Field evidences and theoretical analysis of the gravity-driven wetting front instability of water runoffs on concrete structures

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A series of field observations of the evolution of water runoffs over several vertical concrete walls directly exposed to rain falls is reported in this note. In all the cases, the main water flow originated from the top horizontal surface of the walls. The observations show that the gravity-driven wetting front may propagate in a very unstable way by developing well defined and quite regularly spaced vertical finger-like features. The mean width $< d >$ and the mean growth's velocity $< v >$ of the fingers appear locally constant, but may vary from a wall surface to another. A simple relationship between $< d >$ and $< v >$ is deduced from the field data and the narrower the fingers the higher the growth's velocity.

The fingering process is tentatively interpreted by using the theoretical analysis developped by Glass et al (1989b) for the wetting front instability of infitration in unsaturated homogeneous layered soils. It is shown the model accounts qualitatively well for our observations. The variation in the geometry and kinematics of the instabilities from a wall surface to another may therefore be related to variations of the concrete structure at the microscopic scale. The relationship between $< d >$ and $< v >$ reflects the effects of the microstructure. The gravity driven-wetting front instability provides a powerful mechanism for a fast and over large distance moisture transfer along concrete constructions. It also leads to an heterogeneous distribution of the moisture content along the wall surface, which may eventually result in large spatial variations of the moisture-induced damages of the building structures.

Key words: **moisture transport, gravity instability, porous media, building materials.**

1 Introduction

Moisture in porous building materials (bricks, mortar, concrete, etc...) remains a central problem in civil engineering since it may be responsible of severe damages arising for instance from freeze / thaw cycles, salt crystallisation (Amaroso and Fassina, 1983; Chatterji and Thaulow, 1997) or shrinkage (Tazawa and Miyazawa, 1993; Sadouki and Van Mier, 1996). Moisture flow further provides a mechanism for the penetration of deleterious chemical agents like chloride and sulfate ions (Gulikers, 1997). The conjugate action of chemical and mechanical damage may lead to a rapid degradation of the bulk mechanical properties of the building materials and contributes to reduce the service life of constructions.

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Rain absorption and runoffs are among the major sources of water infiltation in buildings. Most theoretical and experimental studies have focused on the mechanisms of water absorption at the microscopic level (Hall and Kalimeris, 1983; Pel et al, 1996; Martys and Ferraris, 1997) but only few have considered the moisture transport at the scale of the entire construction (El-Shimi et al, 1980). It is well known the wetting front of the water runoffs at the surface of walls suffering rain falls is generally not a regular horizontal interface but may in contrary exhibit large scale finger-like instabilities (Addleson, 1972; El-Shimi et al, 1980). However, the origin of the instabilitiy of the wetting front has not received any explanation yet to the author's knowledge. In contrary, wetting front instability of gravity-driven flow in unsaturated porous media has attracted a quite large attention in soils physics since the pioneer experimental study by Hill and Parlange (1972). Its occurence has been recognized in the field (Glass et al, 1988) and extensive experimental and theoretical studies (Philip, 1975; White et al, 1976; Parlange et Hill, 1976; Diment et al 1982; Diment and Watson, 1985; Glass et al, 1988, 1989 a, b, c, 1990; Baker et Hillel, 1990) allowed to specify the main parameters and boundary conditions controlling the development of instabilities along the moisture front in 2D and 3D. This note is organized as follows. The theoretical analysis of the wetting front instability in unsaturated porous media is briefly sketched in the first section. The boundary conditions controlling the occurence of instabilities in gravity-driven moisture flow are reviewed and the recent theoretical analysis by Glass et al (1989 b) is summarized. A set of field observations about the evolution of the moisture front along different vertical concrete walls located on the Campus of Delft University of Technology is reported in the second part. The geometry and kinematics of the fingers are especially focused. The field observations are analysed through the theoretical model of Glass et al (1989 b) in the third section. The assumptions induced by the model are reviewed. The theoretical analysis is shown to account for most of the observations. Some physical characteristics of the underlying concrete structures are deduced from the geometry of the instabilities. The section includes an enlarged discussion about the potential importance of fingering for moisture transport in constructions.

2 Theoretical analysis of the wetting front instability in unsaturated porous media

It has been known since the work by Hill (1952) that instabilities may develop at the interface between two fluids in a porous medium or in a Hele-Shaw cell across which a pressure gradient is imposed. When making some simplifying assumptions, the conditions for an interface to become unstable may be easily derived (Hill, 1952; Saffman and Taylor, 1958; Chuoke et al, 1959). Suppose the displacement of an incompressible Newtonian fluid with a density ρ_2 and a viscosity μ_2 by an other fluid of a density ρ_1 and a viscosity μ_1 in an isotropic homogeneous porous medium (figure 1). By further assuming the flow satisfies Darcy's law for each fluid and no mixing occurs at the interface, then it is shown the displacement at the interface is unstable for all wavelengths if the following inequality:

$$\kappa g(\rho_1-\rho_2)-\theta_s U(\mu_1-\mu_2)>0 \tag{1}$$

is verified. Here, κ is the permeability of the porous medium, U the interfacial velocity, g the gravitational acceleration and θ_s the pore volume accessible to fluid flow. Depending if the two fluids are miscible or not, surface tension or diffusion may modify but not stabilize an interface characterized as unstable by the condition (1) (Homsy, 1987). It directly appears from the inequality (1) that if the gravity force is not taken into account, the interface becomes unstable when a fluid of low viscosity injects a more viscous fluid. Because this situation is typical of secondary oil recovery in petroleum industry, most research has concentrated on viscosity-driven instabilities, also termed "viscous fingering". For a review, one must refer to the paper by Homsy (1987).

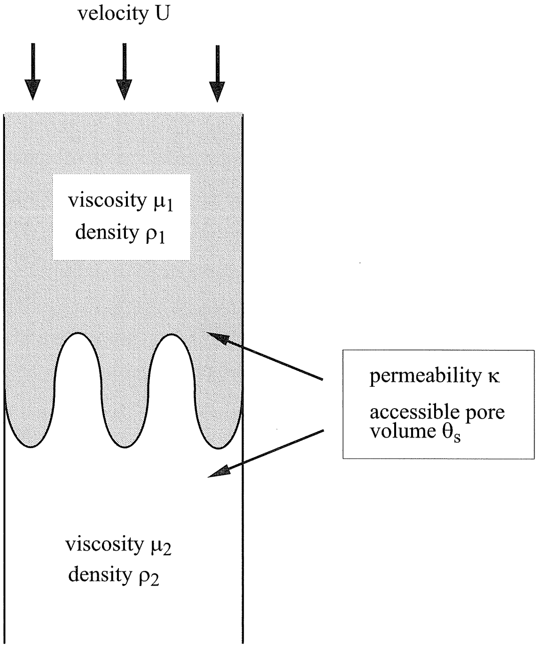

Fig. 1. An illustration of the interface stability problem between two fluids in rectilinear flow (from Homsy, 1987).

The question of the stability of gravity driven infiltration of water in an air-filled or unsaturated porous medium may be adressed in the same way, when assuming the air/water interface is steep and its velocity U is constant. Since the viscosity μ_2 and density ρ_2 of air are much lower than those of water, inequality (1) reduces to:

$$\theta_s U < \kappa g \rho_1 / \mu_1 \tag{2}$$

The wetting front of a water infiltration moving downwards could therefore become unstable if the volumetric flux per unit area $qs = \theta_s U$ at the boundary of the porous system is less than the saturated hydraulic conductivity $K_s = \kappa g \rho_1 / \mu_1$ (Glass et al, 1989 a). It is worth noting that this condition may be encountered in many situations. The most common situation may concern an increase of the hydraulic conductivity K_s of the porous medium with depth. This may be the case for a system of alternate layers with different hydraulic properties. Field and experimental evidences of fingering in layered soils have been reported by many authors (see the reviews by Glass et al, 1988, 1989b). The air pressure increase in front of the air / water gravity driven interface (White et al, 1976) may result in an instability of the wetting front too. At last, Philip (1975) postulated fingering may occur in many other situations such as non ponding rainfall infiltrations, an increase in the initial moisture content or the reduction of the wettability of the porous medium with depth.

Table 1. List of symbols.

symbol	description	units
ρ	Density of the fluid	ML^{-3}
κ	Permeability	L^2
g	Gravity constant	LT^{-2}
θ_i	Initial moisture content	dimensionless
θ_s	Saturated moisture content	dimensionless
U	Wetting front velocity	LT^{-1}
μ	Fluid dynamic viscosity	$ML^{-1}\,T^{-1}$
K_s	Saturated hydraulic conductivity	LT^{-1}
qs	Volumetric flow per unit area at the boundary of the system	LT^{-1}
Rs	Flux-conductivity ratio	dimensionless
σ	Surface tension	MT^{-2}
S	Sorptivity	$LT^{-1/2}$
$< d >$	Mean finger width	L
$< v >$	Mean finger velocity	LT^{-1}

Different theoretical models have been derived in the past to predict the birth and growth of the wetting front instabilities and to infer the most unstable wave length from both the physical characteristics of the porous medium and the boundary conditions of the water infiltration (Philip, 1975; Parlange and Hill, 1976; Glass et al, 1989 b). In the next paragraphs, the principal results of the theoretical analysis by Glass et al (1989 b) are briefly sketched. The reader is encouraged to refer to the original paper for more details. The list of symbols is given in table 1. Here, the porous medium is taken as homogeneous and isotropic and the flow is assumed to be accounted for by Richard's equation. It is further assumed from experimental observations (Hill and Parlange, 1972) that the the moisture content inside the finger is approximately equal to the saturated value θ_s of the porous medium. The water flow at the boundary of the system is characterized by the dimensionless flux / conductivity ratio:

$$Rs = qs/K_s \tag{3}$$

where qs is the volumetric flow of water trough the porous system. The ratio Rs must be less than 1 to satisfy the inequality (2). The analysis of Glass and collaborators yields the following expression for the mean width $< d >$ of fingers at the scale of the porous system:

$$< d > = [S^2/K_s(\theta_s - \theta_i)]f_{ds}(Rs) \tag{4}$$

θ_i is the initial moisture content of the porous medium, θ_s the saturated value of the moisture content and S the sorptivity of the porous material. Both K_s and S depend on the microstructure of the porous medium such as shape, connectivity and size distribution of pores. Note S is evaluated here between θ_s and θ_i, but at the water entry value Ψ_{we} of the capillary pressure head Ψ instead of the more classical value $\Psi = 0$ (Glass et al, 1989 b). The function $f_{ds}(Rs)$ is an undetermined function of Rs. The mean width $< d >$ must be less than the macroscopic length of the porous system to expect the wetting front to be unstable. Since the sorptivity S accounts for the water motion related to capillarity and K_s parameterizes the gravity effect, it can be seen from (4) that the development of instabilities along the wetting front is driven by gravity whereas it is stabilized by capillary action. The mean velocity $< v >$ of the fingers is expressed as:

$$< v > = [K_s(\theta_s - \theta_i)]f_{vs}(Rs) \tag{5}$$

where f_{vs} (Rs) is an other undetermined function of Rs. The two functions f_{ds} (Rs) and f_{vs} (Rs) must be estimated experimentally. This has been done by Glass et al (1989 c) in a series of experiments where Rs was varying between 0.007 and 0.82. These tests were driven at K_s constant and a variable flow rate qs at the boundary. They found the higher the flow the wider the finger and the higher the velocity. The experiments essentially verify the theoretical analysis. The authors further show the finger width may be closely approximated by the linear instability analysis of Parlange and Hill (1976). According to the model of Parlange and Hill (1976) modified by Glass et al (1989 b), the function f_{ds} (Rs) may be of the form $f_{ds}(Rs) \sim (1 - Rs)^{-1}$. This relation is useful since an experimental estimate of (4) and (5) remains difficult.

Since $K_s \sim \rho g r^2 / \mu$ (the permeability κ scales as L^2, see equation 2) and $S^2 \sim \sigma r / \mu$ (Glass et al, 1989 b; Martys and Ferraris, 1997), with g the gravitational acceleration, ρ, μ and σ the density, the viscosity and the surface tension of the invading fluid respectively and r a microscopic length scale of the porous medium (the mean pore size for instance), the width $< d >$ and the velocity $< v >$ of the fingers may be more specifically related to some physical parameters of the system:

$$< d > \sim \sigma / r\rho g \quad \text{and} \quad < v > \sim \rho g r^2/\mu \tag{6}$$

However, the variations of $< d >$ and $< v >$ which may exist between two porous materials can be interpreted as variations of these parameters only if the two materials are scaled, i.e., they obey the principles of similarity (Miller and Miller, 1956, Glass et al, 1989 b).

The application of the theoretical model to analyse the 3D wetting front instabilities is in principle straightforward since the equations (4) and (5) do not depend of the dimensions of the system (Glass et al, 1990). The mean width $< d >$ would this time correspond to the mean diameter of cylindrical fingers instead of the mean width of 2D fingers. The difficulty to vizualise the fingers in 3D is actually the only but serious obstacle to the study of the instability of the wetting front in 3D.

3 Field observations

In this section, a set of field observations is presented of the gravity driven wetting front evolution along several vertical concrete walls directly exposed to rain fall. The observations have been made at two different sites on the Campus of Delft University of Technology. They will be referred to as the "Wood workshop" and as the "Aula Building" sites respectively in the following paragraphs. Since wet concrete is dark grey coloured, the moisture front was easily determined from direct examination. It is worth noting these observations are not specific to these two particular sites and they can be made everywhere. In the two cases, the concrete walls are ornamental parapets. The two edges between the horizontal top surface and the main vertical faces are truncated and form small inclined plans (figure 2). These walls are built in open spaces and no obstacles may prevent the rain to reach their top surface.

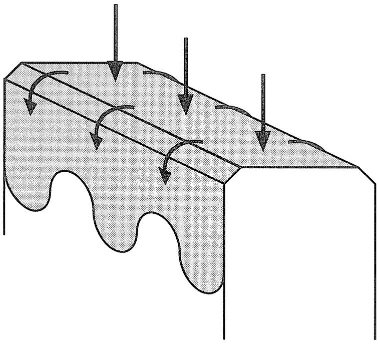

Fig. 2. Schematic view of the geometry of the concrete walls at the "Wood Workshop" and "Aula" sites and illustration of the water supply.

Most of the observations have been made on October the 8th 1997 between 11h 30 and 13h.
The Delft meteorological station indicates a rain rate of 3.3 mm/day for October the 8th. However most of the flow was concentrated between 10 and 13 hours and the actual flow rate qs can hardly be estimated. A flow rate of 5.4 mm/day was observed the day before. The initial moisture content θ_i of the concrete walls can obviously not be 0 at the time of the observations. The relative humidity was 91%. Although the wind was gusty blowing, its direction has remained approximately constant during all the day. The rain was observed to wet the vertical surfaces of the walls in two different ways. First, rain droplets driven by the wind were reaching individually the wall surface. In this case, water was instantaneously absorbed by capillarity into concrete and to locate the drop impact was no more possible after a few seconds. We assume droplets were homogeneously distributed over the whole surface of the walls and were not able to induce a strong variation of the local mois-

ture content distribution. Second, rain droplets were first reaching the horizontal top surface of the concrete walls. Water then flowed downwards along the wall sides (figure 2). This second mechanism largely predominates. The moisture flow along the concrete structures was then essentially a 2D gravity-driven flow.

3.1 *The "wood workshop" site*

This site is located near the wood workshop of the Faculty of Civil Engineering of the Delft University of Technology. The wall is constituted of the juxtaposition of 6 sections 3.50 m long separated by 1cm wide silicone joints and is approximately 1.30 m high and 0.30 m deep. The surfaces are free of any facing, roughcast or paint. The top surface is nearly horizontal with truncated edges (figure 2). The concrete looks quite homogeneous to the naked eye. Buildings around the site are far enough to allow the rain to reach the horizontal top surface without screening.

The figure 3 is a typical view of the vertical surface of the concrete wall after some time of continuous rain. The already wetted surfaces appear as brown to dark grey coloured zones wheras the still dry concrete remains light-grey coloured. It can be seen that the wetting front shows well developped finger-like instabilities. The resulting moisture pattern consists in a series of vertical alternatively dry and wet concrete bands originating from a continuous wet head-band at the top of the wall. A similar feature is observed on the other side of the concrete wall. Beyond this general pattern, the geometry of the wetting front on figure 3 show some variations from right (figure 4a) to left (figure 4b). On picture 4a, the moisture front mainly consists in many narrow (≈ 1 cm wide) regularly spaced fingers separated by large surfaces of still unwetted concrete. All the fingers originated from a horizontal continous wet band 20 to 30 cm large at the top of the concrete structure and most of them are near to reach the wall foot at the time of the observation. It is worth noting that the finger width remains quite constant and that the finger length is almost identical, meaning they have growed downward with the same velocity along the wall surface. The fingers are constituted by a narrow dark brown core surrounded by a more or less symetric less coloured fringe indicating the moisture content is lower. Near the wall basis, most of the fingers enlarged and show a shovel-shaped tip. The wetting front on the left part of the wall (figure 4b) is mostly characterized by a few large fingers rooted at the top of the wall in a large completely wet head band, although the width and density of fingers may laterally show some variations along the wall segment.

The fingers, large at the top of the masonry progressively narrow downward to finally ressemble the fingers on figure 4a. The gradual change of the fingers' geometry from the top to the bottom of the walls gives to each instability a broad triangular shape. As the finger width decreases downward, new narrower fingers initiate and their number progressively increases. Note that the major part of the fingers have not reached the wall foot yet and an almost completely dry continuous band of concrete is still visible at the bottom. The "Wood workshop" site then shows at least two distinct patterns of fingers. One consists in large instabilities with wide and comparatively short fingers which wet almost completely the upper part of the wall surface whereas a large lower band remains almost free of any moisture. The second one shows long and narrow fingers forming an alternance of wet and dry vertical bands from the top to the bottom of the masonry. The vertical joint which underline the contact between the two adjacent wall sections (figure 3) clearly delimits the two patterns. Since no differences can be found nor in the exposure to rain neither in the geometry of the wall, the reasons of the variations of the wetting front geometry may be looked for in variations of the physical characteristics of the concrete itself. Such variations may be easily explained if the two wall segments were not cast at the same time for instance. The comparison of the finger pattern indicates that the width and the velocity of the fingers may be related: the narrower the fingers, the higher the velocity.

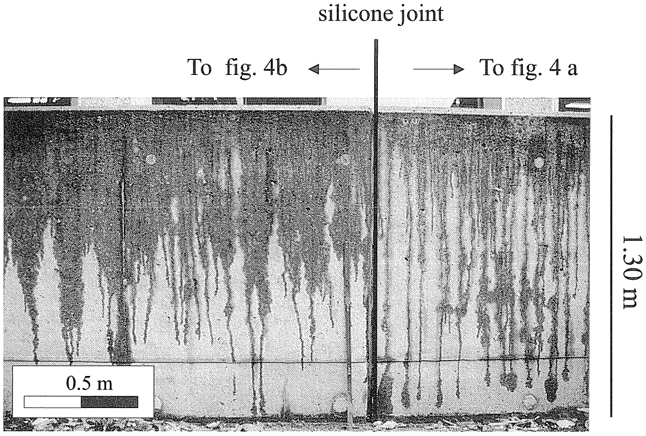

Fig. 3. *Water runoff and wetting front geometry on the vertical surface of the concrete wall at the "wood worshop" site.*

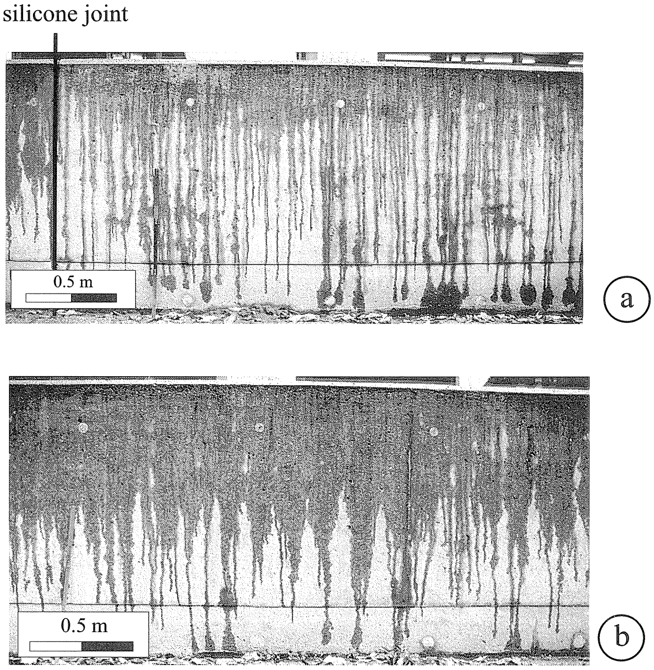

Fig. 4. *a) A view of the wetting front on the right of the wall section on figure 3 and b) a view of the wetting front on the left of the wall section illustrated on figure 3 (at the same time as in figure 3).*

The Figures 5 a and b are almost the same views as the figures 4a and b but about half an hour later. The rain fall has not stopped during this period. The wall surface is now almost completely wet, but some differences between the two wall segments still subsist. Only a few narrow vertical lens-shaped zones remain unwetted on the left (figure 5 b) whereas the fingers are still visible on the right (figure 5 a). In the latter case, it can be seen that the fingers have considerabily widened and the moisture has progressed laterally toward the unwetted surface. However, the initial finger cores may still be distinguished in some cases from the less coloured surrounding fringes suggesting that a difference of the moisture content may still exist. Note also that the interface between the wet and the still dry zones looks more diffuse.

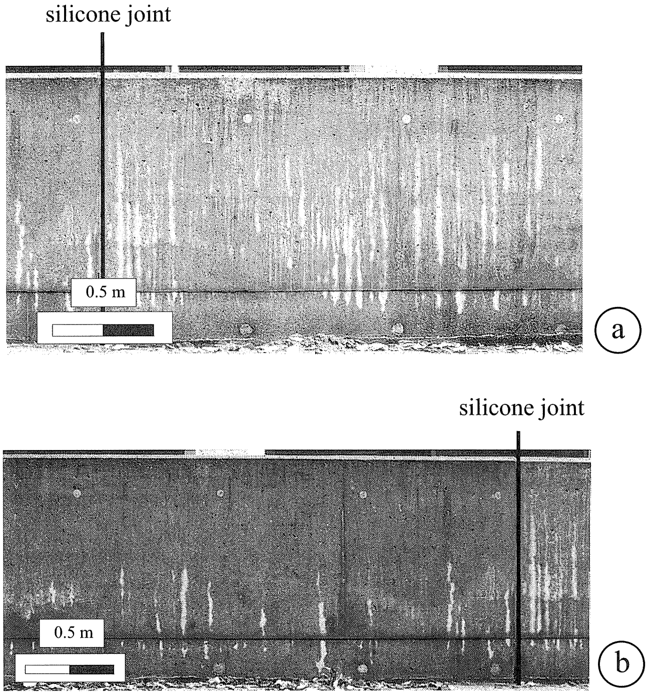

Fig. 5. Evolution of the gravity-driven wetting front at the "Wood workshop" site. The figures 5a and 5b are the same views as the figures 4a and 4c respectively around half an hour later.

3.2 *The "Aula" site*

The "Aula" Building is the conference centre of the Delft University of Technology. The construction is almost completely surrounded by a recent 0.8 m high and 0.2 m deep concrete wall. As for the "wood workshop" site, the top surface is a horizontal plane with truncated edges and all the surfaces are free of any coating. The major part of the wall is screened by the "Aula" Building but two segments are far enough from the main construction and can therefore be reached without perturbation by the rain. These two wall segments are about 30m apart, one facing the North, the other facing the South. Since the orientation of the two concrete walls are different, one can not exclude some variation of the rain flow because of the blowing wind. The two walls of the "Aula" site allowed us to essentially repeat the same observations as on the former site and especially to confirm the unstable nature of the gravity-driven wetting front.

The figure 6a, which corresponds to the North facing wall segment, shows a series of narrow well developed and quite regularly spaced fingers. Most of them have already reached the bottom of the concrete wall forming an alternatively wet and dry vertical bands pattern. It can be seen on the left of the picture that some instabilities have merged to form locally wider fingers. The fingering pattern is quite different for the second wall segment (figure 6b). The fingers are obviously wider and shorter and most of them are far from reaching the wall foot, indicating the wetting front progresses comparatively slowly. The continuously wetted band of concrete at the top of the wall is much more developped and already covers the upper half of the wall surface whereas the half lower part is almost completely free of any moisture. It is worth noting that the wetting interface looks much more diffuse, suggesting the capillary motion may play a more important role in the moisture transfer. As on the former site, a relationship between the width and the velocity growth of the fingers can be deduced from the comparison of the two pictures and the lower the growth velocity of fingers, the wider the fingers.

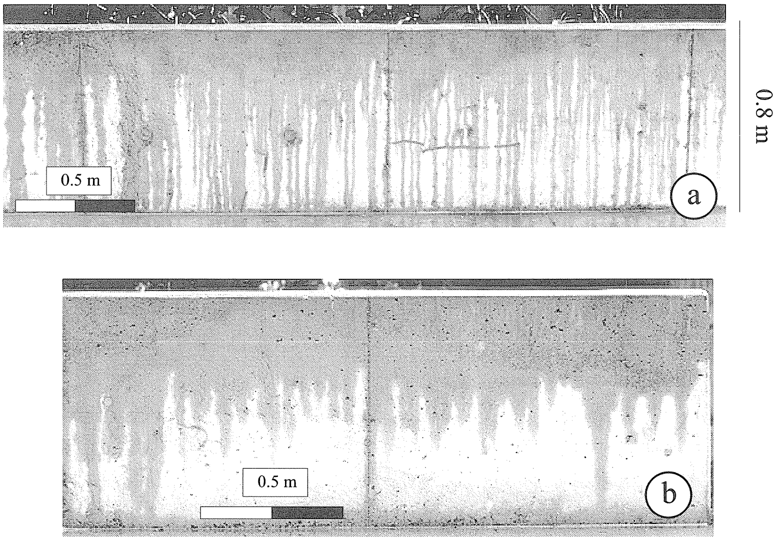

Fig. 6. An illustration of the different wetting front geometries at the "Aula Building" site a) Water infiltration along the North facing wall. b) Water infiltration along the South facing wall.

It is interesting to notice that water infiltrates at the same time at the wall bottom by suction along the wall surface. The resulting moisture front can be easily observed on figure 6b for instance and is on the order of a few cm high. Of course, the water supply may not be continuous along the lower wall boundary so that the absorption process may be in some way slowed down. Nevertheless, the comparison between the two wetting fronts may provide an estimate of the relative efficiency between the gravity-driven flow instability and the absorption for moisture transfer along concrete structures.

4 Discussion

The field observations of rain runoff on concrete structures show the gravity-driven wetting front may propagate in a very unstable way by developping a series of regularly spaced and well shaped fingers. It is noteworthy that the fingers locally show the same width and the same growth rate and the narrower the fingers, the higher the velocity. All these observations strongly suggest the fingering process may be governed by a single mechanism. One could suppose the fingers may result from the existence of preferential flow paths induced for instance by an heterogeneous upper boundary or by local variations of the hydraulic conductivity of the concrete. However, although not impossible, this hypothesis does not match well with the quasi-periodic, regularly shaped finger pattern we have observed. It is important to notice that although the wetting process is initially superficial, it may affect the concrete structure more and more deeply with time as water slowly infiltrates inside the building material by capillarity.

The theoretical analysis by Glass et al (1989 b) introduced in section 2 provides an useful framework to interpret our field observation. Notice, some important informations such as the initial average moisture content $< \theta_i >$, the saturated hydraulic conductivity K_s, the sorptivity S, the composition (aggregates size distribution, water/cement ratio, etc...) and the microstructure (porosity, mean pore size, etc...) for the different concrete walls are missing. The analysis presented below is therefore limited to a qualitative test of the theoretical model, beyond the likeness between our observations and the 2D fingering experiments in soils by White et al (1976), Baker and Hillel (1990) or Glass et al (1988, 1989 a, b and c). The flow rate qs at the upper boundary is given by the rain rate weighted by the horizontal wall section (the drainage area), assuming the infiltration on the horizontal top surface is negligible. The hydraulic conductivity K_s at the different sites can not be estimated but may eventually be high because the wetting process is essentially contained in the plane.

The inequality (2) $Rs = qs / K_s < 1$ may therefore be verified at each site. Note, although K_s and qs are not known, it is obvious that the water runoff is non ponding. A ponding runoff would instantaneously wet the entire vertical wall surface like a fire hose would for instance. It has been seen from equation (4) that the mean width $< d >$ scales as $S^2 \ / \ [K_s(\theta_s - \theta_i)]$. As already noticed, the equation (4) actually reflects the competition between capillary and gravity forces which controls the mechanism of instability. When assuming qs is a constant at a given site, the variations in the fingering pattern may be then simply explained by variations of the relative weight between these two forces related to variations of the concrete microstructure. This interpretation matches well with the sharp change in the finger pattern observed at the "Wood workshop" site along the two adjacent wall segments (figure 3) or between the two wall segments at the "Aula" site. The decrease of the mean width $< d >$ of the fingers with depth on figure 4b can be best explained by a gradual decrease of the influence of capillarity downward. In contrary the shovel-shaped finger tips on figure 4a may locally reflect an increase of the relative influence of capillary forces. These few examples indicate the moisture transfer and the local moisture distribution may be very sensitive to slight variations of the concrete properties. By further assuming the concrete remains similar in the sense of Miller and Miller (1956) at a given site, one can attempt to relate the variations of the finger morphology to the physical characteristics of the concrete. Since the mean finger width $< d >$ is a funtion of $1/r$ whereas $< v >$ is proportional to r^2 (with r the mean pore size, see equation 6), the different patterns may be simply related to the variations of r. It is worth noting the variation of r accounts well for the empirical relationship between $< d >$ and $< v >$ deduced from the field observations. The higher the mean pore size r, the higher the mean velocity $< v >$ and the lower the mean width $< d >$.

The analysis presented above shows that fingering of the wetting front along concrete walls may be well accounted for by the mechanism of gravity-driven instabilities. The theoretical analysis proposed by Glass et al (1989b) provides a means to relate the geometry and the kinematics of the instabilities to the physical properties of the porous building material and the flow rate at the boundary. Both the experimental data on soils (see Glass et al, 1988, 1989 b for example) and the field observations indicate the fingering process may greatly influence the moisture transfer in porous materials. Fingering may have at least two main consequences. First, since the moisture flow is concentrated inside the fingers, the moisture content θ is locally near the saturation value θ_s. The moisture flow is therefore locally of the order of the saturated hydraulic conductivity K_s of the building porous material (Parlange and Hill, 1976; Glass et al, 1989 a). Because of the non-linear dependence of the hydraulic conductivity $K(\theta)$ with the moisture content θ ($K(\theta)$ strongly increases when the θ approaches the saturation value θ_s, see for instance Glass et al, 1989 c; Pel et al, 1996), flow concentration along the fingers then allows the most efficient moisture transport from the top to the bottom of the concrete structure and over a much longer distance than a hypothetical linear horizontal wetting front would. Second, it is obvious the development of the instabilities initially induces important spatial variations of the moisture content on the wall surface. It is further shown the differences of moisture between the finger cores and their surrounding fringes may subsist after the wall surface is entirely wetted. The finger cores may then persist as conduits for the majority of the flow over long periods. Moreover, the experiments by Glass et al (1989 a) show that the moisture flow may use the same fingers from a infiltration cycle to another. Although the permanence of fingers along the building walls is not unambiguously demonstrated, weathering patterns such as moulds, discoloration and staining (Addleson, 1972; El Shimi et al, 1980) provide indirect evidences of the finger persistence trough successive runoffs. The spatial variation of the moisture distribution may therefore persist over long periods along the concrete structures. It may result in the localization of the damages along the concrete structures from both the moisture-induced microcracking (freeze / thaw cycles or shrinkage for instance) and the progressive local concentration of deleterious solutes along the more or less permanent fingers. Mapping the damage distribution on old concrete structures could provide interesting informations concerning this last point.

It is worth noting that the conditions for the instability of the gravity-driven wetting front may be found in many 2D and 3D circumstances in civil engineering. Fingering may arise from any interface implying a porous building material of low hydraulic conductivity over a more conductive one. This may concern for instance horizontal mortar joints between bricks (Pel et al, 1996; Brocken et al, 1997), repair mortar layers overlying an old concrete structure (Sadouki and van Mier, 1997) or bituminous layers on a bridge deck. These few examples briefly illustrate the potential importance of instabilities for moisture transport in constructions. Since the instability of the wetting front may induce long term spatial variations of the moisture content and, eventually, of the damages distribution in the structures, this mechanism may be taken into account to estimate the service life and to improve the quality of buildings. The fingering process must now be quantified by a series of laboratory experiments where both the water flow, the initial moisture content and the microstructure of the building porous materials may be well controled.

5 Conclusion

A series of field observations on the rain runoff along several vertical concrete walls has been presented in this note. It is shown that the gravity driven wetting front may propagate in a very unstable way by developing geometrically well defined and regularly spaced finger-like features. The theoretical analysis developped by Glass et al (1989b) for gravity driven instabilites in layered soils provides a useful theoretical framework to interpret the fingering process along the concrete walls. The boundary conditions for an unstable wetting front are specified and the mechanism which determines both the geometry and growth of the fingers is identified. The theoretical model accounts, at least qualitatively, for most of the field observations and allowed us to relate the variations of the geometry and the growth's velocity of the fingers to the microstructural characteristics of the concrete.

Of particular interest are the properties of fully formed fingers on the moisture distribution along the building walls, as they allow a fast moisture flow from the top to the bottom of the concrete structure and may persist from an infiltration cycle to another. Fingering may therefore be responsible of a persistent heterogeneous spatial distribution of the moisture content on the wall surface which could eventually induce localized damages along concrete structures. Since the conditions for the occurence of the gravity-driven wetting front instabilities are quite ubiquitous, fingering may be an important 2D and 3D mechanism for the moisture transport in constructions.

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