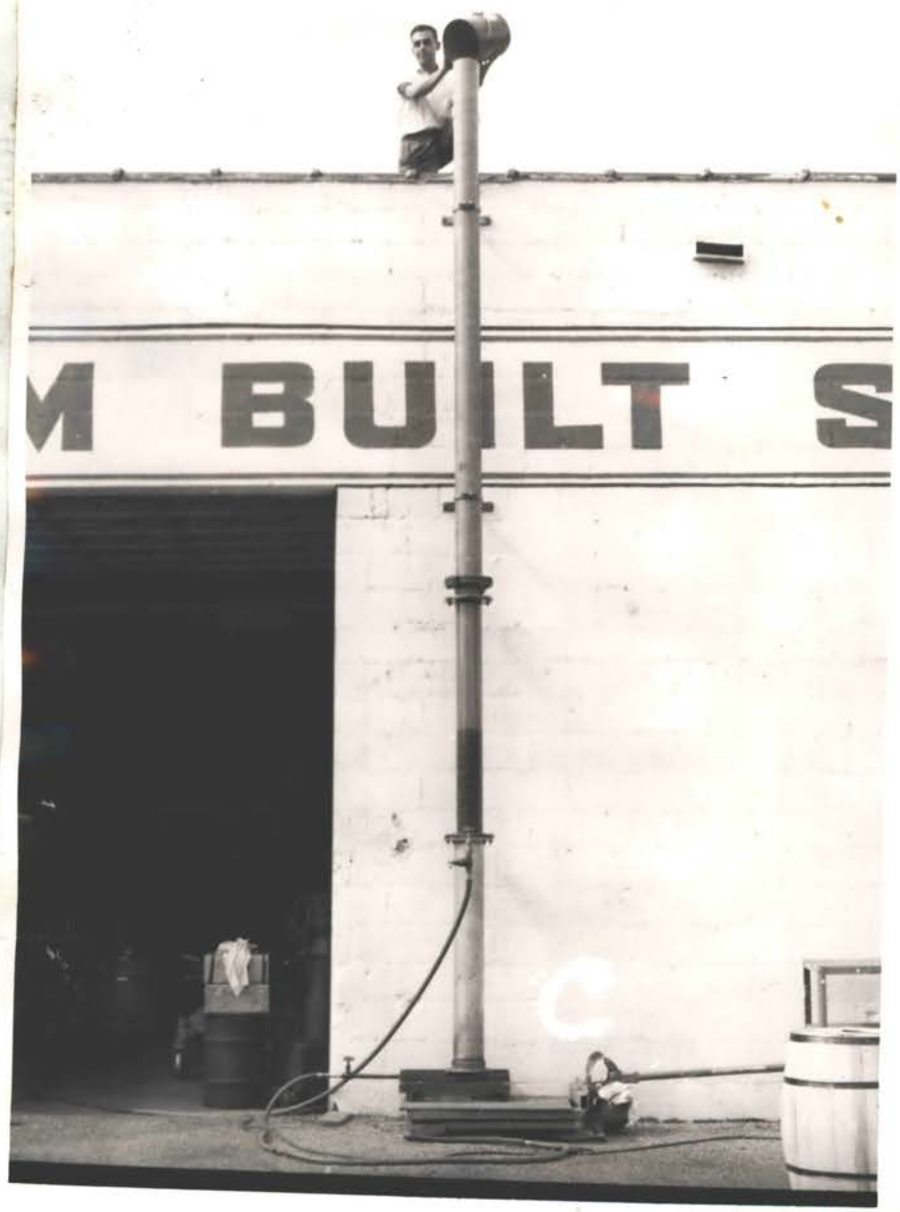


Plate (4)

The Model Well

Experimental Data

The batch was divided into three equal parts and each part was placed separately. The time at which each particle - that specifies a certain size- reached the end of the plastic tube was measured. Pictures were taken for the settlement of each size. The readings are shown in the following table:

First Test		Second Test		Third Test	
Time in (secs.)	Particle Description	Time in (secs.)	Particle Description	Time in (secs.)	Particle Description
5	large sizes only	6	large sizes	6	large sizes
7	second size of the large sizes	8	second size of the large sizes	8	second size of the large sizes
10	medium sizes	10	medium sizes	10	medium sizes
15	mixture of sizes	14	mixture of sizes	16	mixture of sizes
20	mixture of sizes	20	mixture of sizes	20	mixture of sizes
27	mixture of sizes	27	mixture of sizes	27	mixture of sizes
30	fine sizes	30	fine sizes	30	fine sizes
40	" "	40	" "	40	" "
50	" "	50	" "	50	" "
60	" "	60	" "	60	" "
90	silt	90	silt	90	silt

Pictures taken are shown in Plates 5, 6, 7, 8, 9, & 10.

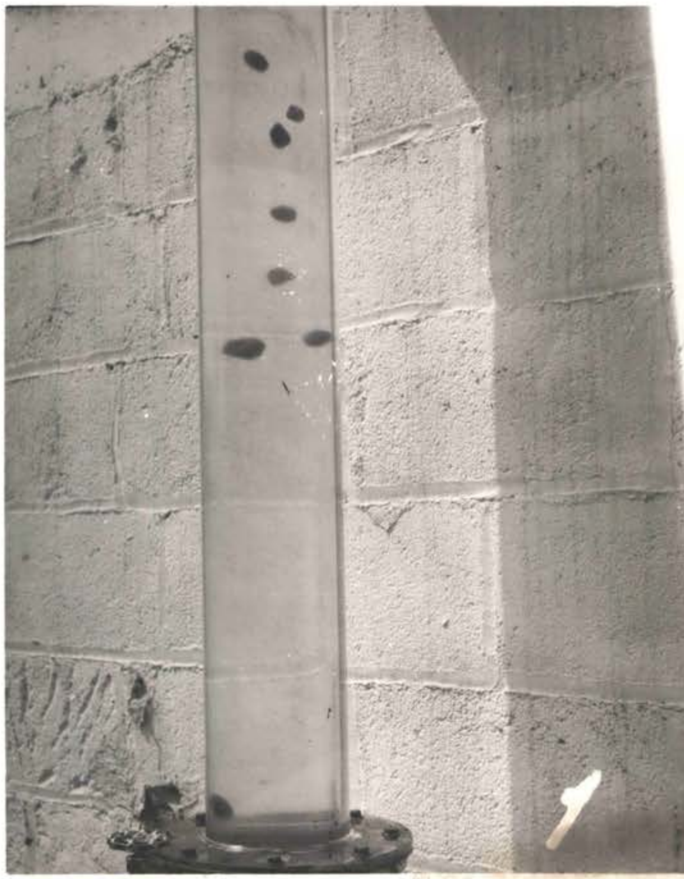


Plate (5)

First appearence of the large size particles

Plate (6)

Large size particles while settling

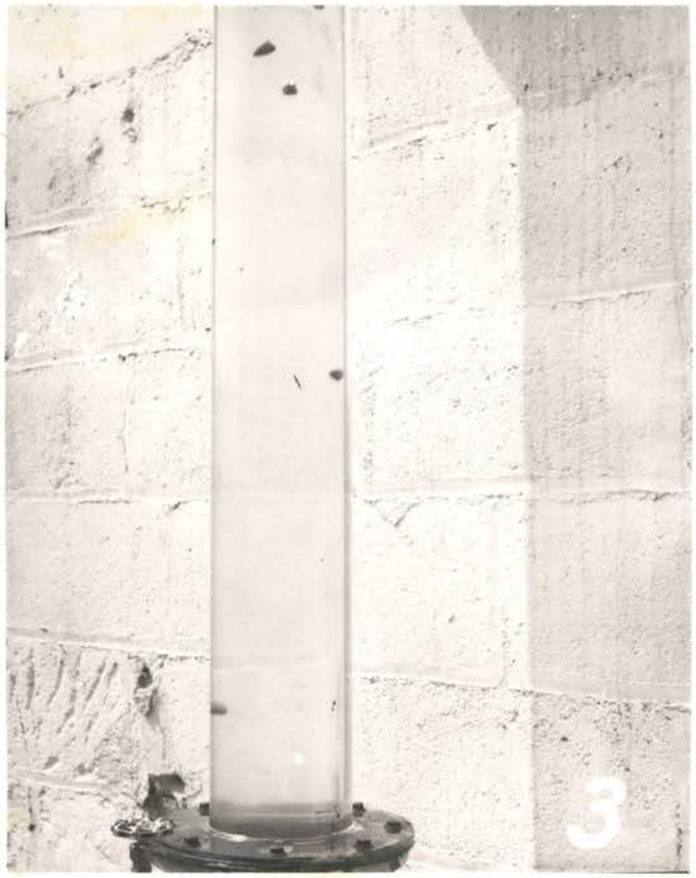


Plate (7)

Settlement ofmedium size particles

(Notice the gap between the particles)

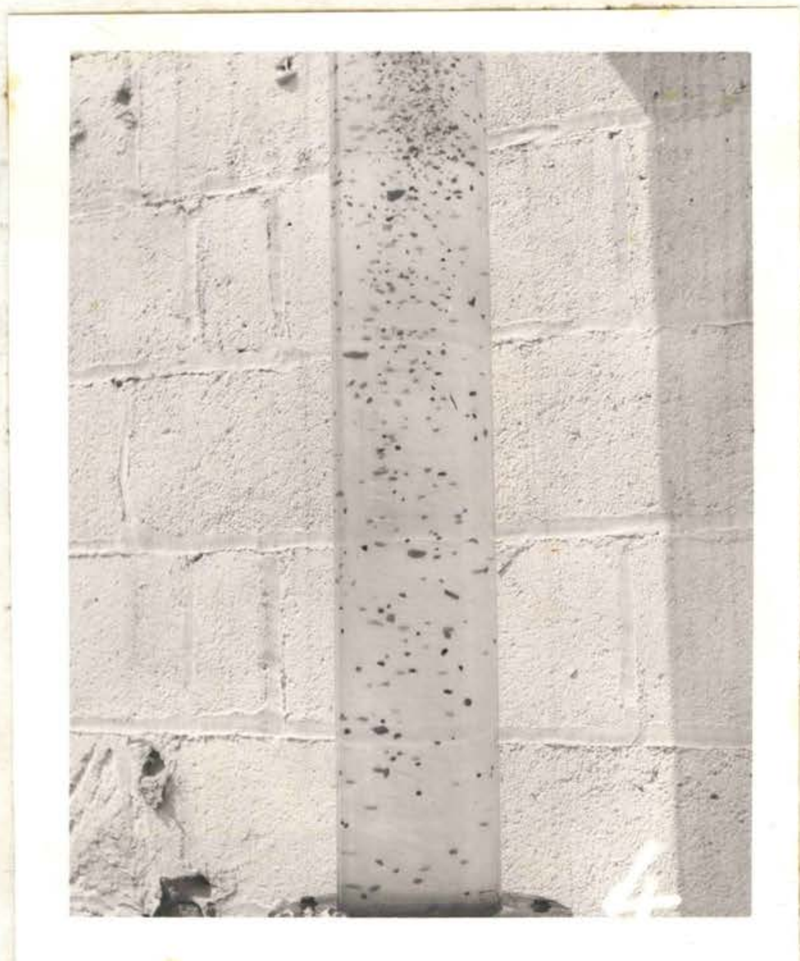


Plate (8)

The appearence of the mixture

(Notice that there was still some large particles)

Plate (9)

The mixture while settling

Plate (10)

The settlement of the fine particles

Observations

From the pictures taken and the data collected we observe the following:

(1) Large size particles traveled faster than any (Plates 5 & 6)

(2) There were no particles observed in the tube between the 7th and the 10th seconds. Suddenly at the 15th second a mixture of particles appeared in a variety of sizes as shown in Plate (8).

(3) This mixture continued for 15 seconds, i.e., until the 30th second as shown in Plate (9).

(4) By the 30th second fine particles were found only in the tube as shown in Plate (10) and they continued for another 30 seconds, i.e., till the 60th second.

(5) The silt continued dripping for 30 seconds, i.e., until the 90th second.

Results & Conclusion

(1) If a pack was formed such that it contained a small percentage of large size particles they will settle faster than any and form a coarse layer at the bottom.

(2) Fine particles always settle at a slow rate and remain at the top.

(3) The pack that will give the best mixing is that one composed of medium sizes only. Their rates of fall are close and they mix with each other before reaching the bottom.

From these results the following conclusion can be made:

"The pack that is composed of medium size particles, or particles whose sizes are close to each other, will give the least amount of segregation i.e. a pack whose structure is close to the uniform pack structure will give the least amount of segregation."

Experiment No(2)

Sample Preparing & Procedures

The sample was prepared with equal weights of each size according to the following table:

Particle Size (inches)	Weight (grms)	Cumulative Weight (grms)	Retained Percentage (%)
0.525	500	500	11
0.371	500	1000	22
0.263	500	1500	33
0.183	500	2000	44
0.131	500	2500	55
0.093	500	3000	66
0.066	500	3500	77
0.046	500	4000	88
0.033	500	4500	100

The sample was well mixed then divided by the mechanical separator to multiple portions i.e. 1/2, 1/4, 1/8, & 1/16 or weights of :

4500/2 = 2250 , 4500/4 =1125, 4500/8 = 562, and 4500/16 = 281 where all weights are in grams.

Each group was washed, cleaned and dried before the test.

Each batch was placed in the model well separately.

Time was measured whenever each size reached the end of the plastic tube.

Pictures were taken for the settlement of the last group (281 grams). They are shown in Plates 11, 12, 13, 14, 15, & 16 with the explanation of each picture opposite to it.

Experimental Data

Batch No. (1) (281 grms)		Batch No.(2) (562 grms)	
Time (secs)	Particle Description	Time (secs)	Particle Description
5	large sizes	7	large sizes
10	large sizes	10	large sizes
15	medium sizes	15	large and medium sizes
		17	large and medium sizes
20	medium sizes mixed with large sizes	20	fine, large, & medium sizes mixed together
25	fine particles and a mixture of sizes together	25	fine particles and a mixture of sizes together
35	fine particles	35	fine particles
46	silt (last drips)	46	silt (last drips)

Batch No.(3) (1125 grms)		Batch No.(4) (2250 grms)	
7.5	large sizes	8	large sizes
12	large and medium sizes	10	large and medium sizes
15	large and medium sizes	14	medium and mixture of sizes
20	fine, medium and large sizes mixed together	17	fine, medium and large sizes mixed together
26	fine particles	25	fine particles
46	silt (last drips)	46	silt (last drips)

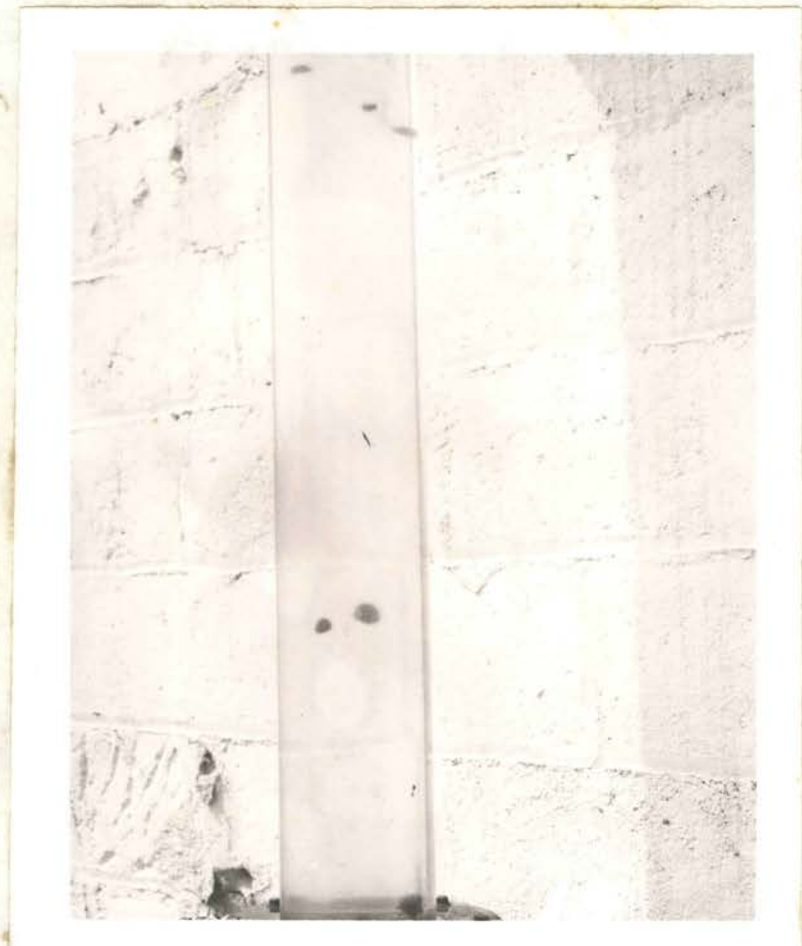


Plate (11)

Settlement of large size particles

(Notice the wide gap at the start)

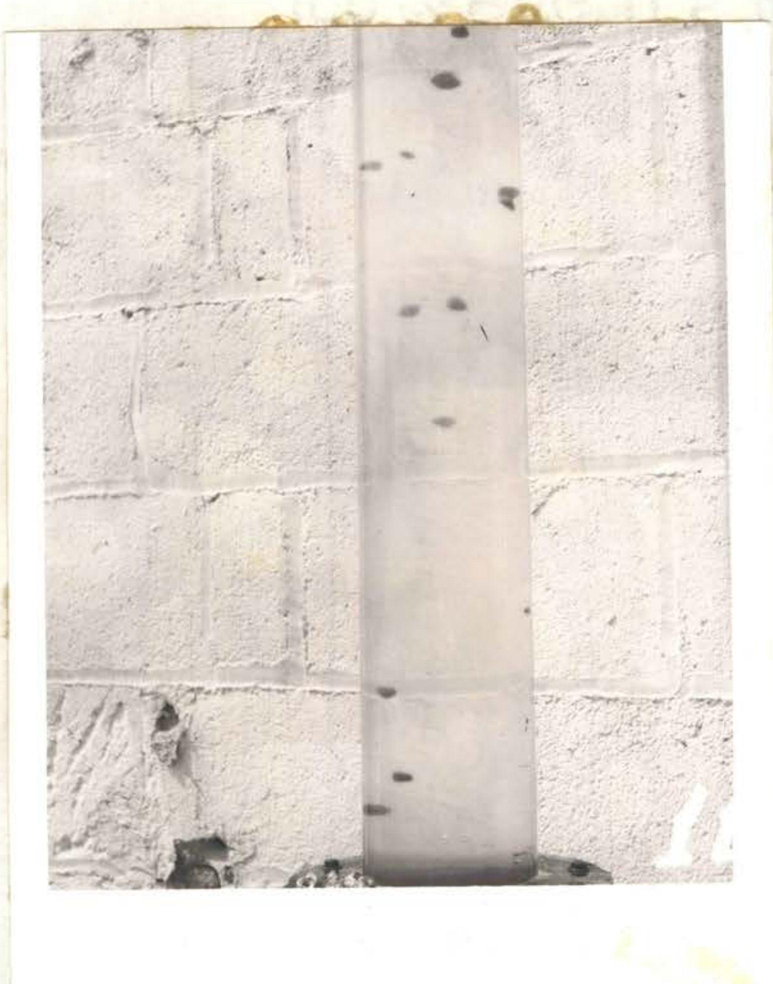


Plate (12)

Large size particles after the start of settling

(Notice the approach of the particles)

Plate (13)

Settlement of medium size particles

(Notice that there was no large size particles)

Plate (14)

Medium size particles at the end of their settling stage

(Notice the approach of the fine particles)

Plate (15)

Settlement og the mixture of the particles

(Notice the suspension of the fine particles)

Plate (16)

Last drips of silt

Observations

From the experimental data taken, we find:

(1) The time for settlement taken by large size particles was delayed by the increase in the volume of the batch as shown by the following table:

For the batch of 281 grams large size particles took 5 seconds to settle.
" " " " 562 " " " " " 7 " " "
" " " " 1125 " " " " " 7.5 " " "
" " " " 2250 " " " " " 8 " " "

(2) The medium size particles moved faster and took shorter time to settle by increasing the size of the batch as shown by the following table:

For the batch of 281 grams at the 15th second medium sizes appeared alone.
" " " " 562 " " " 15th second medium sizes appeared mixed with large size ones.
" " " " 1125 " " " 12th " " " " " " "
" " " " 2250 " " " 10th " " " " " " "

(3) Fine particles also moved faster by increasing the size of the batch as shown by the following table:

For the batch of 281 grams fine particles appeared after 25 seconds
" " " " 562 " " " " " 20 "
" " " " 1125 " " " " " 20 "
" " " " 2250 " " " " " 17 "

(4) Another important observation is that rapid mixing between the particles can be done by increasing the size of the batch as shown below:

When the batch was 281 grams the three sizes mixed after 20 seconds
" " " " 562 " " " " " " 17 "
" " " " 1125 " " " " " " 15 "
" " " " 2250 " " " " " " 14 "

Results & Conclusion

(1) Increasing the size of the batch will delay the rate of fall of the large size particles and accelerate the medium and the fine ones.

(2) The relation between batch size and rate of fall is not a direct relation i.e. doubling the rate of fall can not be done by doubling the batch size, or using a half of the size of the batch.

(3) Faster mixing can be obtained by increasing the size of the batch.

As a general conclusion it can be stated that:

"The larger the size of the batch the faster and the better the particles will mix together, and consequently the less the amount of segregation"

SUMMARY

The previous two experiments show two important points concerning the structure and the size of the batch, i.e.,

(1) The pack should be composed of medium size particles and the closer the sizes are to each other the better results could be obtained.

(2) Large and fine particles in one pack should be avoided by all means.

(3) The batch taken from the pack to be poured into the well should be as large as possible. The larger the size of the batch the less the segregation.

Experiment No.(3)

Sample Preparing & Procedres

The sample was prepared by mixing equal amounts of each size of the sizes from 0.525" to 0.016" throughly with a high viscosity oil.

The mixture was placed from the the opening of the model well while it was empty, because the oil used was soluble in water. Hence the settling medium can be considered the atmoshperic air.

After settlement the sample was extracted and examined under the microscope.

Observations

(1) Sizes of 0.371" or larger were not adhered to the rest of the group, or even well adhered to each other.

(2) Sizes of 0.263" or less were well adhered together.

(3) The smaller the size of the particle the better it was adhered to the other particles.

(4) Angular or rough particles even those of large sizes were more adhered to the group than smooth or round ones.

Results & Conclusion

A sample can be placed with the least amount of segregation by the use of a strong adhering fluid under the following conditions:

(1) The adhering force of the fluid should be greater than the water force resistance or the drag force.

(2) The pack should be composed of medium size particles preferably rough and angular ones.

(3) The fluid should be easy to extract, after settlement, by the surging operation.

CHAPTER V

EXPARIMENTAL WORK TO FIND A METHOD FOR GRAVEL PLACEMENT IN WATER WELLS WITH THE LEAST AMOUNT OF SEGREGATION

Four methods have been selected for experimental work i.e. the bailing, the tremie, the pump, and the package methods. The bailing method is the one first known, while the tremie method has been recently introduced, but both the pump and the package methods are under research considerations & have been selected by Edward E. Johnson, Inc.

Each of these methods will be tried experimentaly, and they will be compared with each other from the point of segregation i.e. which one will give the least amount of segregation.

Procedures & Apparatus

The model well shown in plate (4) was used. Each method was tried according to its specific procedures.

One sample was used for the four methods. It was composed of the particles between 0.033" and 0.185" size. The structure was formed according to a symmetrical curve joining the two points of 5% over the minimum size and 5% below the maximum size, so that the sizes of 0.033" and 0.185" are both included in the pack. The curve was symmetrically divided by the line of 50% retained size i.e. the lower half of the curve was symmetrical to the upper half as shown in Figure (6).

The sample was well mixed by the mechanical mixing machine, washed by the washing machine, then dried before each test.

SAND ANALYSIS

EDWARD E. JOHNSON, INC.

SAINT PAUL, MINN.

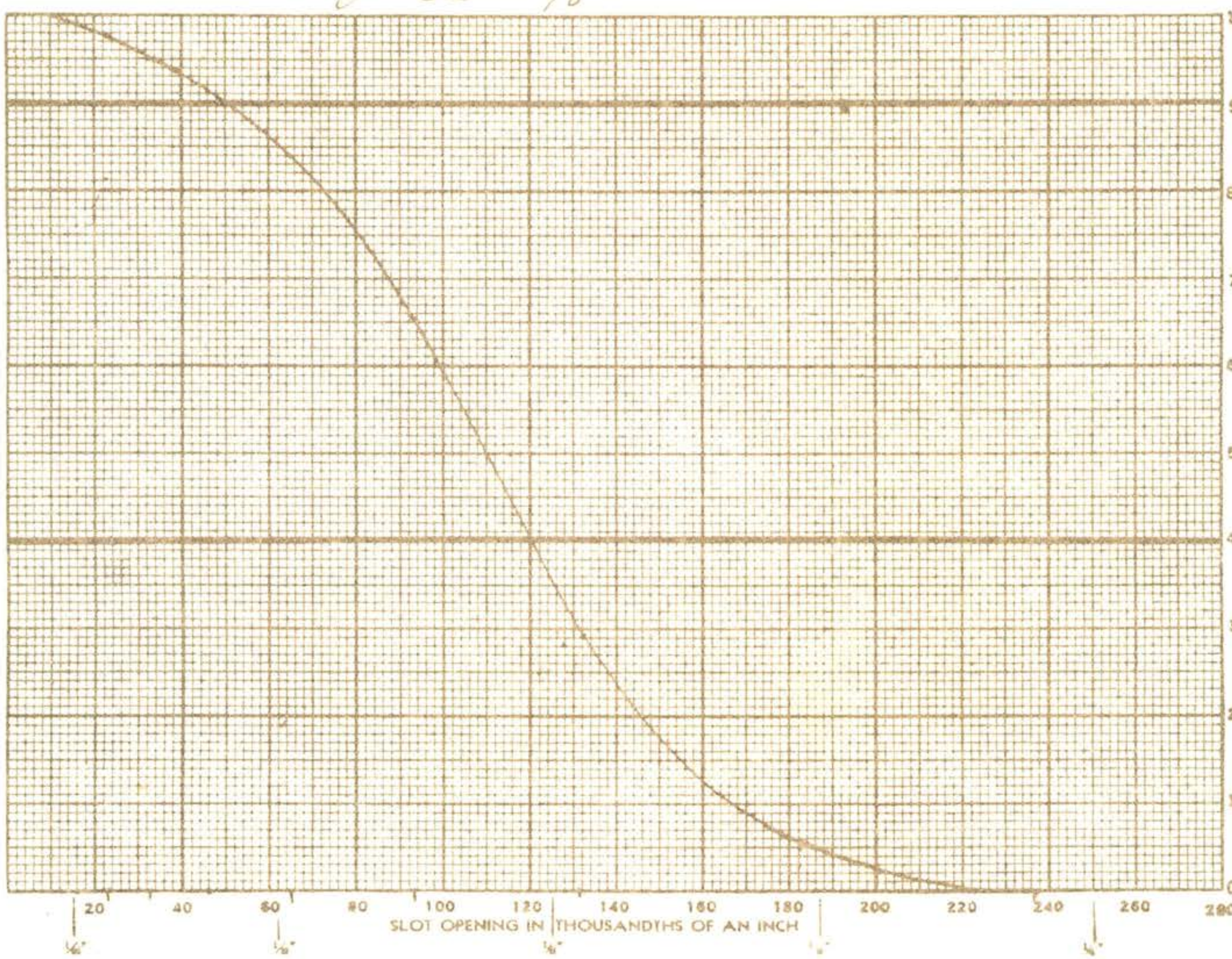
Sample sent in by ________ **Figure (6)**

Town ________ State ________ Date ________

From well of ________

Remarks ________ Sample "C"

commonsize $\frac{1}{32} - \frac{3}{16}$, seive size .033 – .185



	SCREEN OPENINGS	CUMULATIVE WEIGHTS	CUMULATIVE PER CENT
RETAINED ON	.230	0	0
	.185	5	5
	.131	30	[illegible]
	.093	65.5	[illegible]
	.065	84	[illegible].5
×	.046	92	8.0
	.033	95	3.0
PASS THRU	.016	100	5.0
TOTALS			

SLOT OPENING RECOMMENDED UNC = 2.36

SIZE SCREENS ________ IN. ________ FT.

RECOMMENDATION MADE BY ________

SO MANY CONSIDERATIONS ENTER INTO THE MAKING OF A GOOD WELL THAT, WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SAND SAMPLES ARE CORRECT, WE ASSUME NO RESPONSIBILITY FOR THE SUCCESSFUL OPERATION OF JOHNSON WELL SCREENS

After each test had been completed the gravel column was extracted in sections about two inches thick. Each section was dried, analyzed and its sand analysis curves were drawn.

(A) The Bailing Method

According to this method gravel has to be placed by being poured through the well opening and permitted to travel freely till it reaches the bottom.

The same procedure was followed in this experiment, and pictures were taken while gravel was settling.

Observations and Remarks While Running The Test

1 - The sample was divided into two buckets and each bucket was placed after the other.

2 - Time record was as follows:

Time in seconds	Particle Description
0	Start bailing
7	Large size particles
from 7 to 10	A gap with no particles in the tube
10	Large size particles with mixture of different sizes.
15	Medium and fine size particles.
20	Mixture of particles.
25	Fine particles.
30	Fine particles.
85	Silt appears
135	Silt settles completely.

3 - Total time taken was 60 seconds.

4 - There was a gap of time between the placement of the two buckets.

5 - Temerature was 80 degrees Fah.

Experimental Data

After the sample was fully settled in the model well it was extracted in sections about 2" each. Each section was dried and the sand analysis data was collected then the rsults were reported in the given table (page 56).

From this table the sand analysis curves were drawn in Figures 7, 8, 9, & 10.

Figure (7) shows the structure of the upper group. It shows that it is much deviated from the origin, which means that this group is much segregated in its structure.

Figure (8) shows the structure of the central group. It shows that it is less segregated than the upper group.

Figure (9) shows the structure of the bottom group. It shows that it is of coarser structure than the origin.*

Figure (10) shows a comparison between the upper, the central, and the bottom groups. It indicates that the central group is the least segregated one.

Pictures taken are shown in Plates 17, 18, 19, & 20 pages 58 & 59.

Plate (17) shows how large size particles were settling faster than any.

Plate (18) shows how the mixture included a variety of particles.

Plate (19) shows the turbulence that happened while pouring the next bucket. Notice the interference of the large particles of the next bucket into the fine particles of the preceding bucket. The dim part in the picture is due to the silt disturbence.

Plate (2) shows the sample after settlement. Notice the accumulation of the fine particles at the top and the coarse ones at the bottom.

Results: "The above pictures and sand analysis curves prove that the bailing method produces a segregated pack."

(*) The word origin refers to the the sand analysis curve of the original sample, given in Figure (6)

Sieve Analysis Results of The Bailing Method

Section Number	Depth	Sieve Size 0.185	0.131	0.093	0.065	0.046	0.033	0.023	UNC
		Cumulative Per Cent Retained							
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	
1st	1"	0.001	0.955	5.35	12.3	24.8	41.0	88.0	1.6
2nd	3"	0.05	2.50	16.5	37.5	60.0	73.5	97.0	2.5
3rd	5"	0.055	0.80	31.5	55.0	74.0	84.0	98.0	
4th	7"	0.06	17.0	49.0	72.0	87.0	94.0	99.0	2.07
5th	9"	4.20	28.0	63.5	83.0	92.5	96.0	99.0	2.34
6th	11"	5.3	27.5	65.5	83.5	93.5	97.5	99.5	
7th	12"	4.1	28.0	65.0	83.5	93.0	96.0	99.0	
8th	13"	4.0	26.0	63.0	82.5	92.0	95.5	99.5	
9th	15"	6.55	32.8	70.0	86.0	93.0	96.0	99.0	1.55
10th	17"	5.2	33.0	78.0	86.0	93.0	97.0	99.0	
11th	19"	6.15	32.8	71.0	87.0	95.0	97.0	99.0	
12th	21"	5.9	32.5	71.0	88.0	94.5	97.5	99.0	
13th	22"	7.0	35.6	73.5	89.0	95.0	97.5	99.5	1.97
14th	23"	7.0	34.0	73.0	89.0	95.0	97.5	99.5	
15th	25"	4.5	29.0	70.0	88.0	95.0	98.0	99.5	1.77
16th	27"	4.9	37.5	77.0	92.0	97.5	99.0	99.7	1.98
17th	29"	8.0	43.5	77.0	90.5	96.0	98.5	99.6	2.06
18th	31"	6.1	35.5	74.0	90.0	96.0	98.6	99.7	
19th	33"	5.1	31.0	73.0	89.0	97.0	98.0	100.0	1.9
20th	35"	7.0	38.2	77.0	91.5	97.0	99.0	100.0	
21st	37"	6.6	25.0	82.5	95.0	98.5	99.5	100.0	1.51
22nd	39"	9.5	21.5	89.0	96.0	98.5	99.0	100.0	1.31
Origin		5.0	30.0	65.5	84.0	92.0	95.0	100.0	2.36

SAND ANALYSIS

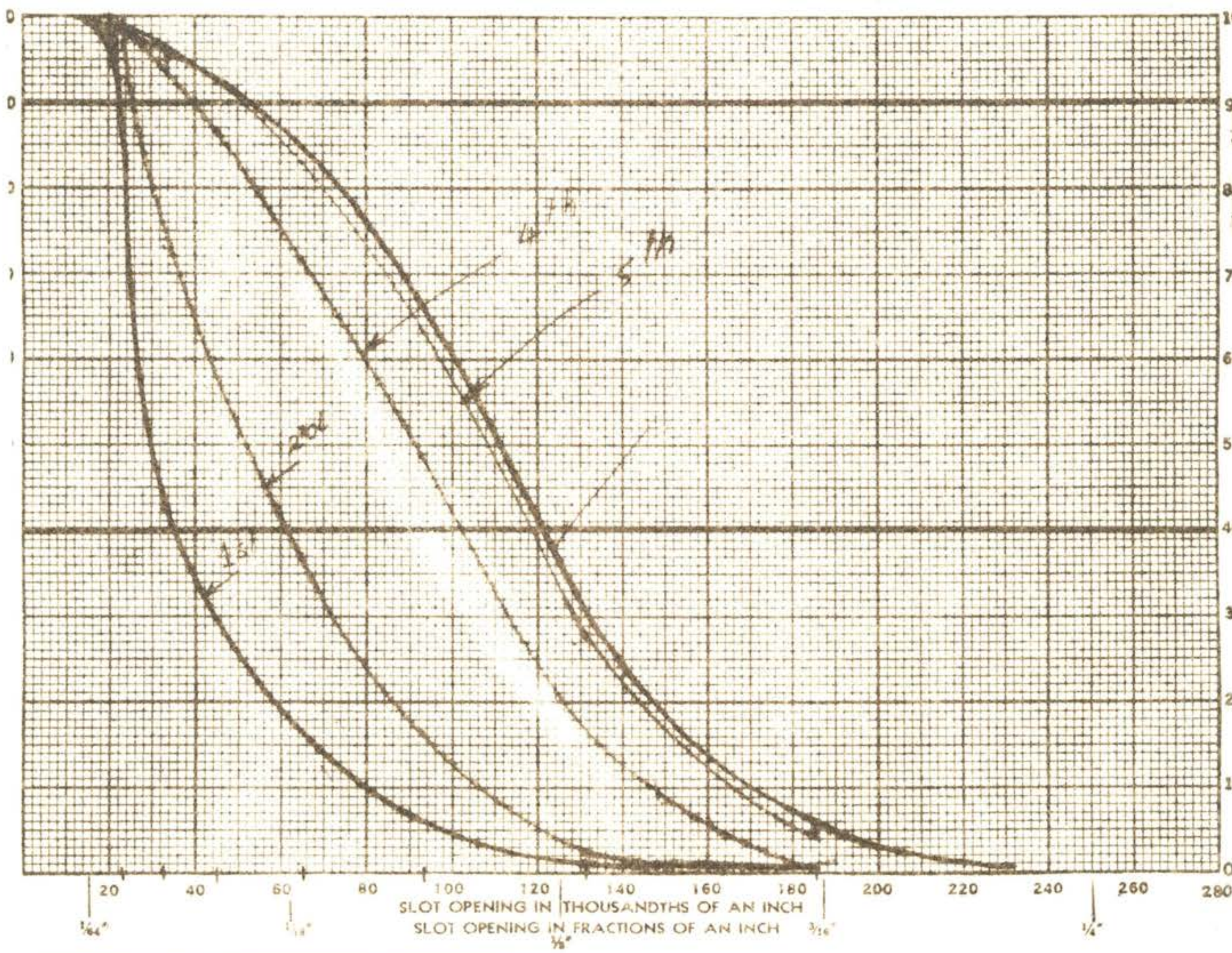
EDWARD E. JOHNSON, INC.
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by: Upper Group. (Sample C)

Town ______ State ______ Date ______

From well of ______

Remarks ______ Figure (7)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES: — 2.28
— 1st one inche 1.6
2nd 2" to 3"
— 4th (6"67") 2.07

SLOT OPENING RECOMMENDED

—5th 2.26

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.

6th, 7th, 8th are almost BY like 5th

SO MANY CONSIDERATIONS ENTER INTO THE MAKING OF A GOOD WELL THAT, WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SAND SAMPLES ARE CORRECT WE ASSUME NO RESPONSIBILITY FOR THE SUCCESSFUL OPERATION OF JOHNSON WELL SCREENS.

SAND ANALYSIS

EDWARD E. JOHNSON, INC.

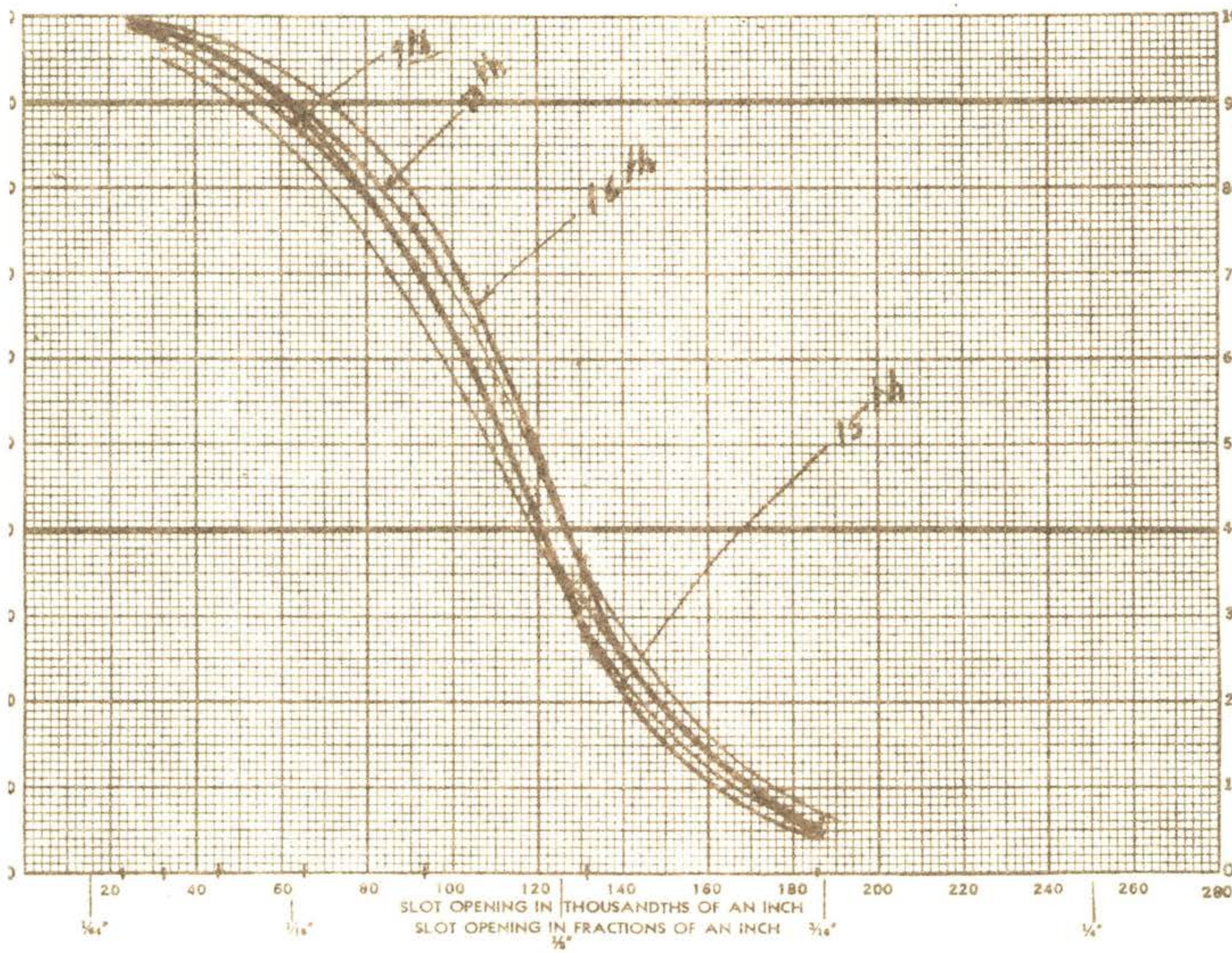
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by Central Group (Sample C)

Town ______ State ______ Date ______

From well of ______ Figure (8)

Remarks ______



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES: — Origin UNC = 2.23
— 9th UNC = 1.55
— 13th UNC = 1.97
— 15th UNC = 1.77

SLOT OPENING RECOMMENDED:
— 16th UNC = 1.985

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.
10th, 11th, 12th similar to 9th
14th, similar to 13th BY: ______

SAND ANALYSIS

EDWARD E. JOHNSON, INC.

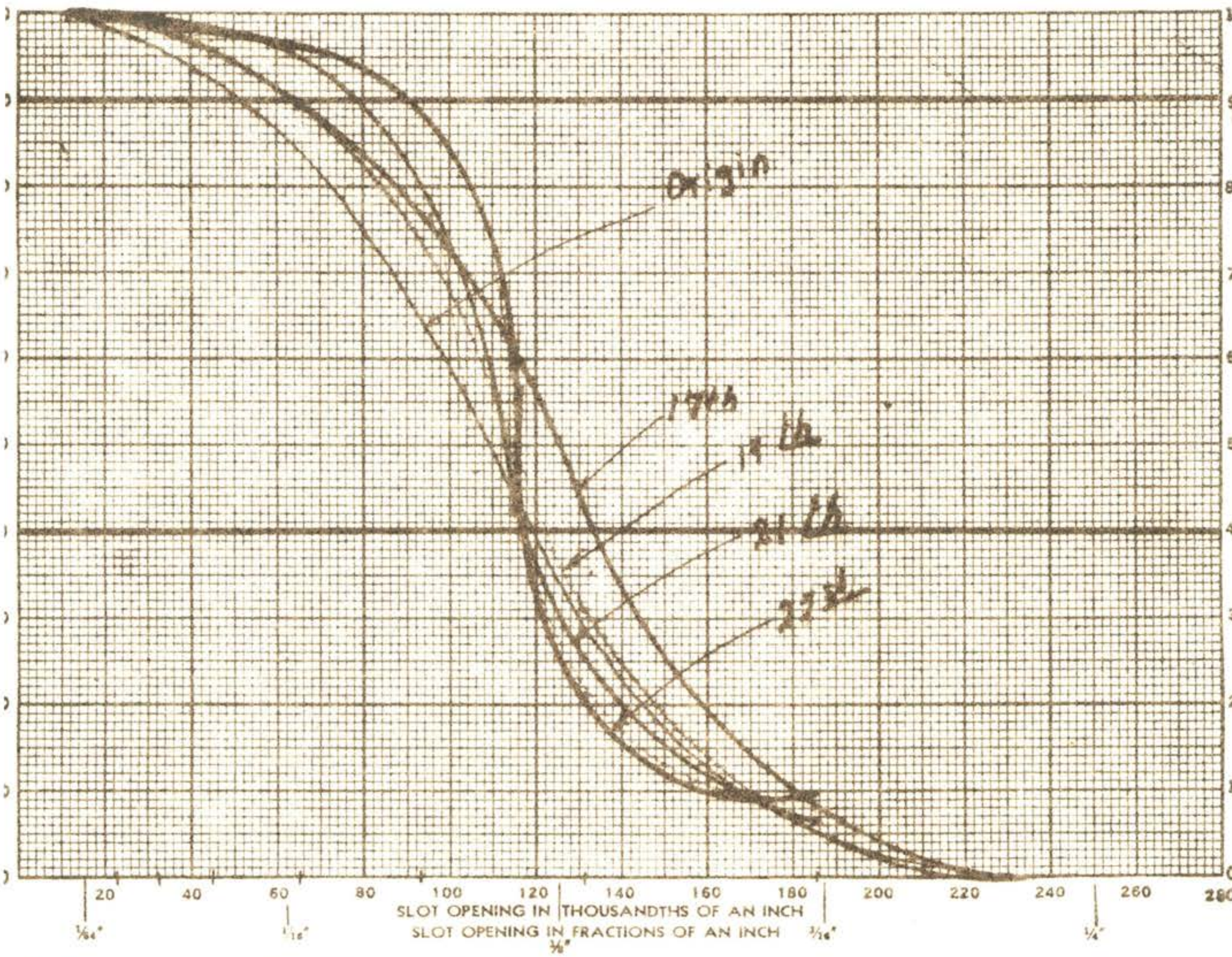
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by Bottom group (Sample C)

Town ______ State ______ Date ______

From well of ______

Remarks ______ Figure (9)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES: — origin UNC = 2.25
— 17th UNC = 2.06
— 19th UNC = 1.90
— 21st UNC = 1.51

SLOT OPENING RECOMMENDED:
— 22nd UNC = 1.31

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.
18th between 17th and 19th
20th between 19th and 21st

BY: ______

SAND ANALYSIS

EDWARD E. JOHNSON, INC.

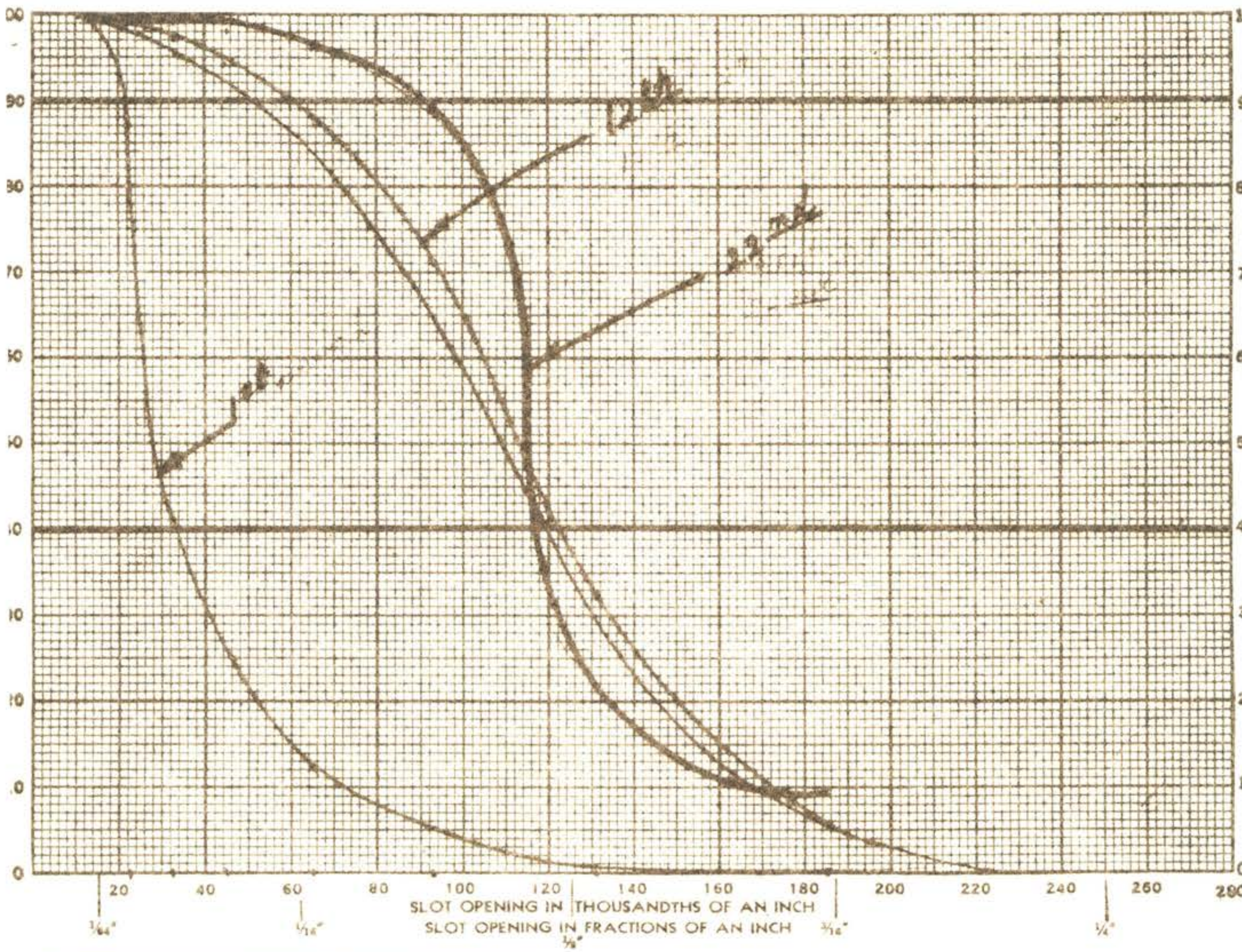
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by *Top, central and bottom curves, (Sample C)*

Town ______ State ______ Date ______

From well of ______

Remarks ______ Figure (10) ______



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES: — *Origin* *UNC = 2.28*
— *1st* *UNC = 1.6*
— *centra* *UNC = 2*
— *Bottom* *UNC = 1.31*

SLOT OPENING RECOMMENDED: ______

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.

______ BY ______

Plate (17)

Settlement of the large size particles

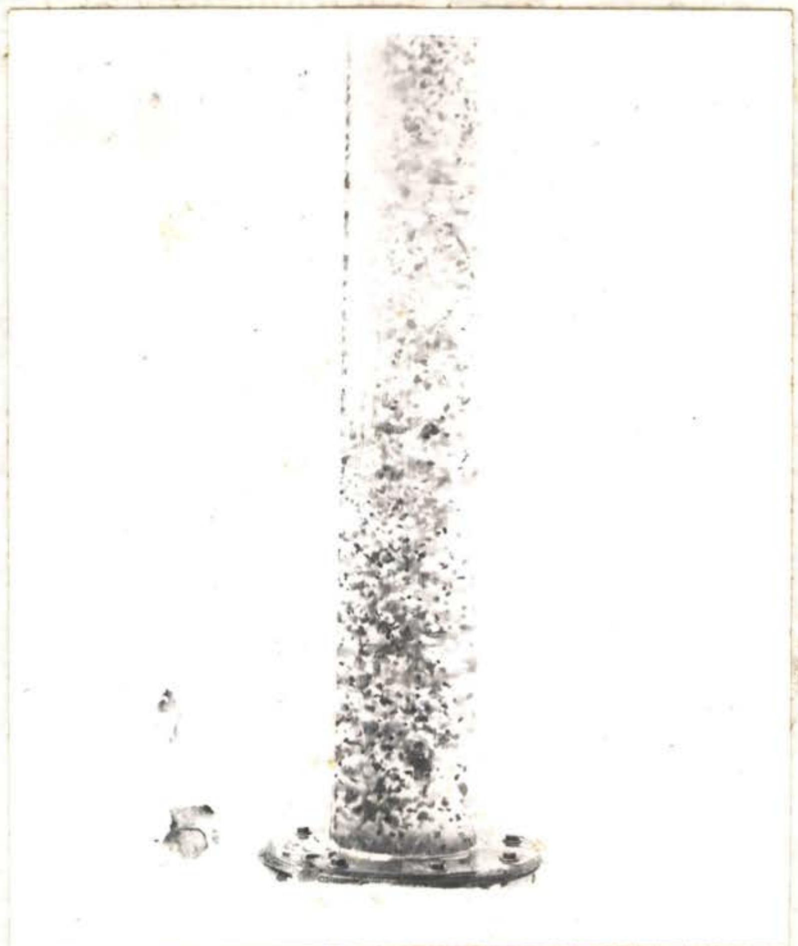


Plate (18)

Settlement of the mixture of the particles

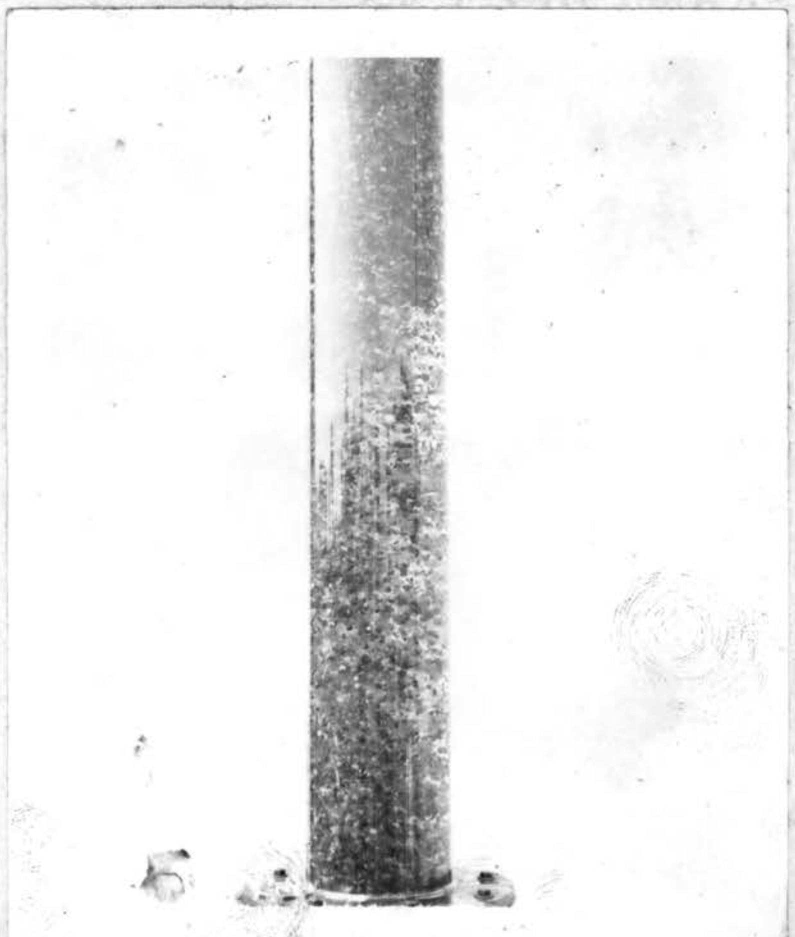


Plate (19)

Bailing the second bail

(Notice the dim part at the top of the picture)

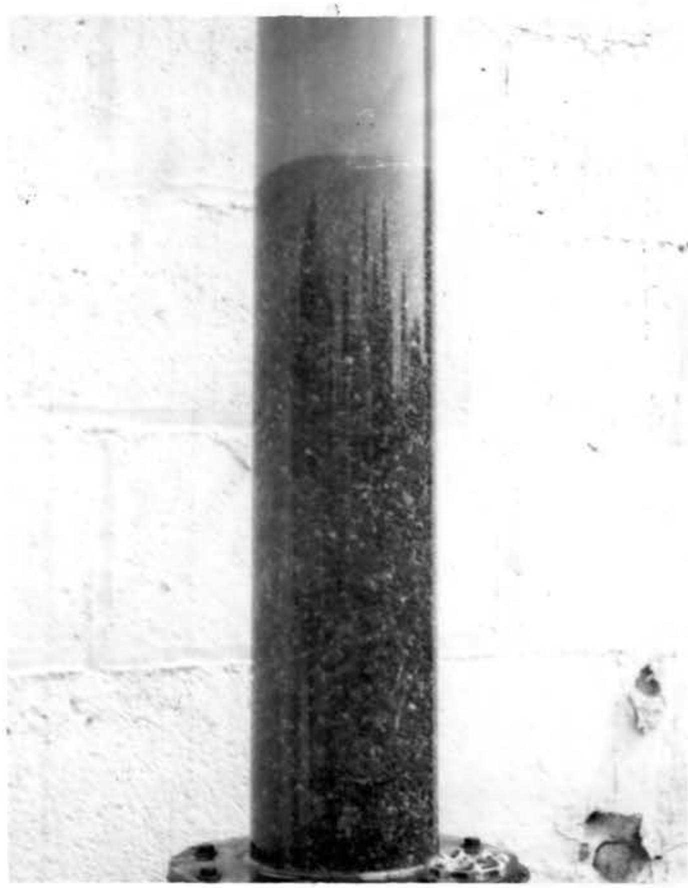


Plate (20)

The complete pack after settlement

(B) The Tremie Method

According to this method gravel has to be placed through a pipe that would be suspended in the well within the requiredheight of the pack. The idea is to control the gravel during its settlement within the pipe cross-section.

Procedures & Apparatus

The same procedures as mentioned before were followed. The model well was used and a 1" internal diameter pipe with a funnel at its top was used as a tremie pipe. The sample used in the bailing method was used but in one bucket.

Observations and Remarks While Running The Test

1 - The 1" diameter pipe proved to be small. It got clogged and had to be cleaned frequently.

2 - Total time taken was 8.5 minutes.

3 -Temperature was 88 degrees Fah.

Experimental Data

After complete settlement the sample was extracted by the usual way in sections of two inches each. Each section was dried, sieved, and analyzed. The table page (66) gives the sieve analysis data, and the sand analysis curves are given in figures 11, 12, 13, & 14.

Figures 11, 12, & 13 give the sand analysis curves for the upper, the central, and the bottom groups . Figure 14 compares the three groups to each other.

Results & Conclusion

(1) The central group is the less segregated group.

(2) The three groups do not follow the standard pattern, i.e. the fine particles at the top and the coarse ones at the bottom. There was a remarkable ratio of the fine particles at the bottom and another of the coarse particles at the top, this may be due to the clogging of the pipe.

(3) The general shape of the curves show that there is less segregation than in the case of the bailing method.

Sieve Analysis Results of The Tremie Method

Section Number	Depth	Sieve Size 0.185	0.131	0.093	0.065	0.046	0.033	0.023	* UNC
		Cumulative Per Cent Retained							
		(%)	(%)	(%)	(%)	(%)	(%)	(%)	
1st	2"	2.0	25.6	64.0	72.0	92.0	96.0	99.0	2.37
2nd	4"	6.0	45.4	80.5	84.0	94.0	97.0	99.0	2.30
3rd	6"	3.5	31.4	67.5	74.0	91.0	96.0	99.0	
4th	8"	4.1	31.6	67.0	75.0	91.5	96.0	99.0	2.13
5th	11"	4.5	29.0	67.0	76.0	93.5	97.5	99.0	2.20
6th	13"	5.25	41.4	76.0	82.0	96.0	98.0	99.0	2.00
7th	15"	3.10	27.6	64.0	70.0	88.0	93.0	98.5	3.30
8th	17"	3.5	31.0	64.0	70.0	87.0	92.0	99.0	
9th	24"	5.05	25.4	62.5	70.0	87.0	92.0	99.0	2.70
10th	26"	6.7	26.0	61.0	69.0	88.0	93.5	99.0	2.85
11th	28"	5.1	27.0	62.5	69.0	80.0	94.0	99.0	
12th	30"	5.3	24.5	59.0	67.0	88.0	94.0	99.0	
13th	32"	3.3	22.0	58.0	65.0	87.0	95.0	99.0	2.70
14th	34"	7.8	23.0	61.0	71.0	92.5	97.5	99.0	2.40
15th	36"	7.9	32.5	80.0	87.0	98.0	99.5	99.5	1.70
Origin		5.0	30.0	65.5	84.0	92.0	95.0	100.0	2.36

(*) UNC = Uniformity Coefficient

SAND ANALYSIS

EDWARD E. JOHNSON, INC.

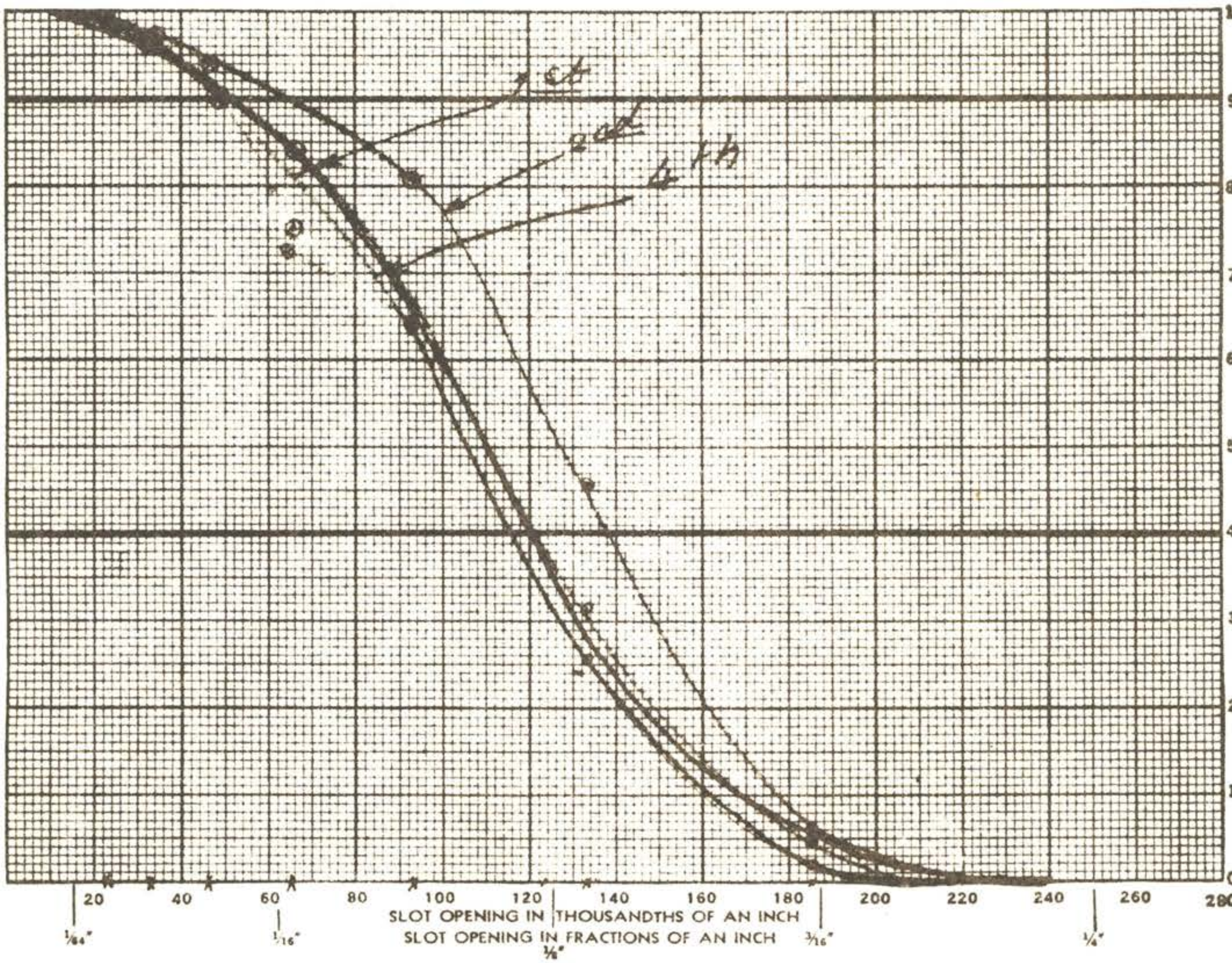
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by *Upper Group (Tremie Method).*

Town ______ State ______ Date ______

From well of ______

Remarks ______ Figure (11)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES:

1st 2" UNC = 2.37
2nd 2" UNC = 2.3

SLOT OPENING RECOMMENDED:

4th 2" UNC = 2.13

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.

3rd, 4th, and 5th are the same.

______ BY: ______

SO MANY CONSIDERATIONS ENTER INTO THE MAKING OF A GOOD WELL THAT, WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SAND SAMPLES ARE CORRECT WE ASSUME NO RESPONSIBILITY FOR THE SUCCESSFUL OPERATION OF JOHNSON WELL SCREENS.

SAND ANALYSIS

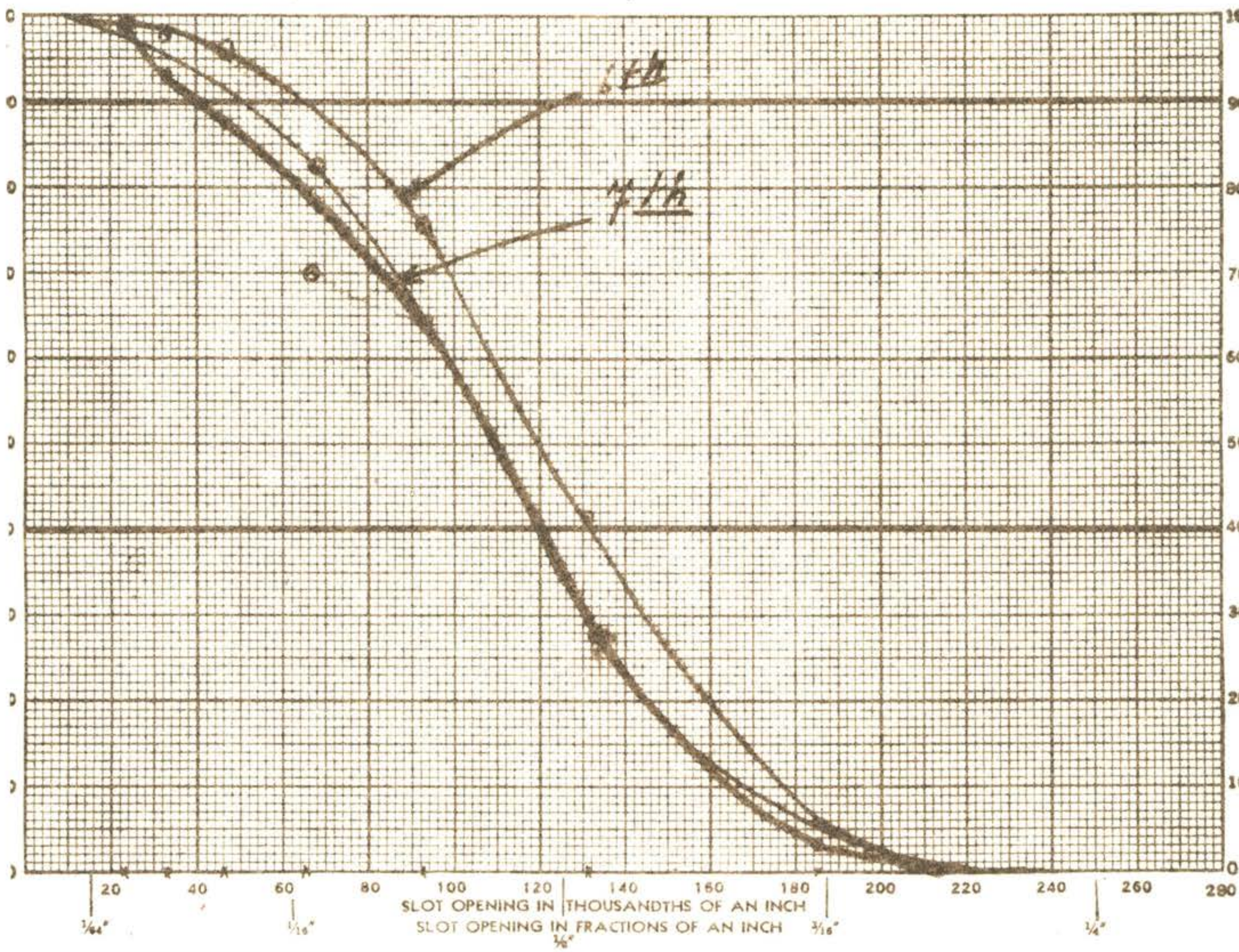
EDWARD E. JOHNSON, INC.
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by *Central Group (Tremie method)*

Town ______ State ______ Date ______

From well of ______

Remarks ______ Figure (12)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES:
6th UNC = 2.
7th UNC = 3.3

SLOT OPENING RECOMMENDED: ______

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.
7th, 8th and 9th are almost the same.

______ BY: ______

SAND ANALYSIS

EDWARD E. JOHNSON, INC.
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

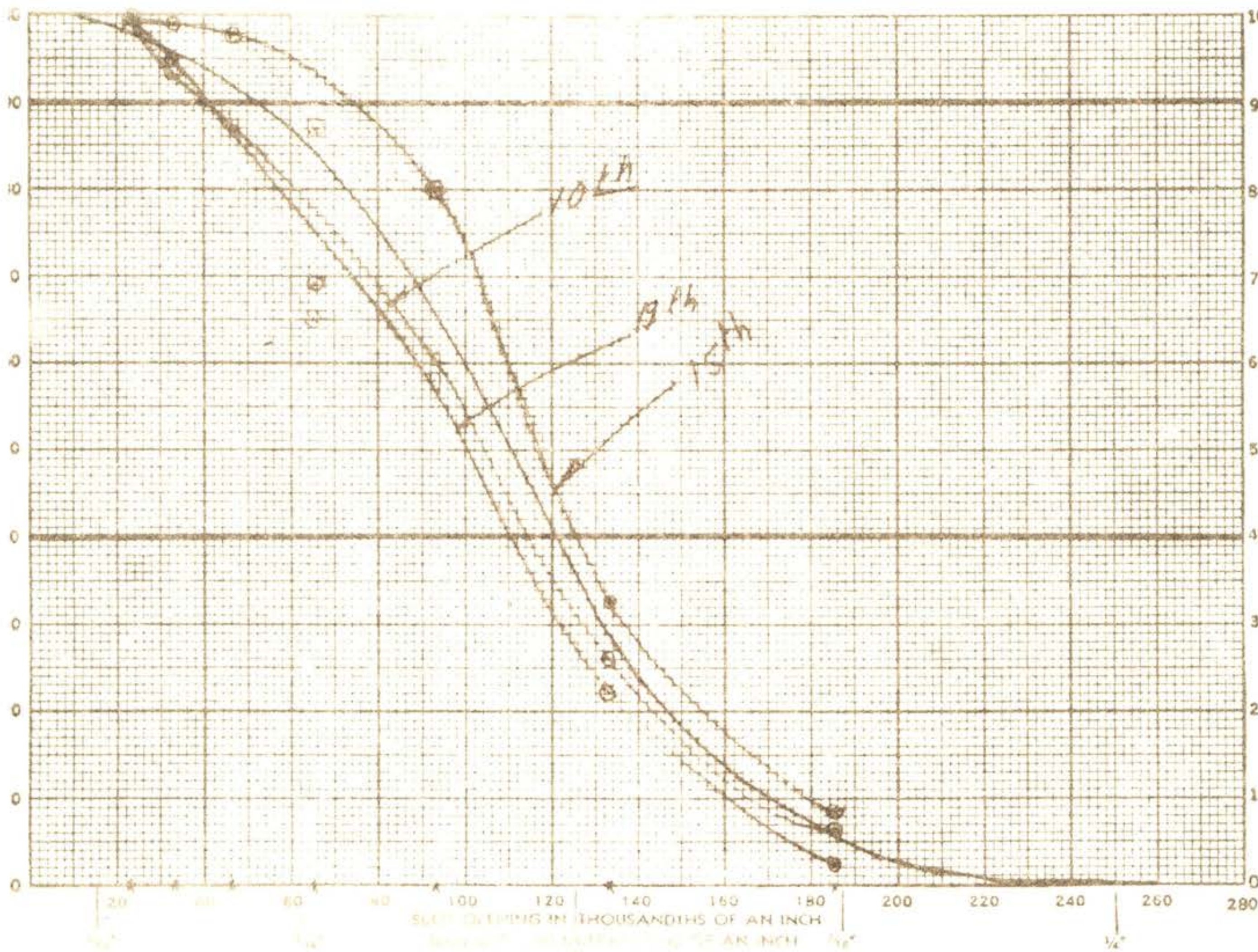
Sample sent in by Lower group (Tremie Method)

Town Date

From well of

Remarks

Figure (13)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES

— 10th UNC = 2.85
13th UNC = 2.7
—15th UNC = 1.7

SLOT OPENING RECOMMENDED

RECOMMENDED SCREEN: DIA. IN. LENGTH FT.

BY:

SAND ANALYSIS

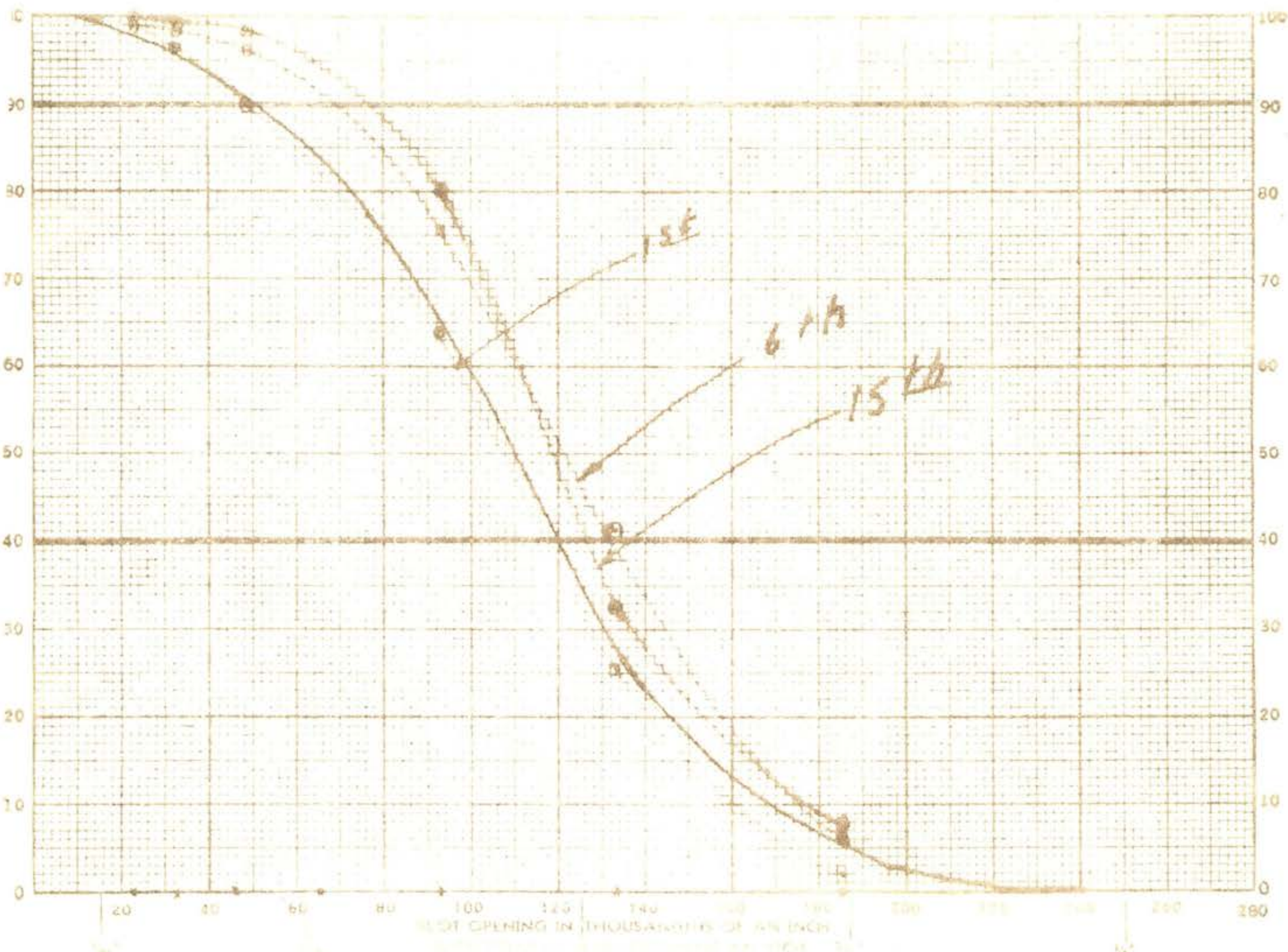
EDWARD E. JOHNSON, INC.
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample(s) Upper, Central, & bottom groups. (Tremie Method)

Town

From Well

Figure (14)



OPENINGS	
.263	
.185	
.131	
.093	
.065	
.046	
.033	
.023	

UAC = 2.37
UAC = 2.
UAC = 2.7

SLOT OPENING RECOMMENDED

RECOMMENDED SCREEN DIA. IN. LENGTH FT

BY

SO MANY CONSIDERATIONS ... WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SAND SAMPLES ARE CORRECT WE ASSUME NO RESPONSIBILITY FOR THE EFFICIENT OPERATION OF JOHNSON WELL SCREENS.

(C) The Pump Method

For this method gravel has to placed by being pumped through a pipe till it reaches the bottom of the well. Pumping rate should be greater than the falling rate of the particle, and the tube should be always continously full of gravel without any interruption during pouring.

Procedures & Apparatus

The model well was used. Gravel was placed through a funnel that was connected to a pipe that was about one foot above the bottom of the well. The pipe was joined by a 90 degrees elbow to the pump discharge pipe. It was also hooked up by a rope & a pulley and was pulled up gradually while gravel was pumped into the well. The pumping rate was 5 gallons each 35 seconds, that amounts to $\frac{5 \times 60}{35}$ = 8.6 gallons per minute. The pipe was 1" diameter hence its cross-section area equals 0.785 inches^2.

Hence: water pumping rate = $\frac{8.6 \times 0.1605 \times (12)^2}{0.785 \times 1.2 \times 60}$ = 42 inches/second.

The maximum rate of fall of the largest particle in this sample (0.158") = 11.9 inches/second (from page (24) Chapter III). Consequently, the rate of fall of the pumped water is greater than the rate of fall of any particle in the sample, which is a condition for the use of the pump.

Observations and Remarks While Running The Test

1 - The gravel flow was smooth without any clogging.

2 - Total time taken was 5 minutes only.

3 - The rate of pouring the gravel was such that the tube was continously full of gravel without any interruption.

4 - The temperature was 86 degrees Fah.

Experimental Data

According to the standard procedures the sample was extracted in sections about two inches each. Each section was dried, sieved, and analyzed as usual. The table in page (73) gives the sieve analysis data.

Figures 15, 16, 17, & 18 give the sand analysis curves.
Figures 15, 16, & 17 give the curves for the upper, the central, and the bottom groups.
Figure 18, gives a comparison between the three groups. It shows that the centeral group is the least segregated one.

Results & Conclusion

(1) The structure of the central group is close to the structure of the original sample.

(2) Comparing these curves with the corresponding ones of the bailing and the tremie methods we find that the gravel is less segregated than when either the bailing or the tremie method are used.

From the above we can make a conclusion that the pump method gives a pack that is almost the same in its structure as the original sample.

Sieve Analysis Results of The Pumping Method

Section Number	Depth	Sieve Size 0.185	0.131	0.093	0.065	0.046	0.033	0.023	UNC
		Cumulative Per Cent Retained (%)	(%)	(%)	(%)	(%)	(%)	(%)	
1st	2"	3.7	26.0	62.5	69.0	88.0	93.5	98.0	2.95
2nd	4"	5.3	27.6	62.0	69.0	86.0	91.5	98.0	3.12
3rd	6"	7.1	37.0	74.0	81.0	95.0	99.0	100.0	2.14
4th	9"	5.9	33.0	74.0	80.0	93.5	97.0	100.0	
5th	10"	6.8	40.0	82.0	85.0	96.0	98.0	100.0	1.90
6th	12"	5.2	26.8	70.0	76.0	92.5	97.5	100.0	2.21
7th	14"	4.9	26.0	65.0	72.0	89.0	93.0	97.0	2.61
8th	16"	6.6	31.5	65.0	72.5	87.0	92.0	98.0	
9th	18"	7.1	38.0	71.0	77.0	89.0	93.5	99.0	
10th	20"	6.5	29.0	60.0	67.0	85.0	91.5	99.0	3.10
11th	21"	4.0	22.0	58.0	66.0	86.0	93.5	99.0	2.75
12th	23"	4.2	25.0	59.0	67.5	88.0	94.0	99.0	2.70
13th	24"	4.2	28.0	60.0	68.5	87.5	93.0	99.0	2.76
Origin		5.0	30.0	65.5	84.0	92.0	95.0	100.0	2.36

SAND ANALYSIS

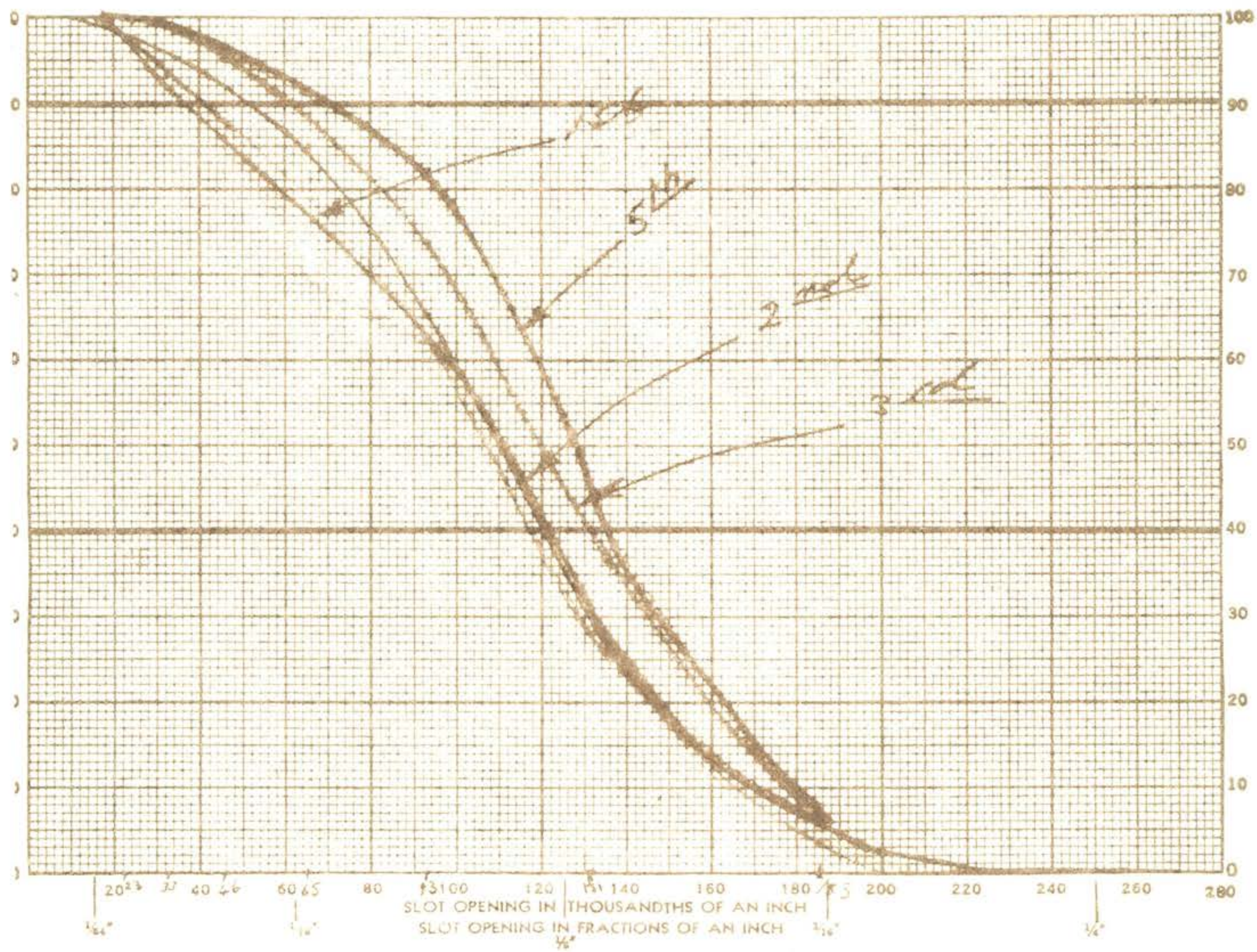
EDWARD E. JOHNSON, INC.
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by Upper Group (Pump test).

Town ____ State ____ Date ____

From well of ____ **Figure (15)**

Remarks ____



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES: — Origin UNC = 2.36
— 1st UNC = 2.95
— 2nd UNC = 3.12
— 3rd UNC = 2.14

SLOT OPENING RECOMMENDED:
— 5th UNC = 1.9

RECOMMENDED SCREEN: DIA. ____ IN. LENGTH ____ FT.

BY: ____

SAND ANALYSIS

EDWARD E. JOHNSON, INC.

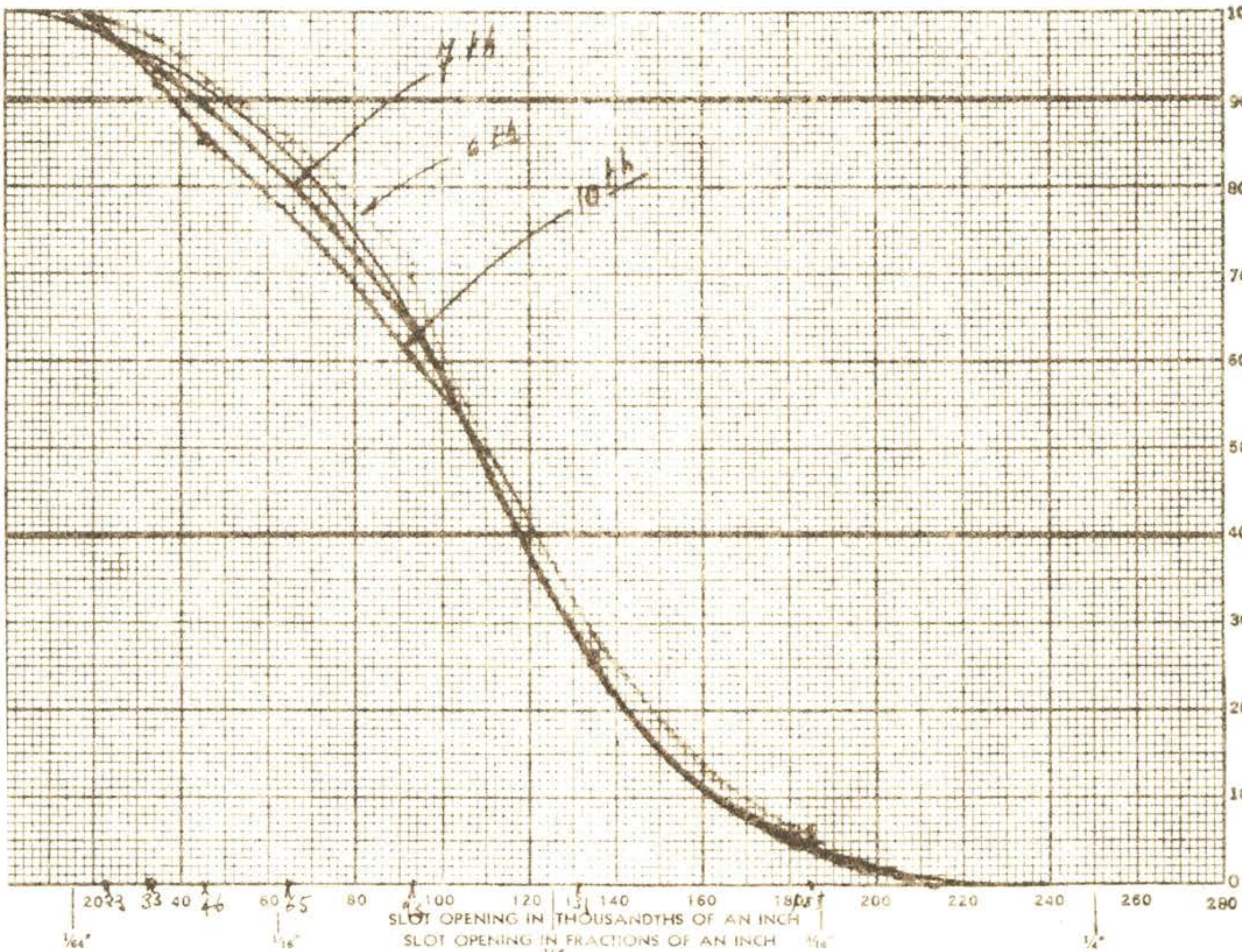
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by Central Group (Pump test)

Town ________ State ________ Date ________

From well of ________

Remarks ________ Figure (16)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES:

– UNC = 2.21

– 7 h UNC = 2.61

– 10 UNC = 3.1

SLOT OPENING RECOMMENDED: ________

RECOMMENDED SCREEN: DIA. ____ IN. LENGTH ____ FT.

BY: ________

SO MANY CONSIDERATIONS ENTER INTO THE MAKING OF A GOOD WELL THAT, WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SAND SAMPLES ARE CORRECT WE ASSUME NO RESPONSIBILITY FOR THE SUCCESSFUL OPERATION OF JOHNSON WELL SCREENS.

SAND ANALYSIS

EDWARD E. JOHNSON, INC.
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

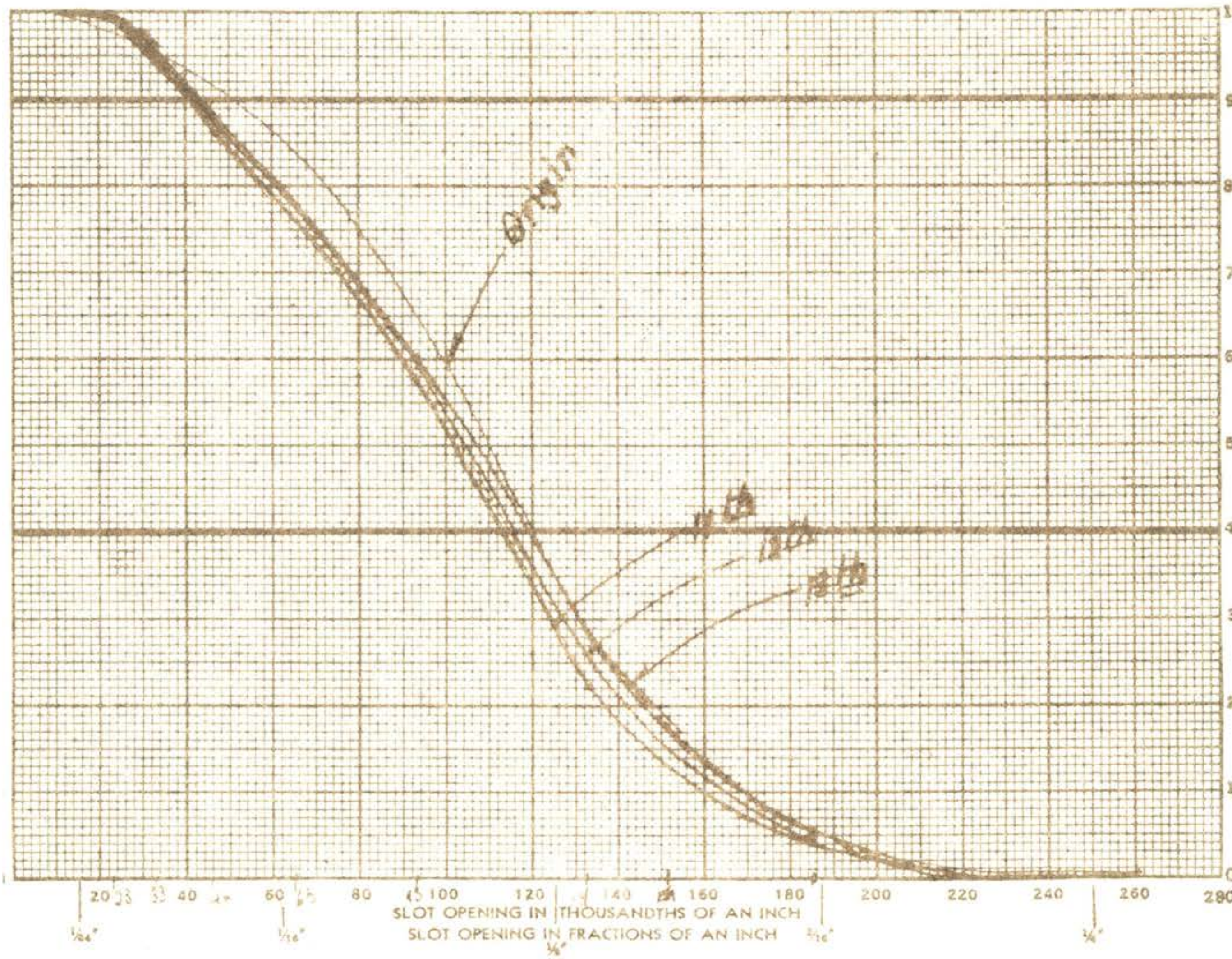
Sample sent in by Lower Group (Pump test)

Town ______ State ______ Date ______

From well of ______

Remarks ______

Figure (17)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES

— 11th UNC = 2.75
— 12th UNC = 2.7
— 13th UNC = 2.76

SLOT OPENING RECOMMENDED: ______

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.

BY: ______

SO MANY CONSIDERATIONS ENTER INTO THE MAKING OF A GOOD WELL THAT, WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SAND SAMPLES ARE CORRECT WE ASSUME NO RESPONSIBILITY FOR THE SUCCESSFUL OPERATION OF JOHNSON WELL SCREENS.

EDWARD E. JOHN...

SAINT PAUL ...

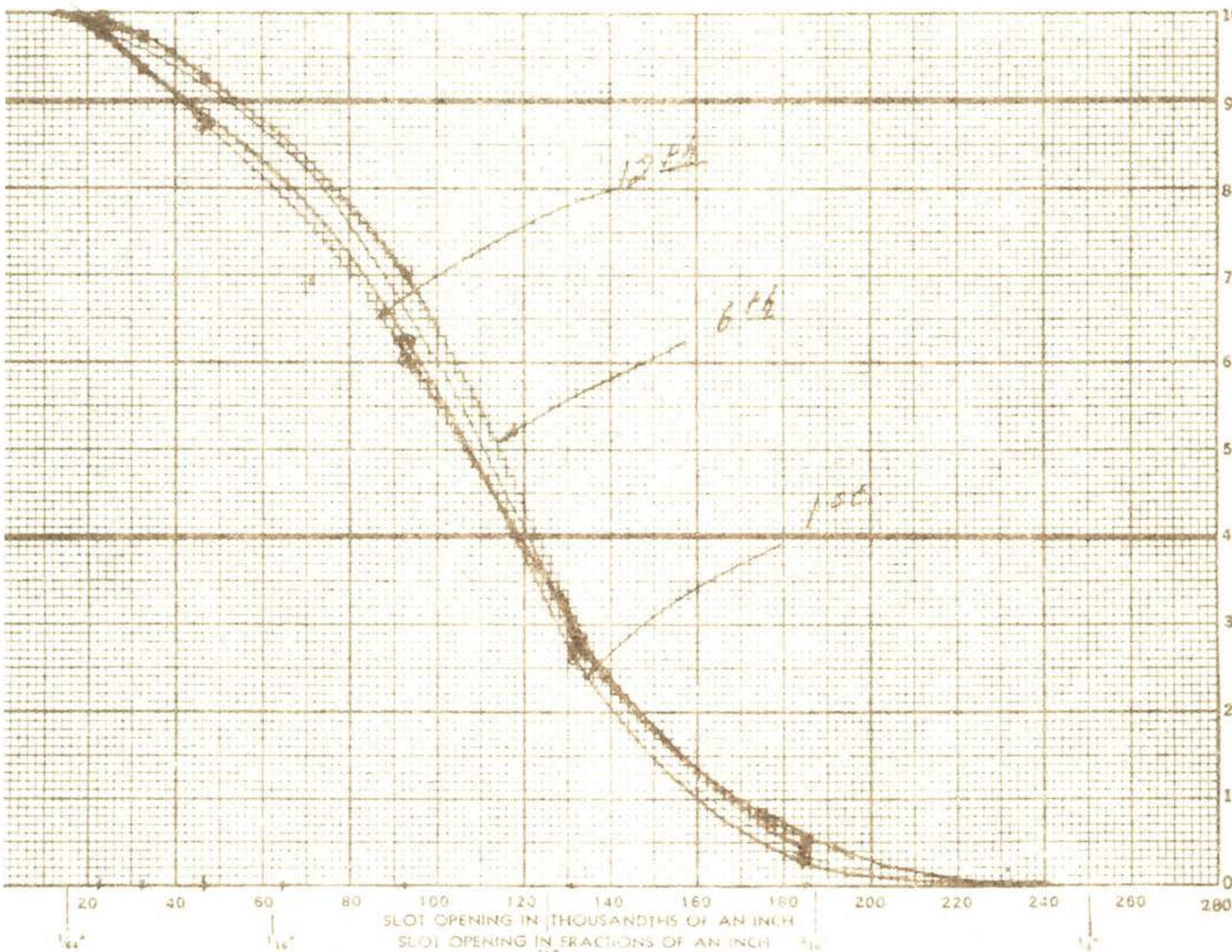
Sample sent in by Upper, central, and lower groups

Town | Date

From well of "Pump test"

Remarks

Figure (18)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES

SLOT OPENING RECOMMENDED

RECOMMENDED SCREEN: DIA. ____ IN. LENGTH ____ FT.

BY

(D) The Package Method

The procedure for this method is to place the gravel in small shovelfuls and give each shovelful enough time to settle before placing the next one.

Procedures & Apparatus

The model well was used. Before starting the test the time required for the complete settlement of one shovelful was measured. It was 45 seconds, and 55 seconds were allowed between each shovelful.

Observations and Remarks While Running The Test

1 - Time taken for pouring one shovel was 5 seconds.

2 - Total time taken for completing the test was 22 minutes or 1320 seconds.

3 - Temperature was 85 degrees Fah.

Experimental Data

The table in page (79) gives the sieve analysis data. Figures 19, 20, 21 & 22 give the sand analysis curves.

Figures 19, 20, & 21 give the sand analysis curves for the upper, the central, and the bottom groups.

Figure 22, gives a comparison between the three groups.

Results & Conclusion

The above curves show that there was more segregation or deviation from the original curve in the upper group only. This means that the package method gives a pack that relatively has a small amount of segregation compared with the other methods.

The final comparison showing which method is more acceptable is made in the detailed comparison that follows.

Sieve Analysis Results of The Package Method

Section Number	Depth	Sieve Size 0.185	0.131	0.093	0.065	0.046	0.033	0.023	UNC
		Cumulative Per Cent Retained (%)	(%)	(%)	(%)	(%)	(%)	(%)	
1st	1"	2.70	20.0	53.0	58.0	82.0	90.0	98.5	2.03
2nd	3"	5.0	30.0	66.0	72.5	88.0	93.0	99.6	2.97
3rd	5"	5.0	28.0	68.0	69.0	86.0	93.5	98.0	2.97
4th	8"	6.6	35.0	71.5	78.0	91.0	96.0	99.0	2.46
5th	10"	4.9	25.0	59.0	67.0	84.0	90.0	98.0	3.15
6th	12"	5.05	27.0	64.0	72.0	90.0	95.0	99.0	2.36
7th	14"	4.7	26.0	63.5	70.0	89.0	92.5	99.5	2.95
8th	17"	2.7	25.0	64.0	70.0	88.5	94.0	98.5	
9th	19"	4.9	28.0	68.0	74.0	90.0	95.0	99.0	
10th	21"	5.0	30.0	68.0	74.0	90.0	95.0	99.0	2.45
11th	24"	6.2	34.0	72.5	78.0	92.0	96.5	99.0	2.36
12th	26"	6.1	35.0	75.0	80.0	93.0	96.0	99.0	2.2
13th	28"	5.5	31.0	68.0	75.5	92.5	96.5	99.5	2.26
14th	30"	6.05	32.0	70.0	77.0	92.0	96.5	99.5	
15th	31"	9.6	39.0	73.5	71.5	92.5	96.0	99.0	2.28
Origin		5.0	30.0	65.5	84.0	92.0	95.0	100.0	2.36

(80)

SAND ANALYSIS

EDWARD E. JOHNSON, INC.

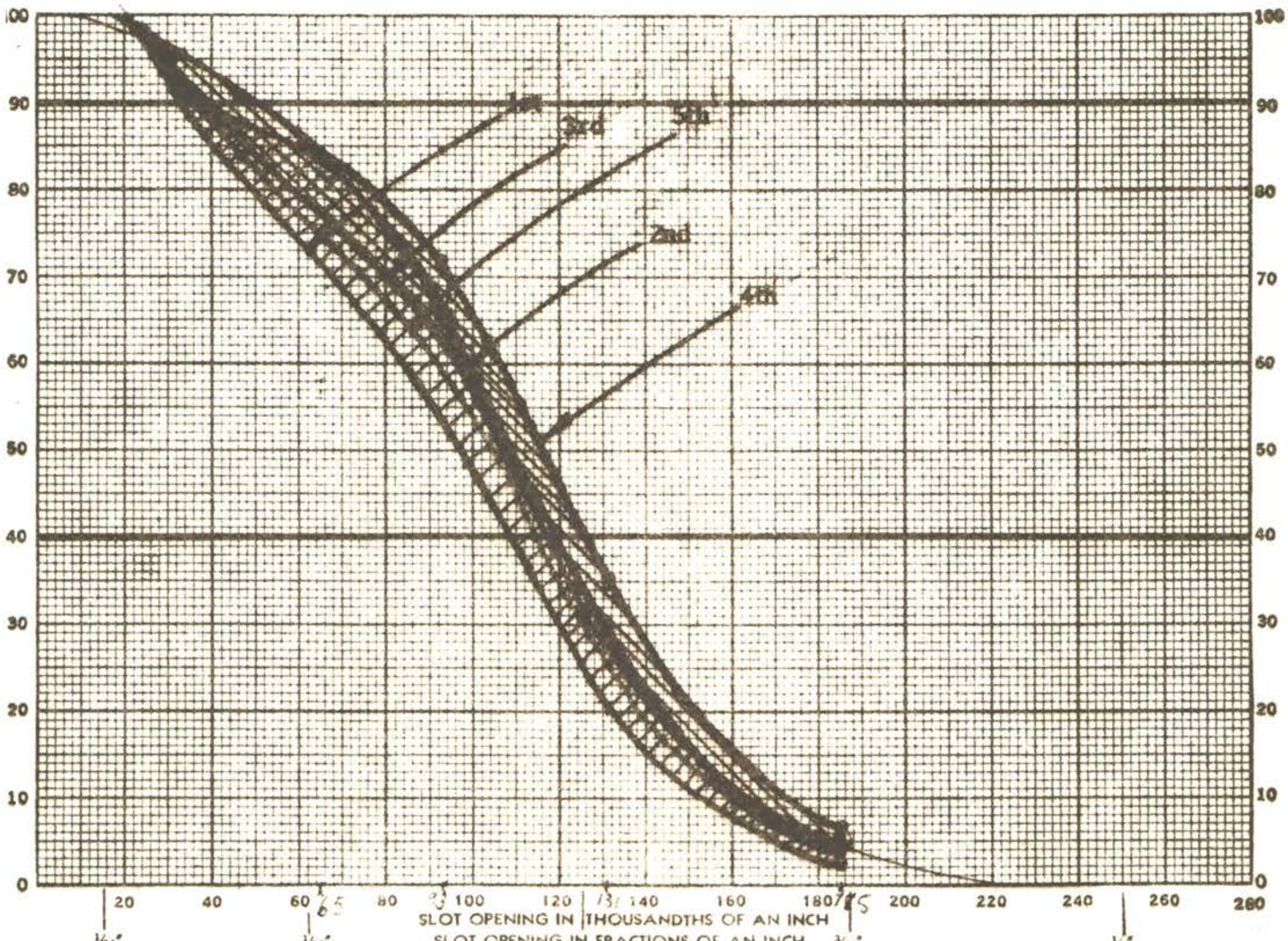
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by Package Method, Upper Group

Town ______ State ______ Date ______

From well of ______

Remarks Figure (19)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES: Origin UNC = 2.36

1st UNC = 2.03

2nd UNC = 2.97

3rd UNC = 2.97

SLOT OPENING RECOMMENDED:

4th UNC = 2.46

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.

5th UNC = 3.15

______ BY: ______

SO MANY CONSIDERATIONS ENTER INTO THE MAKING OF A GOOD WELL THAT, WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SAND SAMPLES ARE CORRECT WE ASSUME NO RESPONSIBILITY FOR THE SUCCESSFUL OPERATION OF JOHNSON WELL SCREENS.

SAND ANALYSIS

EDWARD E. JOHNSON, INC.
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

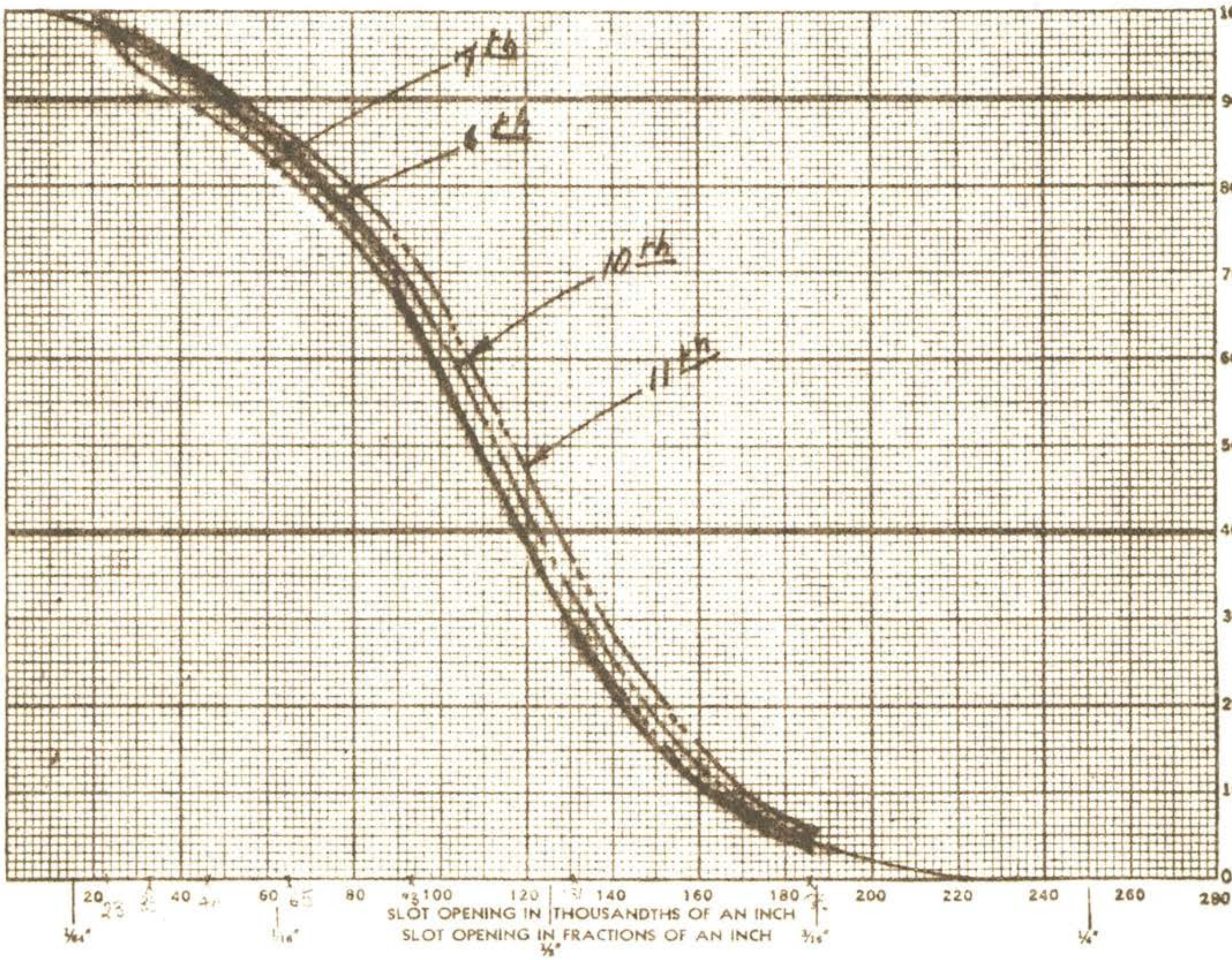
Sample sent in by *Package method; central group.*

Town ____ Date ____

From well of ____

Remarks ____

Figure (20)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES:
— 6th UNC = 2.36
— 7th UNC = 2.95
— 10th UNC = 2.45

SLOT OPENING RECOMMENDED:
— 11th UNC = 2.36

RECOMMENDED SCREEN: DIA. ____ IN. LENGTH ____ FT.
8th is almost coinciding with 7th.
9th is almost coinciding with 10th.

SO MANY CONSIDERATIONS ENTER INTO THE MAKING OF A GOOD WELL THAT, WHILE WE BELIEVE SLOT SIZES FURNISHED OR RECOMMENDED FROM SAND SAMPLES ARE CORRECT WE ASSUME NO RESPONSIBILITY FOR THE SUCCESSFUL OPERATION OF JOHNSON WELL SCREENS.

SAND ANALYSIS

EDWARD E. JOHNSON, INC.

315 NORTH PIERCE STREET

SAINT PAUL 4, MINN.

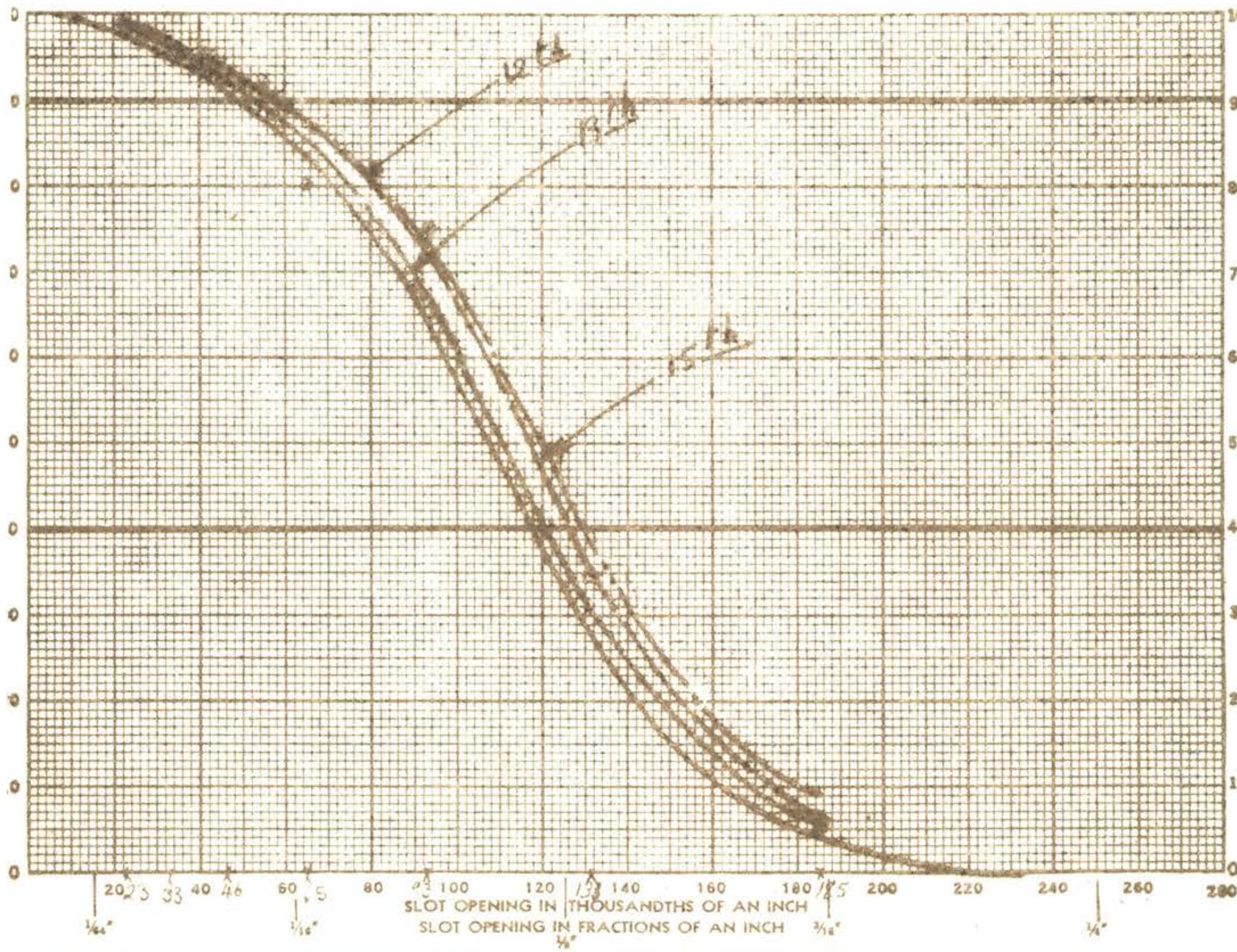
Sample sent in by Package method, lower group.

Town ______ State ______ Date ______

From well of ______

Remarks ______

Figure (21)



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES:

- 12th UNC = 2.2
- 13th UNC = 2.26
- 15th UNC = 2.28

SLOT OPENING RECOMMENDED: ______

RECOMMENDED SCREEN: DIA. ______ IN. LENGTH ______ FT.

14th is almost beteween 13th & 12th

______ BY: ______

SAND ANALYSIS

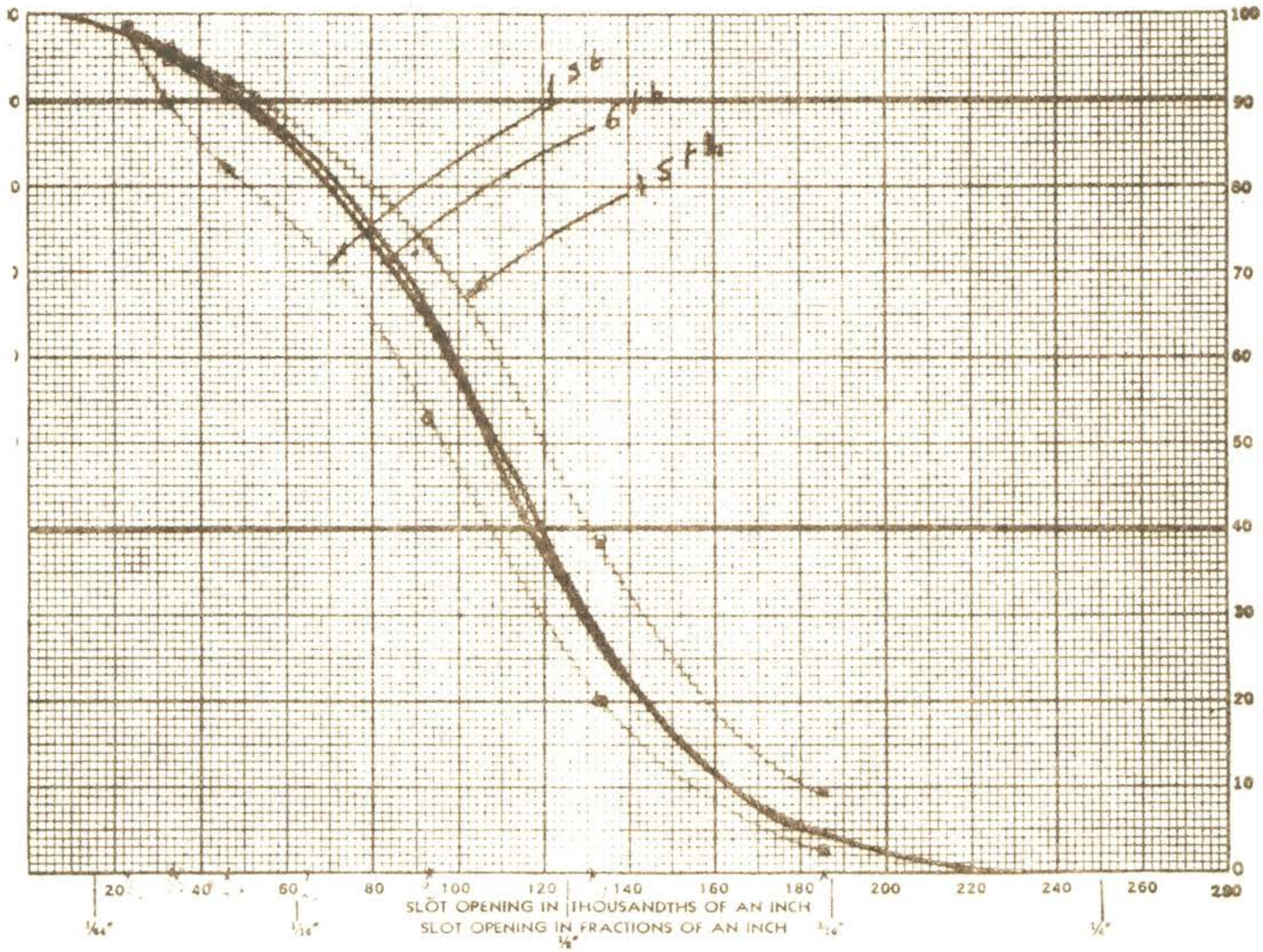
EDWARD E. JOHNSON, INC.
315 NORTH PIERCE STREET
SAINT PAUL 4, MINN.

Sample sent in by *Package Method; upper, central, and lower curves.*

Town ____ State ____ Date ____

From well of ____

Remarks ____ **Figure (22)**



SIEVE OPENINGS	CUMULATIVE PER CENT RETAINED		
.263			
.185			
.131			
.093			
.065			
.046			
.033			
.023			

NOTES: Origin UNC = 2.36
1st UNC = 2.03
6th UNC = 2.36
15th UNC = 2.28

SLOT OPENING RECOMMENDED: ____

RECOMMENDED SCREEN: DIA. ____ IN. LENGTH ____ FT.

____ BY: ____

Comparison Between The Four Methods

The important consideration for comparing these methods is to find which method gave the least amount of segregation. But there is no scale available for measuring the segregation. For this reason the following method has been developed.

This method measures the difference between the coarsest and finest particles' size from the size of the original sample particle at 40% retained size which equals the total amount of segregation.

Hence: total amount of segregation

$$= (D^{*}_{40} \text{ coarsest} - D_{40} \text{ origin}) + (D_{40} \text{ origin} - D_{40} \text{ finest})$$

The first part, (D_{40} coarsest - D_{40} origin) measures the amount of segregation of the coarsest particles from the origin, and the second part which is (D_{40} origin - D_{40} finest) measures the amount of segregation of the finest particles from the origin.

Comparison Between The Amount of Segregation Produced By Each Method

D_{40} origin = 120 thousands of an inch.

(1) The Bailing Method

D_{40} coarsest = 135 th. of an in. D_{40} finest = 35 th. of an in.

Amount of segregation = (135 - 120) + (120 - 35) = 15 + 85 = 100 th.

(2) The Tremie Method

D_{40} coarsest = 138 th. D_{40} finest = 110 th.

Amount of segregation = (138 - 120) + (120 - 110) = 18 + 10 = 28 th.

(3) The Pump Method

D_{40} coarsest = 132 th. D_{40} finest = 113 th.

Amount of segregation = (132 - 120) + (120 - 113) = 12 + 7 = 19 th.

(*) D_{40} = the diameter of the particle at 40% retained size as measured on the sand analysis curve.

(4) The Package Method

D_{40} coarsest = 130 th. D_{40} finest = 108 th.

Amount of segregation = (130 - 120) + (120 - 108) = 10 + 12 = 22 th.

Plotting the values of the amount of segregation against each method of gravel placement we get the curve shown in Figure (23). This curve shows that the pump method gives the least amount of segregation, followed in order, by the package, the tremie, and the bailing methods. This proves that the pump method gives the best pack structure.

A segregation factor can be derived from the amount of segregation as follows :

The segregation factor is defined as :

$$\text{Segregation factor (S. F.)} = \frac{D_{40}\ \text{coarsest}}{D_{40}\ \text{origin}} + \frac{D_{40}\ \text{origin}}{D_{40}\ \text{finest}}$$

The values of the segregation factor for each method are:

(1) The Bailing Method

$$\text{S. F.} = \frac{135}{120} + \frac{120}{35} = 4.54$$

(2) The Tremie Method

$$\text{S. F.} = \frac{138}{120} + \frac{120}{110} = 2.24$$

(3) The Pump Method

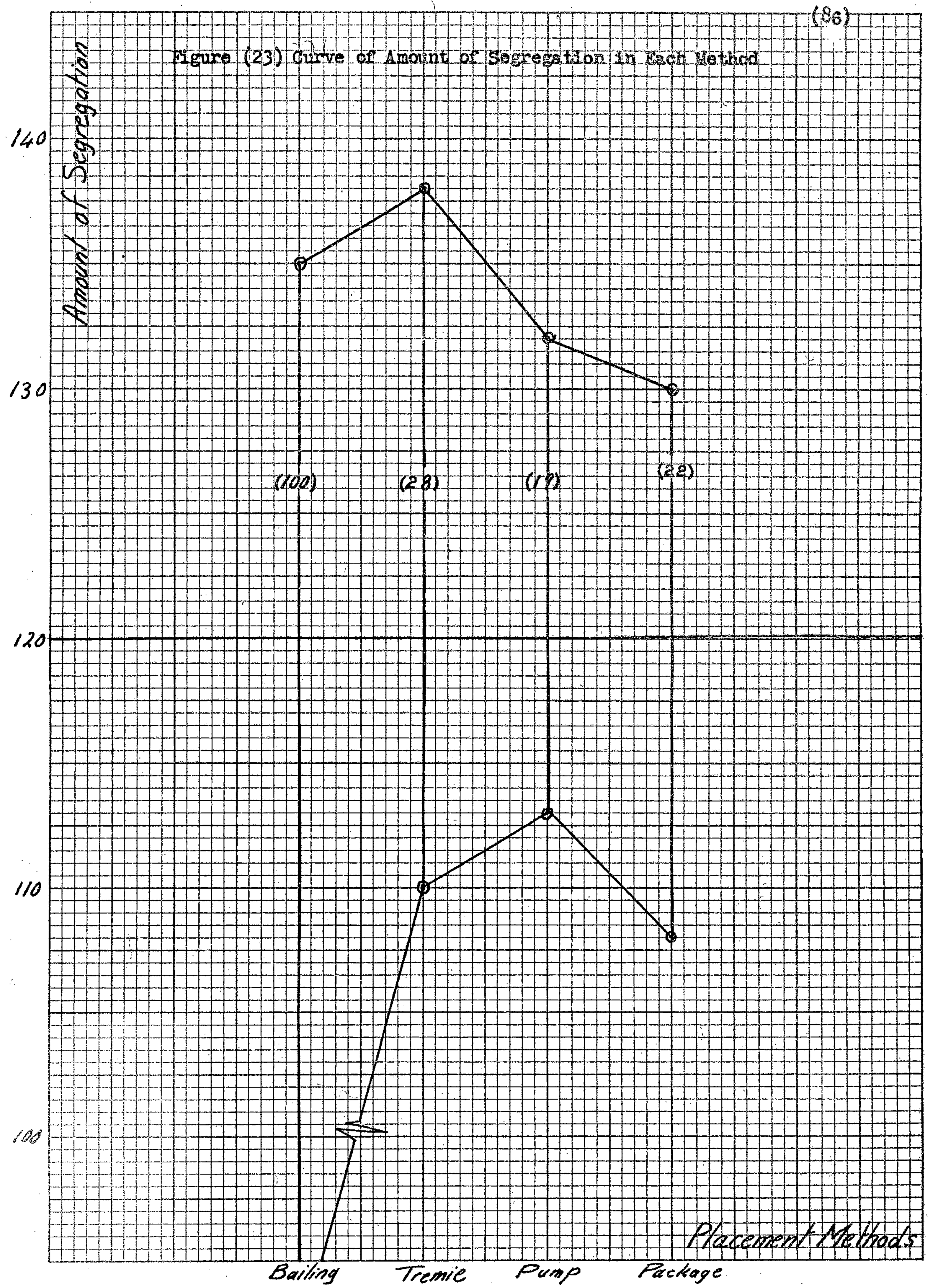
$$\text{S. F.} = \frac{132}{120} + \frac{120}{113} = 2.16$$

(4) The Package Method

$$\text{S. F.} = \frac{130}{120} + \frac{120}{108} = 2.19$$

These values show again that the pump method gives the best pack structure. In order to find which method can best suit the practical purposes the amount of segregation has been limited to 8%* which in our case equals 120 x 8/100 = 9.6 th.

(*) Credit for this ratio is given to Mr. Mogg, Edward E. Johnson, Inc.


(86)
Figure (23) Curve of Amount of Segregation in Each Method
Amount of Segregation
140
130
120
110
100
(100)
(28)
(19)
(22)
Placement Methods
Bailing
Tremie
Pump
Package

None of the above methods gave this amount, except in the case of the finest group of the pump method which gave (120 - 113 = 7 th.)

Conclusion

The pump method gives the least amount of segregation followed by the package, the tremie, and the bailing methods.

But none of the above methods gave a pack structure that was within the limit of (8%). For this reason the writer puts the following two methods under consideration for those interested in further research, or for practice.

(1) The adhesion method given in Chapter IV, page 45.

(2) The container method:

This method aims at transporting the gravel as it is designed to the bottom of the well. The apparatus consists of a container which can be either of a cylinderical or a hollow shape. The hollow container, shown in Figure 24.a.- is to be used if there was not enough space between the screen and the casing, and the wall of the well. In this case it can be let down through its hollow inside, around the casing. The bottom of the container is to be made in the form of a pivoted flap door operated by a rope from the top at the ground level. The whole container is to be suspended in the pulley of the rig.

Gravel should not be poured into the container but it should be filled by the method shown in Figure 24.b.

The procedure for operating this method is to fill the container with gravel and let the container down until it reaches the bottom of the well where the door is opened by loosening its rope to allow the gravel to flow to form the pack without any change in its structure.

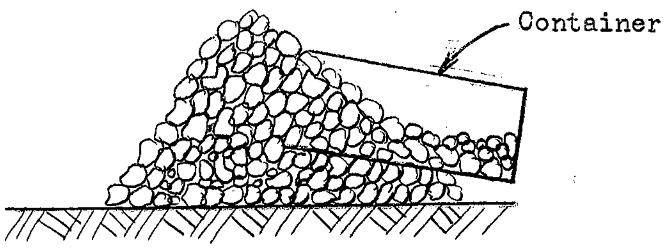


Figure (24. b) Filling the container

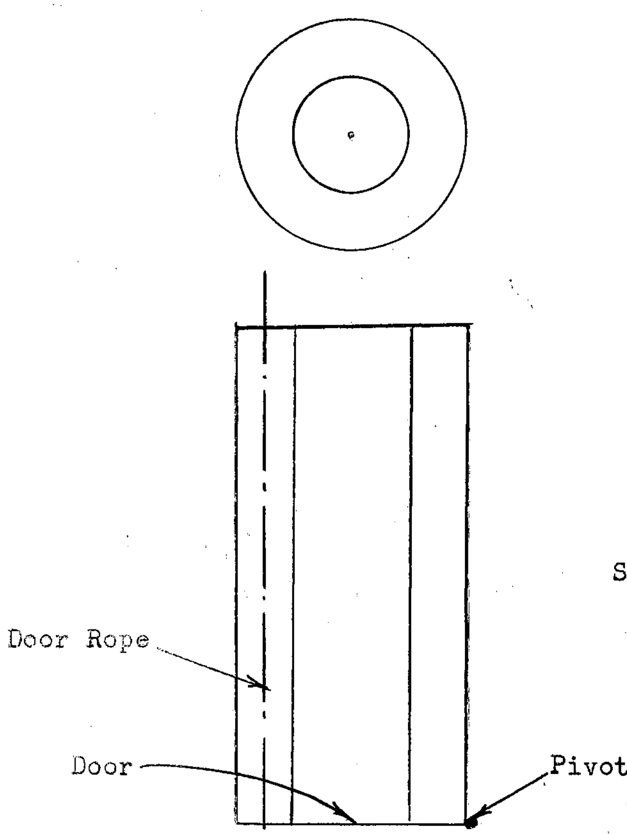


Figure (24. a) A Hollow Container

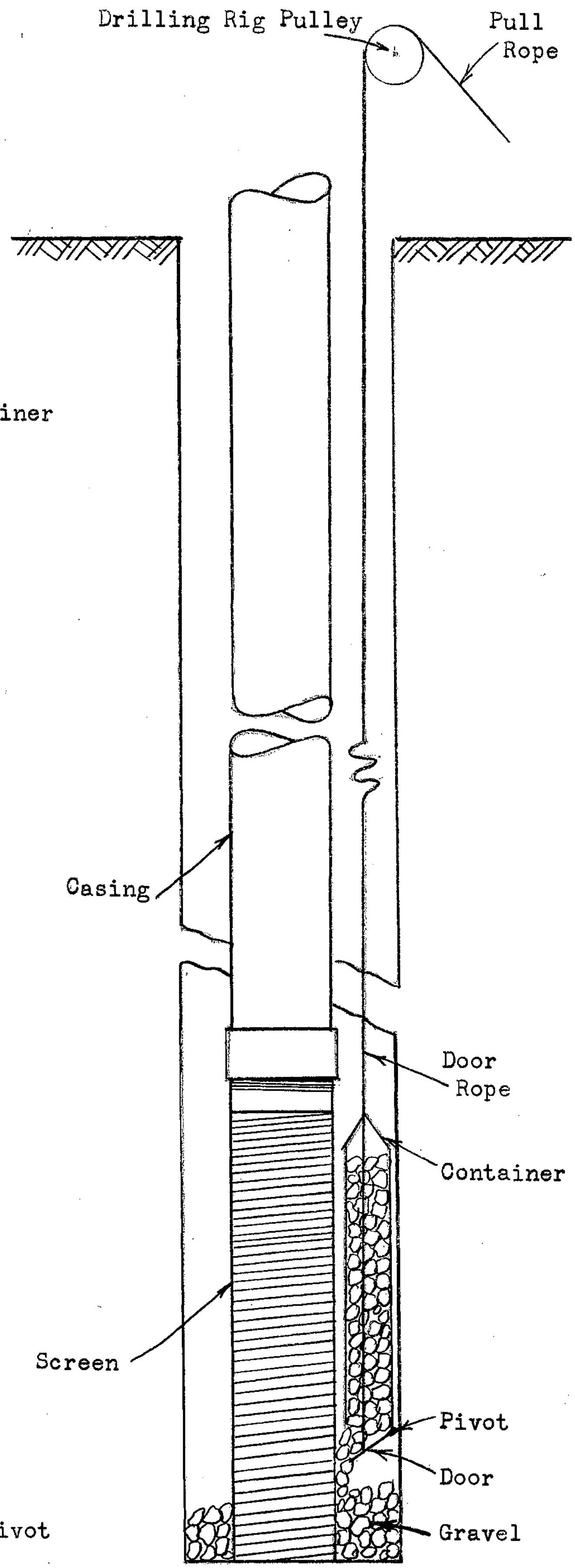


Figure (24) The Container Method

CHAPTER VI

ECONOMIC COMPARISON BETWEEN THE FOUR METHODS OF GRAVEL PLACEMENT

This economic comparison is made to find which method is less expensive considering the amount of segregation that took place.

Since the bailing method proved to be unsuccessful, and gave a great amount of segregation, it will not be considered in the economical comparison. The pump, the tremie, and the package methods are the only three methods that will be compared.

Assume a well 12 inches diameter and 200 feet deep with a screen six inches diameter and ten feet long.

The required gravel pack thickness will be three inches, and its length will be about eleven feet. Hence the required volume of gravel will be equal to $\frac{\pi \times (12^2 - 6^2)}{4 \times 12 \times 12 \times 12} \times 11 = 6.5 \text{ ft}^3$

(A) <u>The Tremie Method</u>

	Required tremie pipe length	= 200 feet
	Required tremie pipe diameter	= 2 inches
	Pipe cost per foot	= \$ 1.00
Hence :	Total pipe cost	= \$ 200.00
	Estimated salvage value	= \$ 00.00
	Estimated pipe life	= 15 years
	Assuming a straight line depreciation,	
	hence pipe cost per year	= 200/15 = \$ 13.30

To find the time required to pack this well it will be compared with the time taken to pack the model well by the same method, experiment (B) page (65).

Time taken in the experiment = 8.5 minutes

Volume of the gravel packed = 0.58 ft^3

Hence : Time required to pack the assumed well = $\frac{6.5 \times 8.5}{0.58}$ = 96 mins.

Estimated time to place and extract the tremie pipe = 4[1] hrs.

Total time required to complete the packing = 4 x 60 + 96 = 356 mins.

Estimated labor cost per hour = $ 3.00

Hence : Total labor cost = (356/60) x $ 3.00 = $ 17.80

Assuming 50 wells to be drilled per year

Hence : Total cost per well = (13.3/50) + 17.80 = 0.27 + 17.80 = $ 18.07

(B) The Pump Method

Assume the maximum size particles used to be 0.317", hence from page (24) we find that the maximum rate of fall for this size is equal to 18.6 in/sec.

Hence: Required pump discharge = $\frac{(2)^2 \times 18.6 \times 60}{4 \times 12 \times 12 \times 12} \times 7.48$ = 15.4 gal/min.

Assuming efficiency = 0.75

Hence: Actual discharge required=15.4/0.75 = 20 gal/min.

Horse power required = 2.27[2] h.p.

Cost of a pump complete with its derive engine and fittings = $ 180.70[2]

Estimated pump life = 8 years

Estimated repair and maintaince cost)(both as percent of = 6%[3]

Estimated insurance and taxes cost) the capital cost) = 10%[3]

Assuming a straight line depreciation and 50 wells per year

Hence: Pump cost per well = $\frac{180.70/8 + 180.70 \times (0.06 + 0.10)}{50}$ = $ 1.06

Pipe cost per well (from the tremie method estimate) = $ 0.27

Hence: Total cost per well = (0.27 + 1.06) = $ 1.33

---

(1) From field observations
(2) From an estimate from Felkins Floyd Plbg & Htg Comp.
(3) From "Engineering Economy" by H. G. Thuesen.

To find the time required we shall compare it with the time taken in the experiment No. (C) page (71).

	Time taken in the experiment	= 5 mins.
	Volume of gravel used in the experiment	= 0.394 ft^3
	Volume of the gravel of the assumed pack	= 6.5 ft^3
Hence:	Time required to complete placing the pack = 6.5 x 5/0.394	= 82.5 mins.
	Estimated power rate in horse power — hour	= \$ 1.25
Hence:	Power Cost = (1.25 x 2.27) x 82.5/60	= \$ 3.96
	Estimated time required to place and extract the pipe	= 4 hrs.
	Estimated starting, preparing, and stopping time	= 1 hr.
	Total time = (4 + 1) + (82.5/60)	= 6.37 hrs.
	Labor rate per hour	= \$ 3.00
	Total labor cost = 6.37 x \$ 3.00	= \$ 19.11
Hence:	Total cost per well = 19.11 + 3.96 + 1.33	= \$ 23.40

(C) The Package Method

Time is the only item involved it this method. Comparing the time required to pack the assumed amount of gravel by the time taken in the experiment No.(D) page (78), we find:

	Time taken in the experiment	= 22 mins.
	Volume of the pack used in the experiment	= 0.536 ft^3
Hence:	Total time required to complete the pack = (6.5 x 22)/0.536	= 266 mins.
	Total cost per well = (266/60 x \$ 3.00)	= \$ 13.30

Results & Conclusion

From the previous comparison we find that the pump method gives the least amount of segregation while the cost estimate proves that it is expensive. It also proves that the package method is cheap meanwhile, its segregation factor is close to that of the pump method. But the tremie method showed to have a high segregation factor at an intermediate cost. This makes the decision on which method to use not an easy one. It requires a compromise between both the cost and the amount of segregation.

The following table offers an economical comparison between them:

	Pump Method	Tremie Method	Package Method
Segregation Factor (S. F.)	2.16	2.24	2.19
Cost per Well	$ 23.40	$ 18.07	$ 13.30
Cost/ S. F. ratio	10.9	8.06	6.07

From the cost per segregation factor ratio we find that the package method is more economical.

Since the package method takes a considerable amount of time the dominating factor will be the time, if the operation is required to be finished soon then the pump method is recommended; but if time is not important the package method can be used.

SUMMARY

Methods of gravel placement can be arranged in the following order according to the amount of segregation produced by each method, starting by the method that gave the least amount of segregation:

(1) The Pump Method. (Segregation Factor = 2.16)

(2) The Package Method (S. F. = 2.19)

(3) The Tremie Method (S. F. = 2.24)

(4) The Bailing Method (S. F. = 4.56)

The pump method is expensive to use, and the package method is less expensive but it takes a considerable amount of time.

Concerning the pack composition, it is recommended that the pack would be of medium size particles. Large and small size particles in the same pack, i.e., a wide range of sizes, will produce a segregated pack.

Concerning the process of placement, it is recommended to be continous and in ample quantities to keep the opening full with gravel all the time. The larger the batch size the less the amount of segregation.

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(2) Tools and Equipment Specification Committee.

(3) Peds analysis committee.

Date of Final Examination: March, 1958.

Thesis Title: A STUDY TO FIND AN ECONOMIC METHOD FOR GRAVEL PLACEMENT IN WATER WELLS WITH THE LEAST AMOUNT OF SEGREGATION

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The content and form of this paper have been checked and approved by the auther and the thesis adviser. The Graduate School Office assumes no responsibility for errors in form or content. The copies are sent to the bindery just as they are approved by the auther and the faculty adviser.

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