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"On Percolation Beds."

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THIS Paper contains an account of observations and experiments relating to the physical conditions obtaining in sewage filter-beds, with special reference to the so-called "trickling-filters" or "percolation beds." The study of percolation beds has been conducted, hitherto, almost entirely with regard to the purification effected by them, as measured by the change in the organic matter content of the liquid due to its passage through the bed. In what follows, however, attention will be paid chiefly to the physical conditions accompanying such purification, as distinct from the chemical and biological changes involved.

Chemists are well aware that a precipitate retains a certain amount of the liquid from which it was obtained, and if the precipitate be washed with distilled water, a mixture of this water and the retained liquid will drain away for quite a considerable time. Bunsen¹ gave a method for calculating the amount of wash-water necessary to reduce the retained water to any given amount; and the amount of water surrounding the particles of medium in a percolation bed would from analogy appear to be an important factor in the passage of liquid through it.

The difficulties of investigating the water-content of a working filter-bed seemed insuperable, on account of the varying nature of the liquid and the unknown and varying amounts of colloidal, organic, and other matters present in the bed. It was therefore decided, after some calculations as to the magnitude of the quantities to be measured, to use an experimental pipe-filter—an 18-inch glazed earthenware-pipe—and to eliminate the variable factors by using tap-water and clean filter-materials. These experiments were devised to answer two questions, namely, (1) What is the amount of water moving through a percolation bed at any moment whilst the

¹ T. E. Thorpe, "Practical Quantitative Analysis." 10th ed., p. 57.

bed is steadily at work? (2) How long does any drop of water take to pass through the bed?

Before describing the experiments it will be useful to consider the measurements necessary to answer the first question. Assuming that a percolation bed is steadily at work, that is, receiving and discharging water at the same rate, it is required to find how much water is present in the bed at any moment, and how much of that water is moving through the bed. The whole of the water present at any moment is partly within and partly on the outside of the particles of medium. The one portion occupies the intra-cellular spaces of the particles, and will be referred to as the "absorbed" water; the other portion, on the outside of the particles, and considered as taking part in the general water movement, will be referred to as the "interstitial" water. The distinction is quite arbitrary, as the one is contiguous to the other, but it is convenient, and, as will be seen, is not altogether unimportant. Again, the whole of the water present at any moment is partly drainable and partly non-drainable, and if the sprinkling be stopped, the drainable portion will drain away and can be measured. The portion remaining in the bed after draining has taken place is that referred to as "non-drainable" water. Since the water might continue draining for a considerable time after sprinkling had ceased, the "drainable" water is defined as that water which drains away from the medium during the 20 hours after the cessation of sprinkling. The drainable water plus the non-drainable water is of course equal to the absorbed water plus the interstitial water, as both represent the water-content at any moment during the working of the bed.

This may be expressed in symbols thus:—

$$D + N = A + I \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where	D	represents the drainable water,
	N	„ „ non-drainable water,
	A	„ „ absorbed water,
and	I	„ „ interstitial water.

Thus I, the water on the outside of the particles and presumably in motion, can be obtained from the equation when D, A, and N are known; D can easily be measured, and A is readily determined in the usual way.

The non-drainable water (N) requires two measurements, as the following considerations will show. If a bed be filled with dry material, and water be poured in, the whole being allowed to stand full like a contact bed, then the material will eventually

become saturated. Call the amount of water required to fill the bed M gallons. Allow the bed to drain 20 hours, and measure the amount of water that drains away. Call this amount m gallons, then the difference between the two will represent the water retained by the material, that is, the non-drainable water. It will be convenient to refer to M as the "first measurement," and m as the "second measurement." Substituting N the non-drainable water by its equivalent $M - m$ in the equation (1), we have :

$$I = M - m - A + D \quad . \quad . \quad . \quad . \quad . \quad (2)$$

which shows the four quantities required to determine the amount of interstitial water.

The Experimental Bed.—The glazed earthenware-pipe, holding the filtering material, was closed at one end, and provided with an outlet fitted with a tap. The depth was 2.4 feet, and the capacity (empty) 4.207 cubic feet. Intermittent sprinkling was effected by a tipping trough, which emptied its contents into a perforated tray supported 2 inches above the medium, and this tray distributed water evenly over the bed.

The Filtering Material.—Four different media were used during the experiments, namely : coal, gravel, blast-furnace slag, and destructor-clinker, and from three to five grades of each were separately investigated. The grading was effected by means of hand-riddles, but the grades of one medium, for several reasons, are not all comparable with those of other media. The sizes are given in the first column of the Appendix, the first figure showing the mesh of the riddle through which the material passed, and the second figure the mesh on which it remained. It will be seen that the sizes ranged from $1\frac{1}{4}$ -inch to $\frac{3}{4}$ -inch material, down to $\frac{1}{4}$ -inch to $\frac{1}{8}$ -inch.

Both the coal and the gravel were well washed and dried at 108° F. before use, and samples of the material so dried showed no marked loss when heated in a water-oven at 212° F. for 24 hours. The destructor-clinker and the blast-furnace slag were obtained clean and dry. The clinker represents two very different materials ; the coarser material was hard, vitreous, and heavy, while the two finer grades were light and porous, consisting largely of breeze.

The order of operations for an experiment was as follows : the graded dry medium was weighed and put into the bed, and sufficient water to fill the bed weighed and poured in ; the surface was then covered to prevent loss by evaporation, and the medium was allowed to soak from 36 to 48 hours. The water-level, which had sunk owing to absorption by the medium, was then made up to a certain mark. The total amount of water weighed gave the quantity which has

been previously described as the first measurement (M). The outlet was next opened, and the medium was allowed to drain for 20 hours; the water which drained away was not measured, as it was found easier and more expeditious to weigh the equivalent amount of water necessary to fill up the bed after draining; this gave the quantity known as the second measurement (m). Then $M - m$ is the non-drainable water. After the bed had drained 20 hours water was sprinkled at a known rate over the medium for about 4 hours, during which time it was percolating steadily through the bed. The distribution was then stopped, and all water which drained away during the ensuing 20 hours was collected and measured; this gave the amount of drainable water (D). The absorbed water (A) was determined in a sample (100 to 500 grammes) of the material taken when filling the bed. This sample was weighed and immersed completely in water for 36 to 48 hours; the particles were then carefully dried with a cloth and re-weighed, the increase in weight giving the absorbed water (A). It was proved that larger (3-inch cubes) pieces of coal and brick continued to absorb water for from 3 to 5 days; still, for the sizes used saturation was probably completed in even less than 36 hours.

Only the coarsest grade of each medium was used for determining the absorbed water, as it was highly probable that the loss by evaporation, during the drying of the smaller particles, would vitiate any results obtained. An exception was, however, made with the clinker owing to the marked difference in the character of the material.

The results showed that the total amount of water present in the bed at any moment varied between 9.5 gallons (coarse gravel) and 32.8 gallons (fine breeze) per cubic yard of medium. The absorbed water (A) varied between 2 gallons (gravel) and $10\frac{3}{4}$ gallons (breeze) per cubic yard; while the coal absorbed 10.4 gallons and the slag absorbed 7.8 gallons per cubic yard. The interstitial water (I), obtained by inserting the values of M , n , A , and D , into equation (2), is given in the Appendix and varies with the grade of the medium and with the rate of sprinkling. Taking the rate of sprinkling at 200 gallons per square yard per day, the amount varied between 7.5 gallons and 16.3 gallons per cubic yard, and the effect of the size of the particles of medium was thus very marked; when the rate of sprinkling was increased 50 gallons per square yard per day, the amount of interstitial water increased by about 0.4 gallon per cubic yard.

Considering the widely different character of the media, the difference between the interstitial water of one medium and that of another, when the particles are comparable in size, is not very great,

except in the case of the finest clinker. The important point to notice is the relatively large quantity of water in contact with the medium, and presumably in motion through the bed. The medium is thus similar to a tank holding 8, 16, or 20 gallons of water per cubic yard, into which liquid flows at the rate of (say) 7 or 8 gallons per square yard per hour.

The object of the next series of experiments was to answer the second question, namely: how long does any drop of water remain in a percolation bed, or, as usually stated, how long does liquid take to pass through a percolation bed when working at its usual rate?

Before describing the experiments, however, it will be useful to review briefly the attempts of others to solve this question. Three methods of ascertaining the time of passage of liquid through filtering media appear to have been tried, two in England, and one at Lawrence, Massachusetts. These are:—

(1) By applying a coloured liquid to the surface of the bed, the time being taken as that between the pouring in of the coloured liquid and the first appearance of colour at the outlet.

(2) By observing the time between starting the sprinkler on a drained bed, and the appearance of liquid at the outlet, or by stopping the sprinkler and noting the time when a perceptible falling off in the quantity of the effluent occurs.

(3) By sprinkling a solution of common salt on the bed in the same manner, and at the same rate as sewage; the time being taken as that required for the chlorine in the effluent to become constant, or nearly so.

The first method, that of the application of colour, though recommended by the Royal Commission,¹ obviously only measures the quickest passage of a comparatively small portion of a coloured liquid. The second method could only measure the time of percolation if the medium had a negligible amount of interstitial water, in which case it would correspond to the method of measuring the time of flow of water down an empty trough; but if the trough had an appreciable water-capacity, the time between the liquid entering the one end, and overflowing at the other, would have little or no connection with the time of passage through the trough. The third method, adopted at Lawrence,² appears to be capable of good results, though from the Author's point of view the interpretation errs in the opposite direction to the colour method, as the slowest moving molecules are taken to measure the time of percolation. The method

¹ Third Report on Sewage Disposal, vol. ii, Evidence, p. 240.

² State Board of Health Report, Massachusetts, 1904, p. 249.

employed by the Author, and briefly described by him before the Society of Chemical Industry,¹ is also a chlorine method, but differs somewhat from that adopted at Lawrence.

It will be evident that the molecules of any drop of applied liquid are soon dispersed by mixing and diffusing with the liquid already in the bed, and take different paths through the bed. It therefore becomes necessary to define what is meant by the time of passage of liquid through a percolation bed. The Author defines the "time of percolation" as the average time taken by all the molecules of any given portion or dose of applied liquid to pass through the bed.

In order to watch the passage of any given dose of applied liquid, it was only necessary to disperse in that dose a number of recognizable (chlorine) molecules; these, unless selective absorption took place, might reasonably be expected to travel in much the same way as the undistinctive water-molecules, and by observing the relative number in samples of the effluent taken at equal and sufficiently short intervals, a chlorine-curve could be drawn and the mean frequency calculated. The position of the mean frequency of the curve corresponds to the average time. This method of calculation corresponds to the well-known theorem for obtaining the centre of gravity of a number of heavy particles; the chlorine numbers represent the weighted particles, and the time of sampling represents the distance of the weighted particle from the origin (of the curve). The experiment consisted in applying a dose of a chloride solution (common salt) to the experimental bed, previously described, whilst the bed was steadily at work; samples of effluent were taken every fifth minute, and the chlorine determined. The figures are given in Column 4 of the Table in the Appendix.²

When the rate of sprinkling was 245 gallons per square yard per day, the time of percolation through 2.4 feet of coarse gravel was 15 minutes, and through fine gravel 33.7 minutes. At practically the same rate coarse coal gave 24.3 minutes, and fine coal gave 54.7 minutes. At the rate of 200 gallons per square yard per day the time taken was 30 minutes for coarse destructor-clinker, and for fine clinker 148 minutes. No order or regularity is observable among the times of percolation themselves, but on comparing these with the rates of sprinkling a certain regularity is

¹ "The Time of Passage of Liquid through Percolating Beds." *Journal of the Society of Chemical Industry*, vol. xxvi, p. 739.

² Experiments were also made with coloured liquids. A solution of common salt coloured with eosin was added on one occasion, but colour was observed in the effluent long after the chlorine had become inappreciable. The retention of the colour was possibly due to selective absorption by the medium.

noticeable, namely, as the rate increases the time decreases, and the product of the time of percolation and the rate of sprinkling, for any one grade, does not vary greatly.

Another point is noticeable on comparing the different grades of one medium. The time of percolation, for approximately equal rates of sprinkling, increases as the grade decreases. Now, as the grade decreases, the interstitial water (I) increases; in other words, the time of percolation varies as the amount of interstitial water.

These two statements may be expressed, approximately, thus:—

$$c T = \frac{I}{R}$$

where c is a constant and R denotes the rate of sprinkling.

With a view to investigate the value of this constant: 1 cubic yard of medium (1 superficial yard and 3 feet deep) was chosen as the unit of reference, the interstitial water was taken in gallons per cubic yard, the time of percolation through 2.4 feet was increased *pro rata* to correspond with the time of passage through 3 feet of medium, and the rates of sprinkling were taken in gallons per square yard per hour. The average constant derived from thirty sets of observations is 0.0307; and excluding the two sets in which fine clinker (breeze) was used, the average is 0.0312.

The constants found in the individual experiments, however, vary so much and so irregularly among themselves (as much as between 35 per cent. above and 23 per cent. below the average of them) that the value of the average for the purposes of calculation can only be regarded as a rough approximation.

It has been observed that the interstitial water is taken as a measure of the amount of water passing through the bed; and the variation is probably due to the fact that only part of the interstitial water takes part in the movement when such a medium as fine gravel is used, while with a porous medium like fine breeze, a portion of the so-called absorbed water is undoubtedly involved. The amount of dilution of the chloride solution, as it passed through the media, lends support to the above explanation.

The general results of the investigation, so far as the experimental work is concerned, may be summed up in the one statement, that the time of percolation through clean filter material varies inversely as the rate of sprinkling, and directly as the amount of water taking part in the water movement through the bed, the amount of water in motion being generally represented by the interstitial water.

In applying the foregoing results to practical problems, sewages might be classified according to the time of percolation, that is, the

time of contact with the medium, required to effect purification. It is evident from the experiments previously described that a percolation bed may be constructed and worked to give any desired time of percolation within very wide limits; for example, a bed of fine breeze ($\frac{3}{8}$ -inch to $\frac{1}{2}$ -inch) 6 feet deep, worked at a rate of 200 gallons per square yard per day, would allow about 6 hours' contact. A similar depth of coarse gravel (1-inch to $\frac{3}{4}$ -inch) worked at the same rate would allow only about 44 minutes' contact. No direct measurements of the time of percolation appear to have been made on working beds, except those at Lawrence, and the latter results are not available, as the average time of percolation has not been calculated. In lieu of exact measurement the Author has attempted to obtain an approximate value indirectly from other data. One section of a large working filter fitted with a travelling distributor contains coal, 6 inches of 2-inch to $1\frac{1}{2}$ -inch cubes at the bottom, and 4 feet 3 inches of $\frac{1}{2}$ -inch to $\frac{1}{8}$ -inch material above. The interstitial water in the finer material when at work would be about 13.4 gallons per cubic yard (the mean value of the three finer grades of coal used in the above experiments), or 19.5 gallons of interstitial water below each square yard of bed-surface. The rate of sprinkling which yielded a non-putrescible effluent (0.08 albuminoid nitrogen per 100,000) was between 150 and 160 gallons per square yard per day, or 6.5 gallons (say) per square yard per hour. From the formula $T = I/cR$ the time of percolation works out to 98 minutes.

Another section contains destructor-clinker, 6 inches of 2-inch to $1\frac{1}{2}$ -inch pieces, and 4 feet 3 inches of $\frac{1}{2}$ -inch to $\frac{1}{8}$ -inch grade. The rate of sprinkling was again 6.5 gallons per square yard per hour, and the interstitial water below each square yard of bed surface would be approximately 26 gallons. This makes the time of percolation 130 minutes, and the purification was distinctly better (0.04 albuminoid nitrogen) than with coal. Assuming that a sewage requires 100 minutes' contact with a filter material for purification, it will be interesting to see what depth of the several materials used in the experiments would give the above time of percolation, with a rate of sprinkling of 6.5 gallons per square yard per hour (156 gallons per square yard per day); and using the formula $I = cTR$ to calculate the total amount of interstitial water below each square yard of bed-surface, the depth is obtained thus:—

$$\frac{\text{Total interstitial water}}{\text{Interstitial water per cubic yard}} = \text{depth of bed in yards.}$$

The following Table shows the equivalent beds with a time of percolation of 100 minutes¹ :—

Gravel.			Coal.			Slag.			Clinker.		
Grade.		Depth.	Grade.		Depth.	Grade.		Depth.	Grade.		Depth.
In.	In.	Ft. In.	In.	In.	Ft. In.	In.	In.	Ft. In.	In.	In.	Ft. In.
1	to $\frac{3}{4}$	8 3	$\frac{3}{4}$	to $\frac{5}{8}$	7 2	$1\frac{1}{4}$	to $\frac{3}{4}$	6 1	1	to $\frac{3}{4}$	6 1
$\frac{3}{4}$	„ $\frac{5}{8}$	7 3	$\frac{1}{2}$	„ $\frac{3}{8}$	5 2	$\frac{3}{4}$	„ $\frac{5}{8}$	5 4	$\frac{5}{8}$	„ $\frac{3}{8}$	3 9
$\frac{5}{8}$	„ $\frac{1}{2}$	6 7	$\frac{3}{8}$	„ $\frac{1}{4}$	4 5	$\frac{5}{8}$	„ $\frac{3}{8}$	4 9			
$\frac{1}{2}$	„ $\frac{1}{4}$	4 4	$\frac{1}{4}$	„ $\frac{1}{8}$	4 0	$\frac{3}{8}$	„ $\frac{1}{4}$	4 0			
						$\frac{1}{4}$	„ $\frac{1}{8}$	3 10			

It is assumed that the interstitial water in 6 feet of medium is twice as much as in 3 feet; this may or may not be true, but in any case the error is not likely to be very appreciable with the above grades. The correspondence of the above depths with those which experience has proved to be satisfactory lends support to the conclusion that few classes of sewage require less than 100 minutes in a bed for purification. The equivalent beds given above are for clean materials only, as after being treated with sewage for some time, the time of percolation would undoubtedly increase with the accumulation of organic, colloidal, and other water-holding substances; and the increase would probably be greater with fine than with coarse material.

The increase of nitrification with the age of a bed is probably accounted for by this accumulation of organic and colloidal matters, which increase the amount of interstitial water, and consequently prolong the time of percolation. The accumulation of these matters is perhaps advantageous up to a certain point, beyond which the air necessary for purification becomes insufficient, and here a knowledge of the air-content of a bed would be of value. The air-content during the above experiments was readily obtained; thus, the second measurement (m) gave the volume of air in the resting bed, and the drainable-water (D) gave the air displaced by the water during the working of the bed, so that $m - D$, gave the volume of air in the working-bed. The air-content of gravel, while the bed

¹ The figures in the Table are, of course, to be regarded as approximate only, and are given chiefly to indicate the utility of the relation $I = cTR$.

The depth of bed for any one medium, grade, and rate of working, to give 100 minutes as the time of passage through the bed, can be obtained by means of the Table in the Appendix; or from the equation by applying the proper constant.

was in action, was 37 per cent. of the total volume of the bed ; coal gave 40 per cent. and slag and destructor-clinker gave from 48 to 50 per cent. Generally the larger the grade the greater the volume of air present in the bed.

Having in mind the difficulties of determining either the time of percolation or the amount of interstitial water, the Author tried to find a simple method of observation. It was noticed on starting the sprinkler that the time before the flow of the effluent became steady varied with the rate of sprinkling. With a view to see if this was connected with the time of percolation, fourteen observations were made with a clock and drum arrangement, which recorded the flow automatically. Excluding one observation, which was questionable, the results were generally from 25 to 30 per cent. low. The method might be used for obtaining approximate values of the time of percolation, when other methods could not be used.

In conclusion, one of the most important points to be settled in the design of percolation beds is the nature, size, and depth of the filtering material, and not less important is the rate and method of sprinkling. The relation of the first four of the factors to the time of percolation is such that a considerable latitude is permissible with any one factor, provided the other factors are adjusted to give the time necessary for purification. The effect of any given method of sprinkling remains to be investigated ; it will, however, be evident that a distributor which gave large doses at long intervals, more especially when the doses are concentrated on a limited area of bed, would afford less time for percolation than one which gave small intermittent doses or light continuous sprays with uniform distribution. A factor of safety is desirable with percolation beds, as with other structures, to allow for irregular distribution and variations in the strength of the liquid to be purified. The problem for chemists is not merely to analyse the liquids, but to correlate the results with the time of percolation ; in other words, to determine the rate of purification, the rate of nitrification, etc., so that sewages may be classified according to the number of minutes' contact required for a given amount of purification. Much, however, yet remains to be done by both chemists and engineers before the purification of sewage in percolation beds is properly understood.

The above-mentioned experiments were carried out at the Wolverhampton Sewage-Outfall Works, and the Author is indebted to the Sewage Committee of the Wolverhampton Corporation for permission to publish them. The Author also desires to acknowledge his

obligations to Dr. Gilbert J. Fowler, and Mr. George Green, M. Inst. C.E., for suggestions in regard to the arrangement of the subject-matter, and to Mr. Harold Wilson for assistance in carrying out the experiments.

The Paper is accompanied by eight Tables containing the results of the various observations described and calculations based thereon. The Table in the Appendix has been selected from among these.

APPENDIX.

APPENDIX.

DATA FOR CALCULATION OF CONSTANT c .

Grade.	Rate of Sprinkling per Square Yard per Day.	Rate of Sprinkling per Square Yard per Hour. (R.)	Average Time of Percolation through 2.4 Feet of Medium.	Average Time of Percolation through 3 Feet of Medium. (T.)	Interstitial Water per Cubic Yard. I.	$c = \frac{I}{RT}$
	Gallons.	Gallons.	Minutes.	Minutes.	Gallons.	
<i>Coal—</i>						
$\frac{3}{4}$ in. to $\frac{5}{8}$ in. {	239	9.96	24.3	30.4	9.5	0.0313
	180	7.50	31.7	39.6	8.8	0.0296
	105	4.38	45.6	57.0	8.2	0.0327
$\frac{1}{2}$ in. „ $\frac{3}{8}$ in. {	307	13.21	26.4	33.0	12.2	0.0289
	134	5.58	49.4	61.8	11.8	0.0341
$\frac{3}{8}$ in. „ $\frac{1}{2}$ in. {	228	9.57	34.0	42.5	14.4	0.0357
	191	7.96	39.0	48.8	14.3	0.0366
	129	5.38	63.6	79.5	13.6	0.0317
$\frac{1}{4}$ in. „ $\frac{3}{8}$ in. {	236	9.83	54.7	68.4	16.0	0.0249
	181	7.54	64.3	80.4	15.7	0.0260
<i>Gravel—</i>						
1 in. „ $\frac{3}{4}$ in. {	245	10.21	15.0	18.8	7.6	0.0396
	200	8.33	17.6	22.0	7.5	0.0409
	154	6.42	22.0	27.5	7.4	0.0417
$\frac{3}{4}$ in. „ $\frac{5}{8}$ in. {	259	10.79	20.1	25.1	9.2	0.0340
	194	8.08	31.5	39.4	9.0	0.0283
	137	5.71	35.8	44.8	8.4	0.0328
$\frac{5}{8}$ in. „ $\frac{1}{2}$ in. {	250	10.42	31.2	39.0	9.8	0.0241
	192	8.00	37.2	46.5	9.5	0.0255
	166	6.92	40.0	50.0	9.3	0.0269
$\frac{1}{2}$ in. „ $\frac{1}{4}$ in. {	246	10.25	33.7	42.1	15.1	0.0350
	197	8.21	40.0	50.0	14.6	0.0356
	155	6.46	44.1	55.1	14.2	0.0399
<i>Destructor- Clinker—</i>						
1 in. „ $\frac{3}{4}$ in. {	230	9.58	27.1	33.9	10.7	0.0332
	200	8.33	30.0	37.5	10.5	0.0337
	155	6.48	36.8	46.0	10.1	0.0338
$\frac{3}{4}$ in. „ $\frac{5}{8}$ in. {	250	10.42	47.1	58.8	16.2	0.0265
	200	8.33	60.9	76.3	15.6	0.0246
	147	6.12	84.7	105.9	15.2	0.0235
$\frac{5}{8}$ in. „ $\frac{1}{2}$ in. {	246	10.25	120.0	150.0	24.1	0.0157
	200	8.33	148.0	185.0	23.5	0.0153
					Average—	0.0307