DEVELOPMENT OF DRAINAGE GEOCOMPOSITES FOR GAS CAPTURE AND EXTRACTION

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ABSTRACT
A gas drainage system's design is essential for controlling gas emissions into the atmosphere and consequently their environmental impact, particularly for these two types of applications: buildings built on polluted soils (hydrocarbons, radon, etc.) and landfill covers (methane, carbon dioxide). As part of a sustainable development strategy, the use of drainage geocomposites with incorporated mini-pipes presents a technical and environmental benefit specifically for these two applications. This paper describes a preliminary study for an experimental evaluation of air and water discharge capacities through mini-pipes in order to ultimately extend results for further kinds of gas (methane, radon, etc.) for geoenvironmental applications. Several configurations and length of mini-pipes were tested in order to model pressure losses. the verification of the equivalence of measurement of drainage capacity through mini-pipes between air and water is evaluated in this project.

RÉSUMÉ
La conception des systèmes de drainage des gaz joue un rôle important dans la gestion des leurs émissions dans l'atmosphère et par conséquent sur son impact environnemental, particulièrement pour ces deux types d'applications; Au niveau des bâtiments construits sur des sols pollués (hydrocarbures, radon, etc.) et au niveau des couvertures des lieux d'enfouissements techniques (LET) des déchets (méthane, CO_2). Dans le cadre d'une stratégie de développement durable, l'utilisation des géocomposites de drainage avec des mini-drains incorporés présentent un avantage technique et environnemental pour ses applications. Ce papier présente une étude préliminaire pour la détermination expérimentale des capacités de décharges à l'air et à l'eau à travers les mini-drains afin de pouvoir extrapoler par la suite les résultats pour d'autres types de gaz (méthane, radon, etc.). Plusieurs configurations de mini-drains ont été testées afin de pouvoir modéliser les pertes de charges à travers les mini-drains. La vérification de l'équivalence de mesure de drainage à travers les mini drains entre l'air et l'eau est évaluée dans ce projet.

1 INTRODUCTION

Drainage geocomposite are widely used to replace granular drainage materials and consequently reduce overall project carbon footprint (Durkheim et al, 2010). Indeed, the design of gas drainage systems, generally with a granular layer and a depressurization system, has a major environmental impact on the management of emissions into the atmosphere and the reduction of exposure of humans to toxic gases. This is particularly important for the following applications:

- Subslab depressurizaton system under buildings built on polluted soils (hydrocarbons, radon, etc.). The implementation of a polluted gas collection system with a draining layer of granular material requires: excavation of polluted soil over the entire surface of the building to a thickness of several tens of centimetres (to enable the granular material layer to be laid), transport and disposal of the excavated polluted soil, quarry extraction, and finally transport and laying of granular draining material (several tens of centimetres thick).
- Landfill covers and landfill operations. There have been a number of incidents around the world involving natural disasters and loss of life (e.g. the Loscoe explosion in the United Kingdom), due to misunderstandings or risks associated with the increased pressure of toxic gases (Williams and Aitkenhead,1991).

The integration of the geocomposite concept containing corrugated mini-pipes in these two applications, as a replacement for traditional granular layers, will make it possible to:

- Offer an under-slab depressurization solution to prevent the concentration of toxic gases in homes. The use of geocomposite reduces the need for excavation work, transport of granular materials and landfilling of polluted soil. In addition, it also reduces nuisance to local residents by reducing truck traffic during construction.
- Limit the risk of gas diffusion and/or explosion in the atmosphere at landfill covers, as has been reported in the UK.
- Maximize biogas collection on final landfill covers for possible energy recovery to produce renewable natural gas, while reducing the use of non-renewable natural materials such as sand and gravel.

The project aims to investigate how gas collection and transport occur in geocomposites that include mini-pipes, comparing their effectiveness to traditional aggregate drainage materials. This is crucial because aggregates are costly, non-renewable, and may not be readily accessible depending on project locations. Therefore, exploring sustainable alternative materials is essential.Through the drainage geocomposite (see Figure 1), the gas collection, transport and evacuation are controlled by the geotextile drainage layer, the mini pipes then the main collector. It is assumed that the drainage capacity of the whole product is essentially controlled by the mini-pipes (Faure et al., 1993). For that reason, the project proposes to develop a predictive model of gas transport drainage through the mini-pipes to optimize the design of gas capture and transport according to field conditions (types of gas, project geometry, site conditions, product configuration and installation).

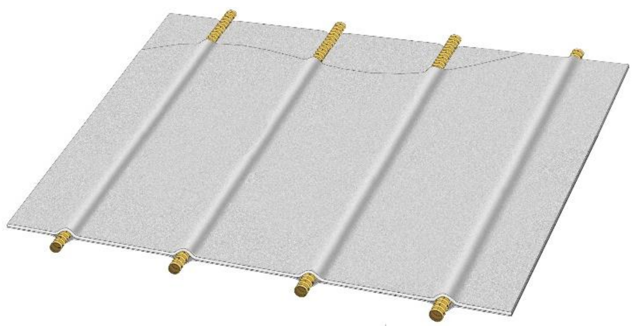

Figure1. Drainage geocomposite description

Although the study is focused on an experimental study of air drainage capacities of mini-pipes to access the flow regime, establish a verify the accuracy of existing fluid compatibility theories (in this case water and air) and quantify pressure losses through the mini-pipes. The ultimate out comes of this study is to refine existing design tools for gas drainage systems established for drainage geocomposite with mini-pipes.

2 BACKGROUND

The determination of the drainage capacity of drainage geocomposites is based on the in-plane flow capacity laboratory tests according to ASTM D4716, GRI GC15, and ISO 12958. Because of the different physical characteristics of the drainage geocomposites, the laboratory tests performed as per the standards may not be as accurate as expected. For example, the size of the testing device typically used has a length of 250 mm to 300 mm, underestimating by at least 30% the drainage capacity of multi-linear drainage geocomposites (Blond et al. 2013). This is because the entrance and exit transition flow to the tested length causes additional head losses. It is then important to characterize the hydraulic properties of each component of the geocomposite and develop a theoretical model allowing analytical calculations for design purposes. Indeed, the analytical design of these gas drainage systems relies on analogies between liquid and gas according to theory assumptions and specific experimental conditions and will be verified in this study. Indeed, Faure et al. (1994) established experimental evaluation of water and air discharge capacity of 2 m length mini-pipe presenting a diameter of 20 mm. According to its specific experimentations, Faure et al. (1994) established and validated experimentally theoretical considerations addressing the fact that to compare the air and water flow through the geocomposite, we assume that, for the same Reynolds number R_e, the head loss coefficient λ (friction coefficient also called *f*) remains the same in the draining web or in the mini draining tubes as follows.

$$Re = \frac{Q\,D}{S\,\nu} \quad \text{and } \lambda = \frac{2g\,i\,D}{\left({}^{Q}/_{S}\right)^{2}} \tag{1}$$

where:

- Q= flow rate through the mini-pipes (Q_a: air flow rate; Q_w= water flow rate) (m^3/s)
- D=mini-pipe diameter (m)
- S= mini-pipe section (m^2)
- v= Cinematic viscosity of the fluid (m^2/s), (air v_a, water v_w)
- g= gravity
- i= flow gradient given by the ratio of the fluid height by the pipe length (air: i_a, water: i_w)

For mini-pipes, these hypotheses allow the estimation of any fluid flow rate according to water flow rates for a giver gradient as follows:

Fluid flow is typically evaluated using Darcy's law, and as such, the issue of laminar and turbulent flow can complicate the analysis. Faure et. al., (1993) and Faure et. al., (1994) documented that the liquid flow through the mini-pipes as part of a drainage geocomposite is turbulent at gradients lower than 0.001 and indicate that the fluid flow (water, gas) can be expressed by the following formula (Faure et. al., 1995).

$$Q = ai^{b} \tag{2}$$

where:

- i=gradient
- a, b= constant function of the type of fluid and mini-pipes

Based on hypothesis formulated by Faure et. al. (1993) and Faure et. al. (1994) to perform equivalence calculation between air/water drainage flow, if R_e is the same, then:

$$\frac{Q_a}{\upsilon_a} = \frac{Q_w}{\upsilon_w} \tag{3}$$

and if the head loss λ has to remain the same, then:

$$\frac{h_{max}}{{Q_a}^2} = \frac{h_{max}}{{Q_w}^2} \tag{4}$$

with $h_{max}$the maximum measured pressure expressed in fluid height. Under these conditions, it can be analytically verified that $b_w = b_a$ equal to ½ and

$$a_a = \left(\frac{\nu_w}{\nu_a}\right)^{2b-1} a_w = a_w \quad (5)$$

and

$$\frac{Q_a}{Q_w} = \frac{a\,(i_{\,a})^b}{a\,(i_{\,w})^b} = \left(\frac{\rho_w}{\rho_a}\right)^b = 28 \quad (6)$$

This theory is adopted by designers for the establishment of drainage equivalency between fluids. Validation of this equivalency calculation is therefore important for the relevance of the proposed design method and would be important for an accurate assessment of the gas drainage capacity of the geocomposite. The purpose of this study is to access scale effect and mini-pipes characteristics on drainage capacity and on the development and validity of gas equivalency models. Thus, an experimental study was carrying out to validate theoretical model by experimental air drainage test and comparison with previous water drainage tests on mini-pipes.

3 LABORATORY EXPERIMENTAL PROGRAM

Tests have been carried out at SAGEOS laboratory (CTT Group) to characterize the air flow capacity of the mini-pipes themselves and to confirm fluid drainage equivalency presented by Faure et al. (1994).

In this first phase, we propose to evaluate the air drainage capacity for three mini-pipes diameters D16, D20 and D25 presenting respectively an external diameter of 16 mm, 20 mm and 25 mm over various length (10, 20, 100 m) representing site conditions (landfill cover systems, depressurization system for building applications, etc.) to overcome disparate results and singular head losses effects.

For calculation purposes, we present the characteristics of the mini-pipes: roughness ε, internal diameter Di and apparent diameter Dr, which represents the internal diameter Di plus the apparent roughness of the corrugation (Figure 2 and Table 1).

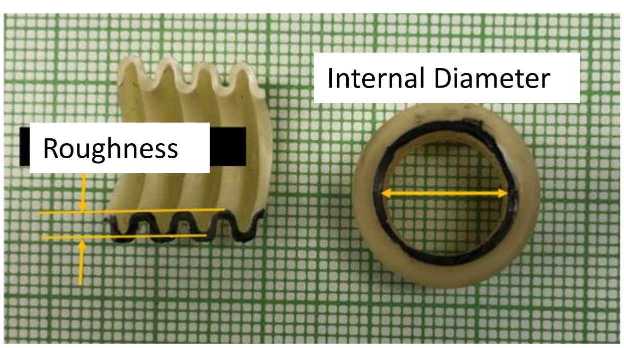

Figure 2. Characteristics of the mini-pipes

Table1. Summary of dimensions of mini-pipes

Type	Roughness, ε (mm)	Apparent Diameter, Dr (mm)	Internal diameter, Di (mm)
D16	1.9	14.2	10.4
D20	1.9	18.4	14.6
D25	2.3	22.9	18.3

The experimental device is presenting two air cells connecting the mini-pipe. The air flow is monitored at the entrance of the first cell by a flow meter. The air flow is then routed though the mini-pipes to the second air cell. Each cell is connected to a manometric system to allow the estimation of the head losses inside mini-pipes between the upstream and the downstream side of the system (Figure 3).

Mini-pipes without perforations were used for these measurements to address only the linear head losses inside the min-pipe.

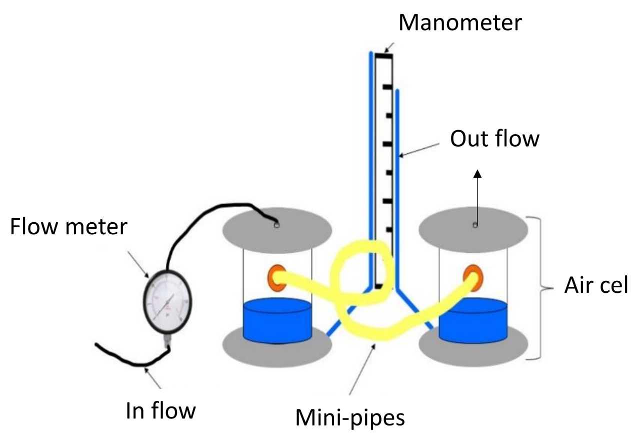

Figure 3. Experimental device for air discharge capacity through mini-pipes

4 RESULTS AND DISCUSSION

4.1 Flow rate results and head losses models

Figure 4 presents the injected air flow rate Q_a as a function of the measured gradient *i* for the three mini-pipes diameters (D16, D20 and D25). In the same way as for water drainage (Fourmont et al. 2023), flow results have been reworked and linearized to eliminate singular load losses and consider only linear head losses for comparing results and validating equivalency hypothesis. Air drainage results show that the air flow rate is not a linear function of the gradient which is indicated a non-laminar flow for gradient higher than 10^{-3}.

As a consequence, Darcy's law could not be applied in the non-laminar regime, as observed in previous works for water and air (Fourmont et al. 2023; Faure et al. 1993).

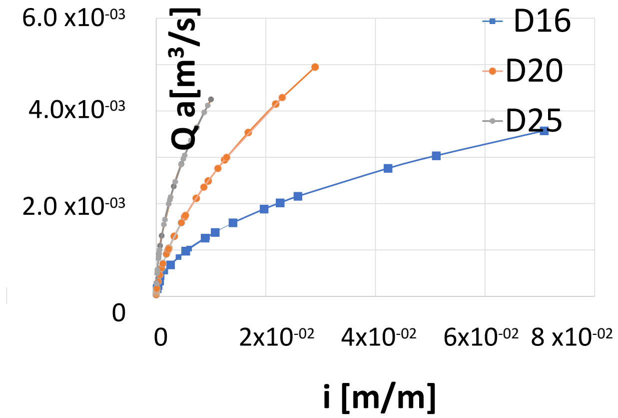

Figure 4-. Air flow capacity of the three mini-pipes diameters

The following empirical Darcy–Weisbach equation relates head losses due to friction along a given length of tube to average fluid-flow velocity (Romeo et al. 2002) and have been adopted to model the flow rate as a function of the gradient (Figure 4) and allows the estimation of *a* and *b* according to Equation 2 as well as the friction coefficient λ.

$$Q_a = \sqrt{\frac{\pi^2 g {D_i}^5}{8\,\lambda}}\, i^{1/2} \tag{7}$$

The same methodology has been adopted to model the water drainage capacity of the mini-pipes (Fourmont et al. 2023) which suggest to compare water and air drainage kinetics according to Darcy–Weisbach equations for air and water for the range of gradient higher than 10^{-3} and for the three corrugated mini-pipes diameters tested.

4.2 Equivalency verification between air and water according to hypotheses

The assumptions formulated to perform equivalency calculation between air/water drainage flow imply that if R_e is the same, then

$$\frac{Q_a}{\upsilon_a} = \frac{Q_w}{\upsilon_w} \tag{3}$$

and if the head loss λ has to remain the same:

$$\frac{h_{max}}{{Q_a}^2} = \frac{h_{max}}{{Q_w}^2} \tag{4}$$

A verification of these assumptions according to our experimental results is investigated to support equivalency calculations between fluid drainage capacity through mini-pipes.

Table 2 shows the ratio of respectively correlations between air and water trials for respectively D16, D20 and D25 according to Equations 1, 3 and 4.

Table 2- Correlation between water and air drainage results through mini-pipes

	Re	$\frac{Q_w}{\upsilon_w}$	$\frac{Q_a}{\upsilon_a}$	$\frac{h_{max}}{{Q_w}^2}$	$\frac{h_{max}}{{Q_a}^2}$	ratio
D16	2,000-7,000	25-67	45-106	7-10 $\times 10^7$	3×10^7	0.47
D20	3,000-9,000	75-172	70-334	9×10^6	1-2 $\times 10^7$	1.43
D25	4,000-14,000	111-384	62-287	1-2 $\times 10^6$	4-5 $\times 10^6$	2.91

Indeed, the equivalency hypothesis assumes as a result that the graph $\frac{h_{max}}{Q^2}$ =f($\frac{Q}{\upsilon}$) remains the same for air and water. Given a range a Reynolds number, we provided the values of hydraulic gradient and flow rate respectively for water and air. After calculating the corresponding $\frac{Q_w}{\upsilon_w}$, $\frac{Q_a}{\upsilon_a}$, , $\frac{h_{max}}{{Q_w}^2}$, $\frac{h_{max}}{{Q_a}^2}$ for D16, D20 and D25, the ratio represents $\frac{\frac{h_{max}}{{Q_a}^2}}{\frac{h_{max}}{{Q_w}^2}}$ which vary depending on the mini-pipe diameter from 0.47 to 2.91.

Indeed, the larger the diameter, the larger the ratio $\frac{\frac{h_{max}}{{Q_a}^2}}{\frac{h_{max}}{{Q_w}^2}}$ between air and water which suggest that there is a dependency of the flow rate equivalency results on corrugated mini-pipes characteristics (Internal diameter *Di* and roughness ε).

Regarding Equation 1, The results presented in the figure 5 indicates that the friction coefficient λ is not constant and suggest that it is not only dependent on fluid characteristics itself but also on the mini-pipes characteristics (diameter, roughness).

Some approaches have been carried out to link the friction coefficient to mini-pipes characteristics. Indeed, extending the Darcy-Weisbach equation to smooth-walled pipes leads to the following general equation, expressing λ, the head loss coefficient (also called f coefficient of friction), as a function of roughness ε and the mini-pipe internal diameter *Di* from the Nikuradse approach with *A* and *B* equation parameters:

$$\frac{1}{\sqrt{\lambda}} = A + B\, ln\left(\frac{\varepsilon}{D_i}\right) \tag{8}$$

A good correlation was found between water friction coefficient λ_w as well as the air friction coefficient λ_a and the ratio $\frac{\varepsilon}{D_i}$ (Figures 6 and 7) which suggest that the Nikuradse equation could be adopted in this study for air and water drainage characterisation though the mini-pipes.

When analyzing and calculating analytically the ratio $\frac{Q_a}{Q_w}$ according to Darcy-Weisbach equation (Equation 7) and

Nikuradse equation (Equation 8) to access equivalency between fluid drainage through mini-pipes, it was found out that:

$$\frac{Q_a}{Q_w} = \left(\frac{\lambda_w\,\rho_w}{\lambda_a\,\rho_a}\right)^{1/2} = \left(\frac{A_a+B_a\,ln\left(\frac{\varepsilon}{D_i}\right)}{A_w+B_w\,ln\left(\frac{\varepsilon}{D_i}\right)}\right)\left(\frac{\rho_w}{\rho_a}\right)^{1/2} \qquad (9)$$

with A_a, B_a, A_w and B_w Nikuradse equation coefficients for respectively air and water.

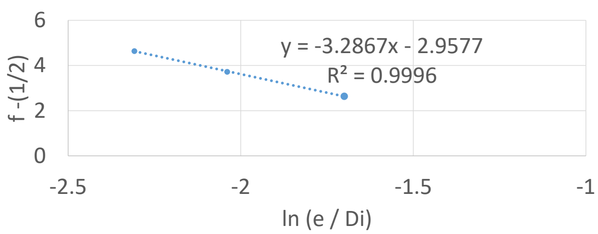

Figure 5. Nikuradse equation correlation for water results

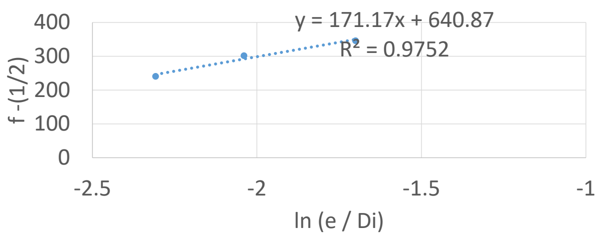

Figure 6. Nikuradse equation correlation for air results

From the Figures 5 and 6 and the Equation 9, it is clear that the ratio $\frac{Q_a}{Q_w}$ for a given gradient is dependant not only on fluid characteristics but also on the mini-pipes characteristics (internal diameter *Di* and roughness ε) especially for high density fluids like water. To verify if results obtained in this study are consistent with those of Faure et al. (1994), the ratio $\frac{Q_a}{Q_w}$ was calculated in order to check the relevance of the results compared to Faure et al. (1993) results. According to authors, this ratio is equal to 28 (Equation 6 and Table 3).

Table 3. Calculation of the ratio Q_a/Q_w and comparison with Faure et al. (1994)

	Q_a/Q_w [m³/s]		
	D16	**D20**	**D25**
Bannour et al. (2024)	128	78	52
Faure et al. (1994)	-	28	-

These results show that the ratio Q_a/Q_w and the air/water analogy are dependants on the mini-pipes characteristics as when the diameter increases the ratio decreases.

It should be noted that Faure's approach provides conservative and safe results, since it enables us to calculate drained air flow rates lower than those expressed in reality (obtained experimentally as part of this project on mini-pipes lengths representative of site dimensions). Given the fact that this issue is extremely important, additional tests have to be carried out on other gas to obtain more extended results on equivalency drainage calculations between fluids. Faure's approach will continue to be adopted as it constitutes a conservative approach in the estimation of the drainage capacity of the mini-pipes.

4.3 Air flow rate modelling according to Nikuradse and Darcy Weisbach approaches

Nikuradse's approach enabled us to estimate the air friction coefficient (linear head loss λ) with a good correlation to the mini-drain parameters (Equation 8 and Figure 6). Calculating λ for each mini-pipe diameter (D16, D20 and D25) allows to determine the drained air flow rate as a function of the injected gradient according to the Darcy-Weisbach expression (Equation 7). A good correlation can be deduced between the experimental air drainage values and the modeling approach used, enabling us to extend the results to larger gradients (see Figure 7).

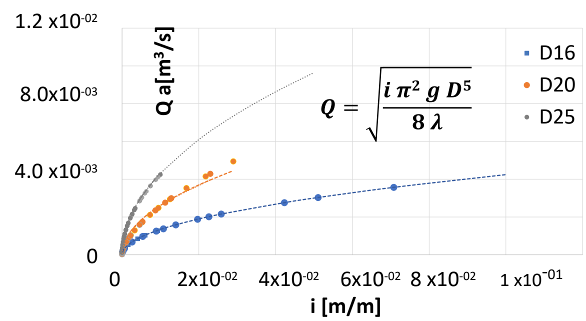

Figure 7. Air flow rate modelling according to Nikuradse and Darcy Weisbach approach

5. CONCLUSION

This study deals with several applications of geocomposite with mini-pipes for landfill gas collection and control, sub-slab depressurization and radon mitigation. Although the study is focused on an experimental study of air drainage capacities for three different mini-pipes length and diameters D16, D20 and D25 to investigate the effect of the pipe characteristics (diameter and roughness) on the flow rates. Previous hydraulic drainage results performed under the same experimental conditions allows correlation between flow rates and understand the calculation of fluid equivalence for the mini-pipes.

The results of this study show that Faure's approach provides conservative and safe results, since it gives drained flow rates lower than those expressed in reality (obtained experimentally as part of this project on mini-pipes lengths representative of site dimensions). The approach adopted in this study also enabled the gas transport modeling solution to be deployed for each mini-pipes diameter. It should be noted that as the diameter increases, the $\frac{Q_a}{Q_w}$ ratio decreases, showing that this air/water analogy is dependent on the characteristics of the mini-pipes (diameter and roughness).

Air flow rate modelling according to Nikuradse and Darcy Weisbach approach allowed a good estimation of air drainage capacity of the mini-pipes which suggest that it is important to consider the mini-pipes characteristics for a safe and consistent estimation of fluid drainage through mini-pipes and consequently through the drainage geocomposite.

Additional experimentations must be carried out with other gases to validate the accuracy of this study and to further understand the fluid equivalency drainage calculation with mini-pipes.

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