Choice of the sand for sand filters used for secondary treatment of wastewater

A. Liénard, H. Guellaf and C. Boutin

Cemagref, Research unit: Water quality and pollution prevention, 3bis, quai Chauveau – CP 220, 69336 Lyon Cedex 09, France

Abstract In a range from 100 to about 1,000 People Equivalent (PE), Secondary Wastewater Sand Filters (SWSF) are used by a lot of rural communities in France. A series of case studies however point out that several criteria concerning global and detailed design and implementation of these systems have to be approached scientifically, in order to obtain the expected results on a long-term basis.

The choice of the sand constituting the infiltration bed, core of the biological reactor, is of course one of the key elements and is the main subject of this article. It must have a sufficient initial permeability in order to ensure an adapted infiltration speed, after colonisation by the purifying biomass. The d10 fines content and degree of uniformity mainly control this permeability. The quarry or the aggregate extractor, who masters his production this way, usually gives these elements, based on granulometric analysis. However the adjustment of an infiltration test with clear water is essential to check on site the conformity of the deliveries.

Keywords Fines content; percolation test; permeability; sand filters; wastewater treatment

Introduction

In numerous countries, wastewater treatment plants use sand as media for the microorganisms processing the degradation of the organic matter and the oxidation of the nitrogenous compounds coming from small rural communities and from individual or grouped houses. These treatment systems, of the "attached-growth cultures on fine media" type, can be implemented without any electromechanical equipment if topography allows. A town employee can easily provide the operation constraints, which are known to be simple. These biological reactors usually are preceded by a primary treatment step: a septic tank or a primary settling tank.

Today it is a general understanding and practice to have several infiltration beds in parallel, alternately fed, in order to allow: i) a mineralization of the superficial organic deposits brought by the suspended residual matters, ii) a self-regulation of the purifying biomass, and iii) a re-oxygenation of the pores. On the other hand, the batch feeding and water distribution systems for infiltration beds, which are also of major importance for a good working, still are imperfectly designed, especially for buried filters for which distribution networks are not submitted to pressure and water distribution tests before covering.

In addition, the dimensioning methods designed by Otis *et al.* (1982) or Lesavre and Zaïri (1988), are still insufficiently known and made accessible to the equipment designers. The market possibilities are too low for companies which could specialise in prefabricated plants to be optimised with the size of each community.

But part of the problem is also coming from gaps in the infiltration beds design. The purpose of this study is mainly to focus on the choice of the sand.

Equipment and methods

For 21 alluvial sands and 5 crushed sands coming from several origins (working wastewater treatment plants, extraction sites and quarries), the following analyses have been carried out.

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Sand granulometry

This is the main part of the study because it leads to definition of deciding factors: the d10 [mesh diameter allowing 10% of the sand mass to go through, in mm], the d60 [mesh diameter allowing 60% of the sand mass to go through, in mm] and the coefficient of uniformity (CU) [ratio: d60/d10, ad].

Dry sieving. A sample is placed into an oven at 105°C during 24 hours, then cooled down in a dessiccator during 20 minutes. Then, it is introduced in a column composed of a sieve with increasing mesh sizes, and subjected to a 20 minutes vibration. Mesh sizes are : 0.08, 0.1, 0.16, 0.2, 0.25, 0.315, 0.4, 0.5, 0.63, 0.8, 1, 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3 mm. It allows us to screen all types of sand. The sample size M, generally greater than 500 g, was meeting the prescription: M > 0.2 D (AFNOR, 1990), with M stated in kg and D highest diameter dimension of the sand in mm.

The sieving residue is then collected on each sieve and weighed with a 0.01 g accuracy.

Humid sieving. As for dry sieving, some stacked sieves are used with mesh sizes : 0.08, 0.125, 0.2, 0.5, 1, 2, 4, 5 mm, but here a clear water circulation washes the grains and separates fine particles. Sieving time is also of 20 minutes. This method is more accurate than the previous one if fine particles (<0.08 mm) in the sample have to be quantified. Both methods give some similar results for granular diameters higher than 0.2 mm.

Infiltration test

The test principle is the one used by Grant (cf. Cooper *et al*., 1996) in the United Kingdom, who was also dealing with the problem of sand choice for reed bed filters. The operation process is similar to Grant's one, but the utilised material is slightly different as described in Figure 1.

For each test, the operating procedure is the following.

1. Sand is poured on a 20 cm height, proceed by layers of 4 to 6 cm which are progressively soaked with water, without any surface disturbance and any segregation between the grains of different sizes, so that the sand is uniformly tapped. The exact sand height $H_{s\ exp}$ [in m] is precisely measured a posteriori. The sand is then saturated (even though it is free flowing) by unmeasured additions of clear water during about ten minutes so that the saturation is complete and stable at the full height.
2. Five trials are then performed with, for each of them, the record of the infiltration time of a 500 ml water volume [V_{exp}, in m^3]; their average [t_{exp}, in s] gives the infiltration time characterising this sand.

The "wall effect" is estimated to be on a layer adjacent to the wall with a thickness of $D/2$, so, for the studied sands, this effect can be neglected.

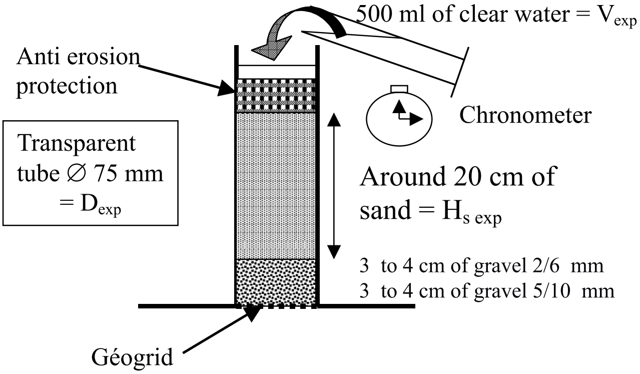

Figure 1 Adaptation of the Grant's infiltration test (Cooper *et al*., 1996)

Sand porosity and density

The measured grain volume [v_g, in m^3] is the displaced water volume when a sand mass [m_g, in kg] is added into a known water volume. The total volume [v_t, in m^3] of this same sand mass is measured. These measurements are done on sands which have been previously washed on a 80 µm sieve and dried in an oven at 105°C.

Voids volume [v_v, in m^3] is defined by the difference: $v_v = v_t - v_g$.

Specific volume mass [ρ, in kg m^{-3}] is defined by the ratio: $\rho = m_g/v_g$

Porosity F [ad] is determined by the following equation: $\phi = v_g/v_t$

Volume content of fines smaller than 80 µm [φ_v, ad]

It is calculated by the following formula proposed by Marion *et al.* (1992) and taken up by Revil and Cathles (1999).

$$\varphi_v = \frac{\rho_s}{\rho_f}\,\frac{1 - \Phi_s}{1 - \Phi_f}\,\frac{\varphi_w}{1 - \varphi_w}$$

where: ρ_f: fine particles specific density, taken at 2650 kg m^{-3} (Revil and Cathles, 1999).

ρ_s: measured specific volume mass of a sand from which fines have been previously separated by humid sieving.

Φ_s: measured porosity of a sand from which fines have been previously separated by humid sieving.

Φ_f: fines porosity, taken at 0.6, the value chosen by Revil and Cathles (1999) for shales.

φ_w [ad]: fines mass content determined from the curve of granulometry by humid sieving.

Results and discussion

In France as well as abroad, most of the recent studies giving on-site efficient recommendations, are usually agreeing upon a minimum effective sand diameter (d10) of 0.2 mm (Gold *et al.*, 1992, Reed *et al.*, 1988, Guilloteau, 1994). But advice concerning the Coefficient of Uniformity (C.U.) is rare and not precise at all (Boutin *et al.*, 1998), even lacking when dealing with a wide granulometry curves-zone, as it applies for on-site treatment (AFNOR, 1998), which often inspires the designers of small community treatment plants.

Infiltration test

In order to interpret the experimental measurements, the geometrical characteristics of the available material have to be taken in account, especially for the infiltration test, which is usefully compared to Grant's test. This test is representative of the maximal hydraulic conductivity obtained with clear water saturation. Normally the systems feeding is of course done with wastewater and their normal functioning is more characteristic of a non saturated medium. Nevertheless, being performed on clean sand, this test can give a realistic indication for the choice of the sand, taking into account the risk bound to the reduction of a waste water permeability, because it still contains residual suspended solids and flows in a colonised medium.

In order to adapt our experimental conditions to Grant's ones, Darcy's equation is necessary. This equation gives the hydraulic conductivity at saturation [K, in m s^{-1}], thanks to a permeability test in saturated medium.

$$K = \frac{H_s}{t_f - t_i}\ln\left(\frac{h_i + H_s}{h_f + H_s}\right) \qquad (1)$$

with: h_i: initial height of the water [in m] corresponding at the initial time t_i [in s].

H_f: final height of the water [in m] corresponding at the final time t_f [in s].

H_s: sand height [in m].

In this trial, the water flows completely out, $h_f = 0$; $t_i = 0$, t_f is the measured time so called "infiltration time". The equation becomes:

$$K = \frac{H_s}{t_f} \ln\left(\frac{h_i + H_s}{H_s}\right) \tag{2}$$

h_i depends on the experimental conditions:

$$h_i = \frac{V}{\frac{1}{4}\pi D^2}$$

with: V initial water volume [in m^3], D diameter of the experimental column [in m].

In the case of Grant's defined conditions, $D_g = 0.1$ m and $V_g = 0.5\ 10^{-3}$ m^3. In the case of the present experimental conditions, $D_{exp} = 0.075$ m and $V_{exp} = V_g$ (see Figure 1).

Equation (2) at Grant's conditions and at slightly different experimental conditions defines "Grant's time" [t_g, in s]:

$$t_g = \frac{0.0553}{H_{s\ \exp} \ln\left(\frac{4V_{\exp}}{\pi D_{\exp}^2 H_{s\ \exp}} + 1\right)} t_{\exp} \qquad [3]$$

With Equation (3), an experimental system, not strictly identical to the Grant's one, can be used. The infiltration time [t_{exp}, in s] has to be compared with the thresholds defined by Grant of which the limits (between 50 and 150 seconds) have been judged as adequate (Cooper *et al.*, 1996).These values correspond to a permeability varying between 1.1×10^{-3} and 3.7×10^{-4} m s^{-1}.

d10 influence

As indicated in Figure 2, the infiltration time [t_g] is strongly depending on *d*10. A "power type" adjustment based on a study of 21 alluvial sands having a *d*10 between 0.13 and 1.13 mm, well represents the relationship between these two parameters:

$$t_g = 6.70\ d10^{-2\cdot 00} \tag{4}$$

Many years ago, Wolfgang Beyer (1964), empirically established a relation between the permeability coefficient *K* and *d*10. This equation is:

$$K = C^*\ (d10) \tag{5}$$

C: empirical coefficient (in m^{-1} s^{-1}), variable with the CU, according to Table 1.

By applying Equation (2) with Grant's conditions, $K = 0.0553/t_g$ (6)

When combining the Equations (5) and (6), we obtain what we can call "Beyer-Grant's time" [t_{bg}, in s]:

$$t_{bg} = \frac{0,0553}{C} d10^{-2} \tag{7}$$

The different t_{bg} values calculated this way have been written in Figure 2 and reveal, with a correlation factor even more improved, a very close correlation to those previously calculated. With respective infiltration times of 150 and 50 seconds, the *d*10 obtained this way go from 0.2 up to 0.35 mm. However, Beyer shows that in addition to the *d*10, the coefficient of uniformity also affects the infiltration time.

Table 1 Experimental values of coefficient C according to the Coefficient of Uniformity

CU	[1.0–1.9]	[2.0–2.9]	[3.0–4.9]	[5.0–9.9]	[10.0–19.9]	>20.0
C	1.1×10^{-2}	1.0×10^{-2}	9×10^{-3}	8×10^{-3}	7×10^{-3}	6×10^{-3}

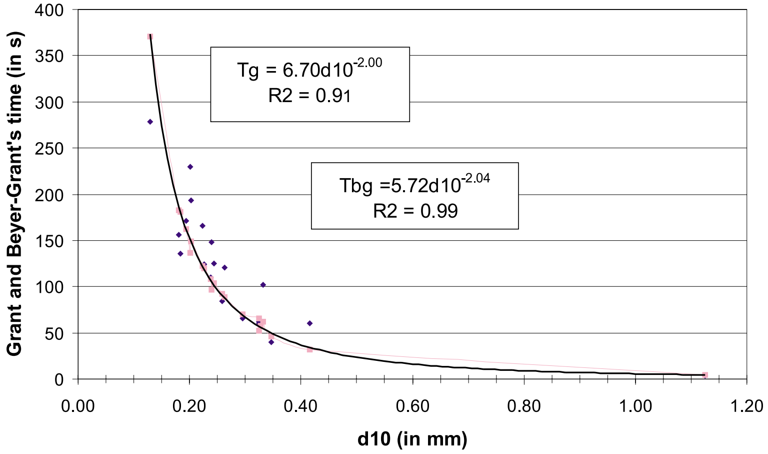

Figure 2 Evolution of infiltration time as a function of *d*10 for alluvial sands (in black, t_g and power adjustment – in grey, t_{bg} values calculated from Beyer's relation)

In actual practice, and to keep a good security level, we recommend to use a sand with a *d*10 ranging from 0.25 to 0.40 mm.

Fines influence

For alluvial sands, fines can be defined with a size less than 80 µm, but also contain shale and clayey particles. For sands issued from parent rocks crushing, fines presence is more frequent because they are produced in larger quantities during crushing.

To reduce production costs, producers tend to keep the fines in order to modify the curve of granulometry and decrease the d10. If such a practice can be accepted for many civil engineering uses, it is disastrous for wastewater treatment as shown in Figure 3.

As shown before, the permeability is submitted to non equivalent but simultaneous influence of different parameters. So, a relation has to be found to describe the influence of the fines on permeability. Revil and Cathles (1999) propose such a type of equation which describes the influence of the volume of fine particles composed of shale. They give an equation which defines the permeabilities of a sand-fines mixture and of the washed sand according to the fines content.

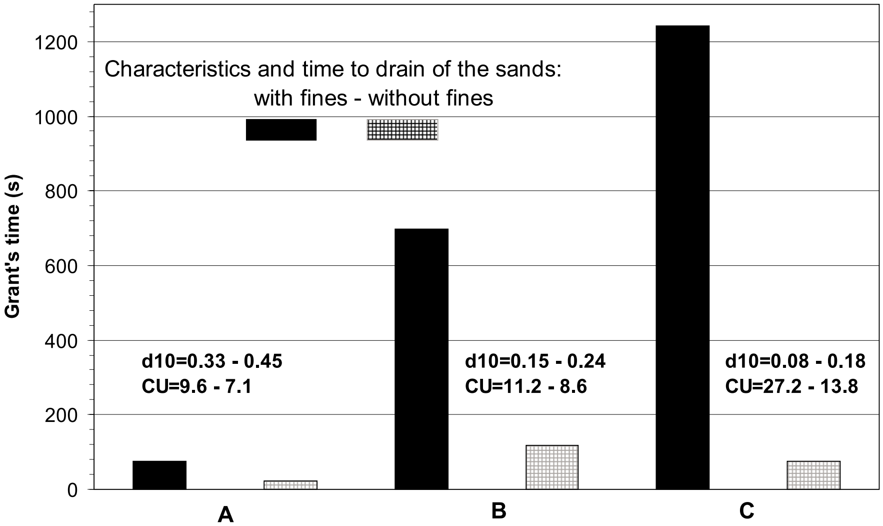

Figure 3 Fines influence on d10, CU and "Grant's time" for 3 crushed sands

$$\frac{K}{K_s} = \left[1-\varphi_v\left(\frac{1-\Phi_f}{\Phi_s}\right)\right]^{3m} \text{ with } \varphi_v \le \Phi_s \tag{8}$$

where: $m = 1.8 + \varphi_0 j_v$

with K: Permeability of the sand

K_s: Permeability of the sand in which the fines have been extracted by humid sieving.

m_0: Calculated value for a given sand.

Table 2 summarises the characteristics of eight sands allowing us to calculate the coefficient m_0 for each one. It can be noticed that heterogeneity and fines content of the crushed sands are higher than for alluvial sands. So, for each sand, a relation between permeability and fines volume content is available.

As permeability is linked to infiltration time (Equation 2), it is possible, as shown in Figure 4, to plot these 8 curves which are characteristic for each sand and link theoretical variable fines volumic content and theoretical Grant's time. These curves clearly indicate how fines content can modify the permeability.

The curves for sands B and D which are very close and especially those for sands C and H almost stacked are surprising. At first glance, it looks impossible that the same fines quantity is giving a t_g quasi identical with two very different $d10$. On the other hand, the CU are also very different and can create many ways between very heterogeneous grains. In addition, the crushed sand "angularity" may have a negative influence on permeability but is not yet well known. Complementary work is necessary in order to conclude on the fully integrating importance of the porosity of the sand.

For the fines, questions are similar: their porosities and densities have not been measured on these very different sands. The transformation of the fines mass content in volume

Table 2 Characteristics of 3 crushed sands and 5 alluvial sands

	d10 (mm)	CU	Φ_s	φ_v (in %)	t_g (in s)	t_g without fines (in s)	m_0
A crush.	0.33	9.63	0.45	6.2	75	23	83
B crush.	0.15	11.21	0.40	7.9	698	120	68
C crush.	0.12	27.15	0.50	13.9	1242	74	44
D all.	0.20	2.27	0.40	3.2	230	107	186
E all.	0.42	2.88	0.43	1.6	60	27	1056
F all.	0.23	3.79	0.40	3.8	124	110	0
G all.	0.33	7.23	0.41	2.9	102	70	85
H all.	0.26	3.78	0.42	2.6	120	73	187

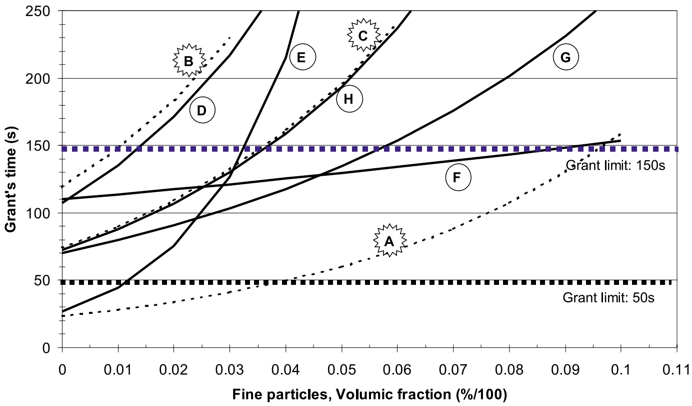

Figure 4 Evolution of infiltration times as a function of the volume fines content (Crushed sands correspond to dotted lines and are symbolised by stars, alluvial sands by full lines and circles)

content gives ratios φ_v/φ_w which are varying in a 1.39 to 1.54 range for the three crushed sands while there are very close from 1.45 for the five alluvial sands.

If the relevance of Equation (8) is confirmed, it can be, as a matter of priority, adapted for granulates producers as a tool to control their process.

For a *d*10 greater than or equal to the advisable threshold of 0.25 mm, the fines volume content must not exceed 2%. It is approximately corresponding to a mass content of 3%. As no known studies permit us to precisely quantify the negative influence of fines, previous recommendations (Agences de l'Eau, 1993) have already made the designers aware of it.

Influence of the coefficient of uniformity

In order to approach the maximum number of parameters which can influence permeability, the CU of 3 sands having d10 of 0.20, 0.24, and 0.33 mm have been modified by sieving. The 14 sands so obtained with CU ranging from 2.27 to 7.23 have been submitted to infiltration tests.

Figure 5 points out that the coefficient of uniformity (and therefore the sand heterogeneity level) has less influence than d10 and fines content on the infiltration time variability. This conclusion can be moderated by the small CU amplitudes of each tested sand. Nevertheless, we can suspect that when the average grain size is more important, the pores geometry and therefore the macropores geometry increases also, but not necessarily with an equivalent increase of the total porosity. Complementary experiments are therefore necessary to clarify this.

Influence of geotextiles

Moreover some trials (not described here – Guellaf, 1999) show that the use of geotextiles in order to separate the sand from the gravel composed draining layer, increases considerably the clogging risks. This latter could have two origins: i) direct clogging by sand residual fines, suspended solids brought by the effluent or purifying microorganisms, and ii) oxygenation limitation caused by a capillary fringe at the bottom of the infiltration bed. By over-blocking the porosity, the water harms the gaseous exchanges by convection during the wastewater infiltration, and by diffusion between two batches and during the necessary rest periods.

Conclusion

Despite some recent guidebook publications (Boutin *et al.*, 1998) advising more restricted ranges than those published a few years earlier (Inter Agences, 1993), it seemed helpful,

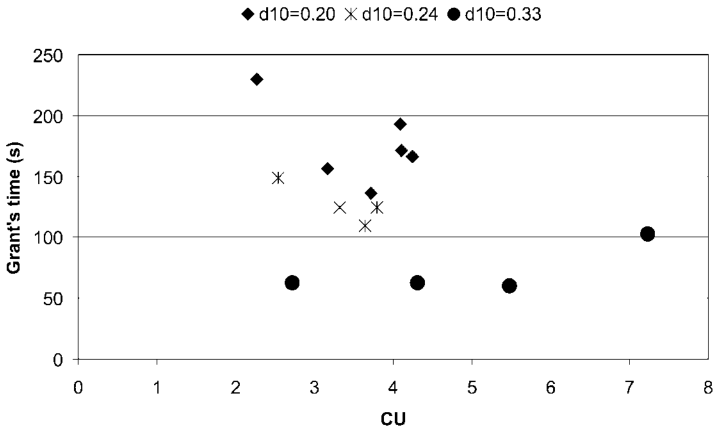

Figure 5 Evolution of infiltration time as a function of CU on 3 types of alluvial sand

because of some malfunction cases, to again propose some quality criteria useful for the architects and designers working on SWSF.

Concerning the $d10$, the best range seems to be : $0.25 < d10 < 0.40$mm. The uniformity coefficient could range between 3 and 6, in spite of the fact that the grains heterogeneity influence in the sand permeability has been shown insufficiently. The maximal fines content (in % of the mass) should not exceed 2.5 to 3%.

In addition, the general foreman must have the possibility to check the conformity of the deliveries to the characteristics of the project after its acceptance. In order to improve the plants, it is decisive to create means of control which must be simple enough to be given to the builders at the delivery of the sand supply. The Grant's infiltration test and its proposed adaptation in this paper fulfils this need.

In order to warrant a reliable treatment process for a minimum 10 years without any important sand replacement, it seems now to be necessary to advise, even to impose, some very strict sand characteristics. It may happen that additional studies, especially on-site working results after two or three years operation, will lead to even more restrictive values.

This requirement is today the most sensible, even if for a given site it is not technically and economically interesting to find the adequate sand. It is in fact better to stop a project than to find a compromise which will quickly lead to malfunction and to a complete and most expensive sand replacement.

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