



HAL
open science

Quantitative methods used to characterize the impregnation of a glass multifilament yarn by a cementitious matrix

Hana Aljewifi, Bruno Fiorio, Jean-Louis Gallias

► To cite this version:

Hana Aljewifi, Bruno Fiorio, Jean-Louis Gallias. Quantitative methods used to characterize the impregnation of a glass multifilament yarn by a cementitious matrix. 4th Colloquium on Textile Reinforced Structures (CTRS4), Jun 2009, Dresden, Germany. hal-00563826

HAL Id: hal-00563826

<https://hal.science/hal-00563826>

Submitted on 7 Feb 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Quantitative methods used to characterize the impregnation of a glass multifilament yarn by a cementitious matrix

Hana Aljewifi¹; Bruno Fiorio²; Jean-Louis Gallias³

Summary: This paper presents two experimental methods that allow to quantify the impregnation level of the yarn / matrix interface, in the case of Textile Reinforced Concrete (TRC). These methods have been tested on three different glass yarns laid in a cementitious matrix, with three different impregnation levels resulting from the manufacturing process. The first method (comparative mercury intrusion porosity test) is based on the evaluation by mercury intrusion porosity of the pores volume associated to the porosity inside and near the yarn. The second method (flow test) consists in measuring the flow rate of water along the yarn, with imposed flow conditions. The physical parameters measured by these two methods are both related to the pore size and to the porosity of the yarn / matrix interface. The results of the two methods are discussed and drawn in parallel to a qualitative characterization of the yarn / matrix interface made by scanning electronic microscopy. As a result, it is shown how the two methods described here can participate to characterize the yarn impregnation. Limitations of the methods are also discussed.

1 Introduction

Concrete is a widespread material known for its easiness to use and good compressive strength. As concrete has low tensile strength, it should be reinforced to be used for structural applications. Classical reinforced concrete (RC) uses steel rebars as reinforcement. In this case, corrosion troubles can appear due to the penetration of water and corrosive agent through the micro-cracks and the porosity of concrete. Consequently, steel rebars in RC structure should be protected by increasing the concrete cover to about 3 to 5cm (JESSE ET

¹ PhD, Laboratoire de Mécanique et Matériaux du Génie Civil, Université de Cergy-Pontoise, France.

² Dr., Laboratoire de Mécanique et Matériaux du Génie Civil, Université de Cergy-Pontoise, France.

³ Prof., Laboratoire de Mécanique et Matériaux du Génie Civil, Université de Cergy-Pontoise, France.

AL. [1]), depending on the environmental conditions. This concrete cover is an additional weight that can be important, especially in the case of thin RC elements.

To produce concrete with homogenous tensile properties and reduced cracks opening, the development of micro cracks must be suppress (WONG [2]). The introduction of fibers (short or continuous) was brought in as a solution to develop concrete in view of enhancing its flexural and tensile strength (BENTUR AND MINDESS [3]). Textile reinforced concrete (TRC) is a fiber concrete composite material which begin to be used about three decades ago (BANHOLTZER [4]). This composite is suitable for many new applications because of its low weight and high load-bearing capacity. It is produced by incorporation into a cementitious matrix of a textile structure made of oriented continuous yarns, themselves constituted from thousand of micrometric filaments (usually AR-glass) with diameter in the range 10-30 μ m.

The mechanical properties of TRC depend on the mechanical properties of its constituents and on the characteristics of the binding between the yarn and the matrix, which determined the way the matrix and the yarn interact. In particular, the specific constitution of yarns induces a partial impregnation by the cementitious matrix. As a consequence, filaments can be separated into two families: sleeve filaments, in the impregnated area of the yarn, and core filaments (OHNO AND HANNANT [4], LANGLOIS [5]). Sleeve filaments are anchored, when core filaments are not. Mechanical models of the yarn / matrix interaction have to define parameters related to the impregnation level, to determine the portion of each of the families of filaments and their contributions to the load (BANHOLTZER [6], HEGGER ET AL. [7], LANGLOIS ET AL. [8]). Usually, these parameters are defined arbitrary and it is very difficult to connect them to the physical parameters of the interface.

The research hereafter presented focuses on this last point, and in particular on the matrix / yarn impregnation problematic. It intends to produce quantitative indicators of the impregnation level of the yarn. These indicators could be useful to help to determine the interface parameters used in yarn / matrix interaction modelization.

2 Experimental program

2.1 Materials

2.1.1 Cementitious matrix

To avoid yarn damaging by coarse aggregates during the manufacturing process, the cementitious matrix used for this study was a micro-concrete made of CEMI 52.5 cement (C) and 0-1.25 mm fine sand (S). A superplasticizer (SP; 64.4% dry extract according to NF P18-380) was used to obtain a high fluidity of the fresh concrete, needed to allow the easy pouring of the cylindrical mould (3.6cm diameter; 25cm height). The composition parameters were as follow: $W/C = 0.5$, $S/C = 1.4$, $SP/C = 0.0035$. Mixing was made using a standard mortar

mixer with respect to the following sequence: low speed mixing of solid products (1min), low speed mixing with water and superplasticizer (30s), final high speed mixing (30s). Table 1 gives the composition parameters for one batch.

A cement slurry was used in some case to reach a “full” impregnation of the yarn by the cementitious matrix. The mix design was made to obtain the same composition for the cement slurry and the cement paste of the concrete, taking into account the water absorption of the sand (1.10 % according to NF 1097-6). The slurry composition parameters were therefore as follow: W/C = 0.48, SP/C = 0.0035. Mixing was made using a standard mortar mixer. Table 1 gives the composition parameters for one batch.

Table 1: Micro-concrete and cement slurry composition (per batch)

	Water	Cement	Sand	Superplasticizer
Micro-concrete	425g	857g	1200g	3g
Cement slurry	168.2g	350g	/	1.23g

2.1.2 Fibers

Three types of glass roving (named in the following OC1, OC2 and SG1) have been used in this study. OC1 is a multi-end E-glass roving (assembly of strands constituted from elementary filaments). OC2 is a single ended E-glass roving (direct assembly of filaments). OC1 and OC2 came from the same manufacturer. SG1 is a multi-end AR-glass roving that came from a second manufacturer. Using E-glass roving was considered as un-problematical, as the work exposed hereafter do not consider long time evolution of the yarn / matrix interaction and is therefore not submitted to durability problems (and in particular to chemical interaction between glass and cement). It should be noted that a sizing covers the surface of the glass filaments. It serves to various functions, depending on the roving (agglomeration of the yarn, protection of the glass, interaction with the matrix,...). The sizing materials are a mixed of polyhydroxy-phenols, silane, polymer emulsion and additives. The detailed composition of the sizing is unknown due to the industrial protection imposed by manufacturers. The main characteristics of the yarns are given in table 2.

Table 2: Characterization of the multi-filaments yarns

Material	unit	OC1	OC2	SG1
Type of yarn		E-glass multi-end roving	E-glass single-end roving	AR-glass multi-end roving
Filament diameter	μm	12	17	14
Fineness	tex	2400	2400	2450
Glass density	kg/m ³	2530	2530	2680
Average number of filaments		8388	4180	5939

2.2 Specimens preparation and curing

2.2.1 Molding and curing

Specimens are cylinders of micro-concrete (3.4cm diameter, 25cm height) into which a straight yarn is centered. A specific molding device is used to precisely position the yarn in a cylindrical PVC mold before the casting of the micro-concrete. As the cylinder remains vertical, with the yarn crossing the bottom part of the mold, a specific attention was given to the watertightness of the mold. In particular, glue was applied on the lower part of the yarn, at the point where it crossed the bottom of the mold. Despite of this care, a small flow of water was observed at the bottom level of the yarn, which corresponds to a flow of water along the yarn. Therefore, a 1cm layer of water was laid over the micro-concrete after the pouring, to counterbalance the observed water loss and avoid the reduction of the water content of the fresh concrete.

Four specimens were realized from the same batch as follow: three specimens with the same type of yarn, each specimen corresponding to a given impregnation level (see part 2.2.2 the details about the impregnation level control) and one reference specimen of micro-concrete (without yarn). In this way, it was possible to eliminate the variability due to the mixing process when comparing the results obtained for the same type of yarn but for different impregnation levels. Specimens were removed from mould after 24h. They were then cured to 28 days in 20°C water.

2.2.2 Control of the impregnation level of the yarns

The impregnation level of the yarn by the cementitious matrix gives different characteristics to the composite, in particular because the repartition of the filaments between core and sleeve filaments is largely influenced by the impregnation level. For this study, we have used three specific impregnation levels obtained by application to the yarn of one of the processing described hereafter:

- Non-impregnated yarn (N): yarn was saturated with water prior to the casting to fill the inter-filaments voids with water, which prevent the cement paste to enter the yarn. It should be notice that in this case, the capillarity forces induce the agglomeration of the glass filaments. As a consequence, the inter-filaments distance was reduced compared to what is observed in the case of dry yarns.
- Partially impregnated yarn (P): yarn was dried before casting. Capillarity leads to penetration of water and cement particles in the yarn at the time of casting. As the filaments act as a filter, penetration of cement particles into the yarn was limited.
- Completely impregnated yarn (C); to simulate a complete penetration of the cement paste, the yarn was manually saturated with a cement slurry (table 1) before casting .

2.3 Testing plan

Each configuration (one type of yarn, one impregnation level) was used to perform different test methods with the aim to characterize the impregnation of the yarn by the matrix. Two methods were carried out to characterize the impregnation level by quantitative measurements. One is based on mercury intrusion porosimetry, the other on flow test. These methods give quantitative information related to the impregnation level. Qualitative information on the impregnation level was also obtained from scanning electronic microscopy (SEM), which constitute a third method of investigation.

3 Comparative mercury intrusion porosimetry test

3.1 Introduction

Mercury Intrusion Porosimetry test (MIP) is a classical test based on the intrusion of mercury into the pores structure of a porous media under a varying applied pressure. This test allows to obtain the pore repartition of the porous media. It is widely used in the case of cementitious materials (WINSLOW AND DIAMOND [9], FELDMAN AND BEAUDOUIN [10], COOK AND HOVER [11]). The diameter r_p of the thinnest pores wetted by mercury depends on the applied pressure P_{Hg} , regardless to Washburn law (BEAUDOUIN [12]):

$$r_p = \frac{2 \cdot \sigma_{Hg} \cdot \cos \theta}{P_{Hg}} \quad (1)$$

With σ_{Hg} mercury surface tension force
 θ mercury / supporting material contact angle

For cementitious materials, values used for σ_{Hg} (0.474 N.m^{-1} for a temperature in the range $20\text{-}25^\circ\text{C}$) and θ (141.3°) were given by BAROGHEL-BOUNY [13].

In this research, MIP was used to characterize:

- The pores structure of samples of micro-concrete with an embedded yarn (2 samples for each configuration).
- The pores structure of reference samples (micro-concrete without yarn).

All measurements were made after 28 days of curing. Comparison between samples and references gave information about the porosity specifically associated to the yarn / matrix interface and give qualitative data that can help to determine numerical parameters linked to the impregnation of the yarn by the matrix.

3.2 Micro-concrete reference curve

A micro-concrete reference curve was built as the average of the porosity curves obtained for all reference samples. Reference samples were obtained by coring the center of the cylindrical specimens described in part 2.2 to the maximum diameter allowed by the picnometer used for the MIP measurement (1.3 or 2.5cm). As MIP measurements may be affected by the size and geometry of the sample, which may affect the mercury flow (DIAMOND AND BONEN [14]), two types of reference samples were used: one with a centered 2.5mm diameter hole and the second without hole. The hole was obtained by replacing the yarn with a soft plastic thread before realizing the micro-concrete cylindrical specimens. The thread is removed after setting of the micro-concrete. Considering the percolation of mercury into the micro-concrete, samples with a full impregnated yarn approach the behavior of sample without hole (figure 1a), when sample with low impregnated yarn approach the behavior of the reference with hole (figure 1b).

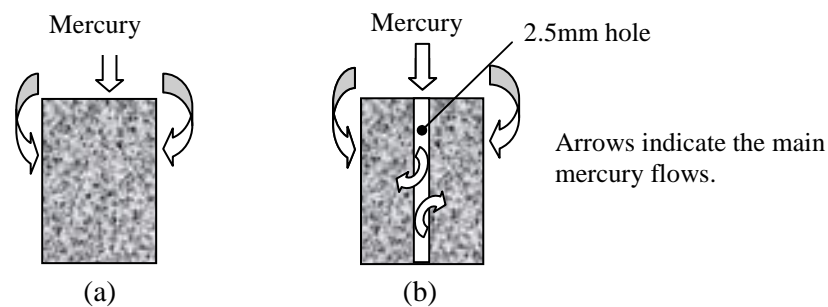


Fig 1. Mercury intrusion into un-perforated sample (a) and perforated sample (b).

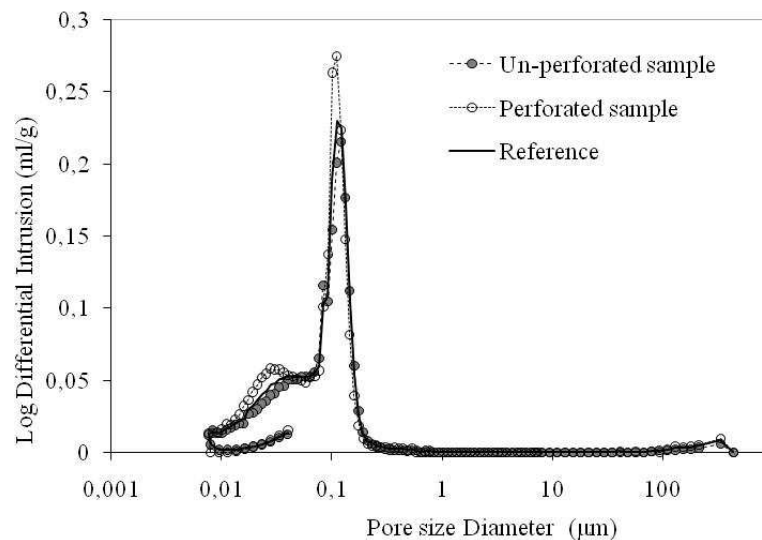


Fig 2. Measured MIP reference curve.

Fig. 2 gives the reference pores distribution curve obtained for the micro-concrete. Pores distribution is also given for both type of references. Small differences can be observed: samples with a hole have a total void volume slightly higher than samples without hole. This is due to the fact that the pore structure of the material is more accessible to the mercury intrusion in the case of perforated samples (shorter mercury flow) than in the case of un-perforated one (longer mercury flow).

Considering the size of the glass filaments used in yarns, and supposing compact arrangements of the filaments of the yarn as shown in figure 3, we roughly estimate the maximum diameter of the inter-filaments pores to 2 to 6 μm . We then choose to focus our attention on the 0.3 to 3 μm pore size distribution of the MIP curves because these pore sizes were therefore expected to be associated to the partial impregnation of the yarn. Figure 4 gives a detail of these curves in the considered pore size range (white zone). In this range, no major differences between the two types of reference samples were observed. We then choose to consider in the following the average porosity curve of all the reference samples.

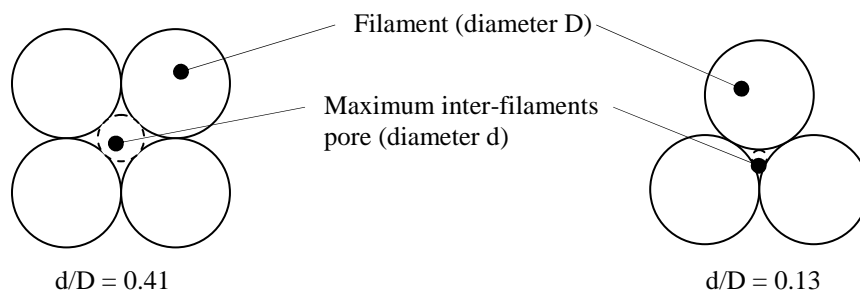


Fig 3. Inter-filaments porosity.

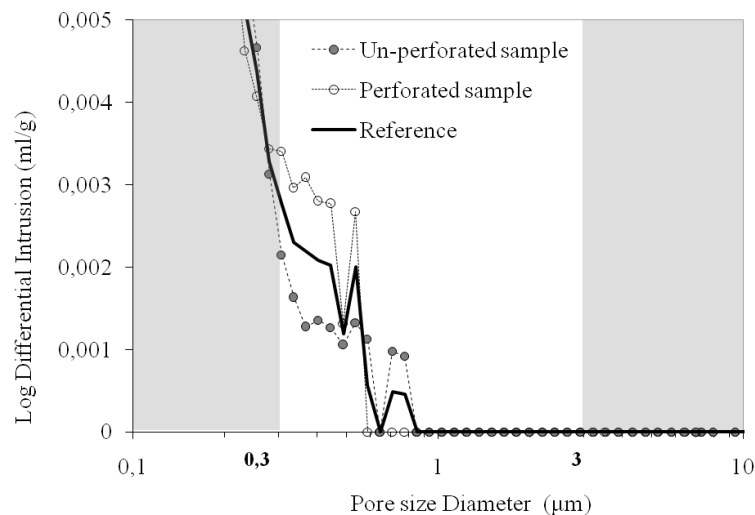


Fig 4. MIP reference curve: detail of the inter-filaments pore range.

3.3 Inter-filaments porosity

MIP was used to characterize the inter-filaments pore range for all configurations. As an example, results for SG1 yarns are given in figure 5. To allow an easy comparison between the different cases, we reduce the porosity distribution to one index, named $v_{0.3-3}$. $v_{0.3-3}$ is the cumulative pore volume in the pore size range 0.3 to 3 μm , determined from the porosity distribution curves, by integration between the corresponding values of the pore diameter.

Table 3 and figure 6 give the values of the cumulative pores volumes for all configurations. Evolution of $v_{0.3-3}$ with the impregnation level is similar for all type of yarn, showing the influence of this parameter. Except for OC1 yarn which shows stable experimental values, $v_{0.3-3}$ is all the more high that the impregnation level is important. This should be connected to the processes used to control the impregnation: the pre-wetting of the yarn (N) induces a high compaction of the filaments, due to capillarity forces, when the manual introduction of the cement slurry in the yarn (C) disorganizes the filaments and creates voids between the cement slurry coated filaments. Partial impregnation (P) has an intermediary behavior.

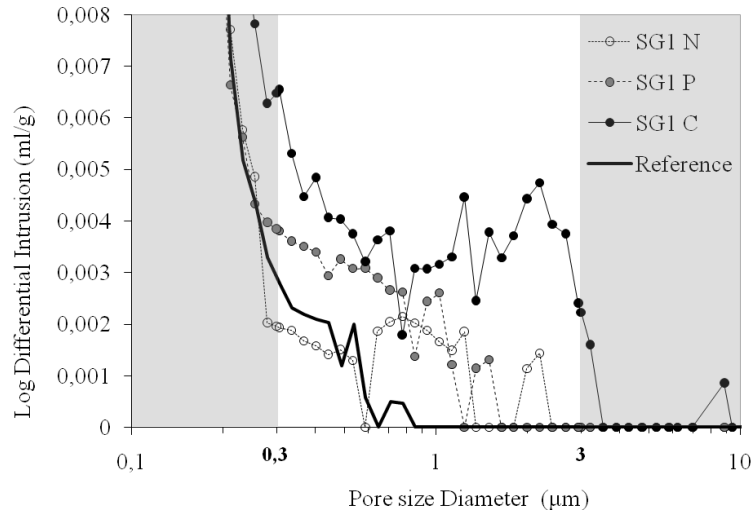


Fig 5. SG1 yarns: MIP in the inter-filaments pore range.

Table 3. Cumulative pores volume in the pore size range 0.3 to 3 μm : $v_{0.3-3}$ (ml/g)

Impregnation level	N	P	C
OC1	$2.789 \cdot 10^{-3}$	$2.209 \cdot 10^{-3}$	$2.677 \cdot 10^{-3}$
OC2	$1.586 \cdot 10^{-3}$	$2.553 \cdot 10^{-3}$	$2.764 \cdot 10^{-3}$
SG1	$1.506 \cdot 10^{-3}$	$2.558 \cdot 10^{-3}$	$4.064 \cdot 10^{-3}$
reference	$1.432 \cdot 10^{-3}$	$1.432 \cdot 10^{-3}$	$1.432 \cdot 10^{-3}$

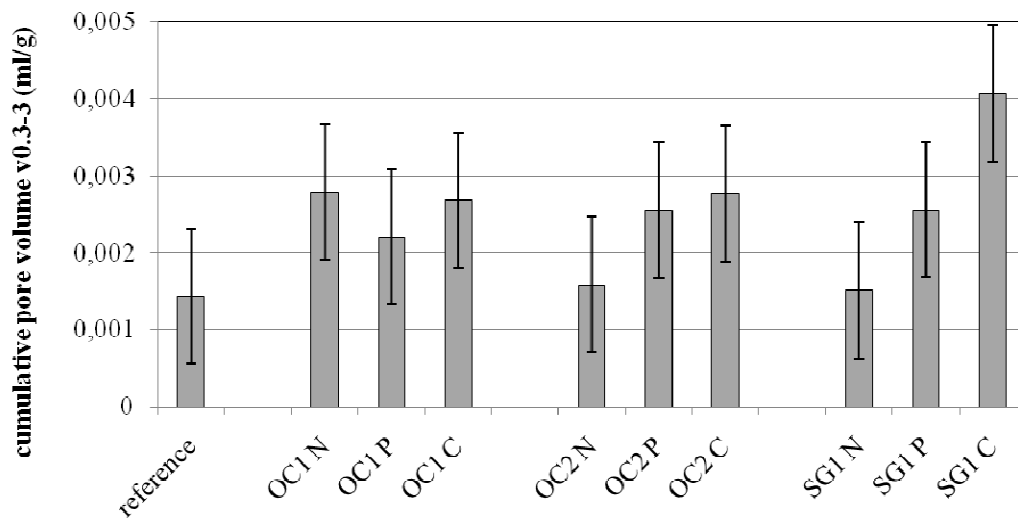


Fig 6. Comparison of the cumulative pore volumes and accuracy of the measurements.

4 Flow test

Flow test consists in measuring the flow rate of water along an embedded yarn, for an imposed pressure gradient of 1.075bar/cm. Samples are 2cm long portion of the cylindrical specimens described in part 2.2. Measurements are made for all configurations and for a micro-mortar reference. 2 measurements are made in all cases. Table 4 gives the values of the cumulative pore volumes for all the configurations. A graphical presentation of these results is shown in figure 7. Rather low flow rate are obtained, except for OC1 P, OC2 N and SG1 N configurations, which denotes in these cases a connected porosity along the yarn. In all the other case, the flow rate is at least 4 time lower, which can be explained by a lower or less connected porosity.

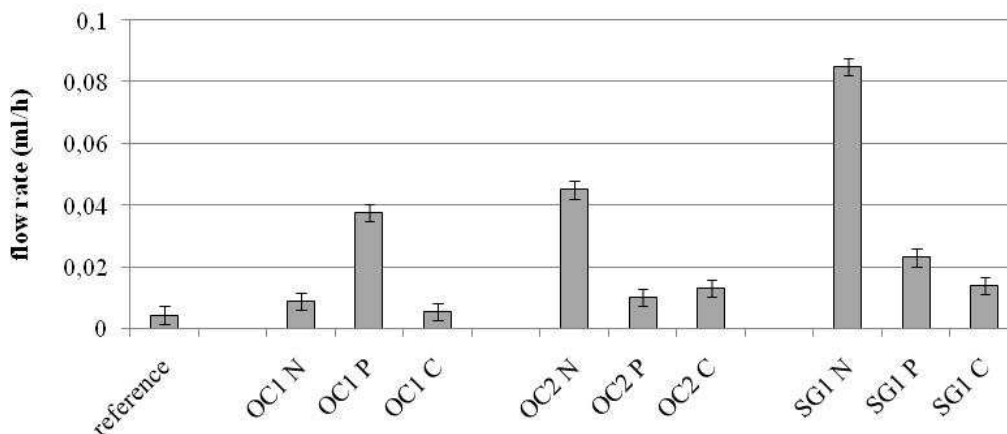


Fig 7. Flow rate along embedded yarns and accuracy of the measurements.

Table 4. Flow rate (ml/h).

Impregnation level	N	P	C
OC1	0.0089	0.0377	0.0054
OC2	0.045	0.01	0.013
SG1	0.085	0.023	0.014
reference	0.0044	0.0044	0.0044

5 Scanning electronic microscopy (SEM)

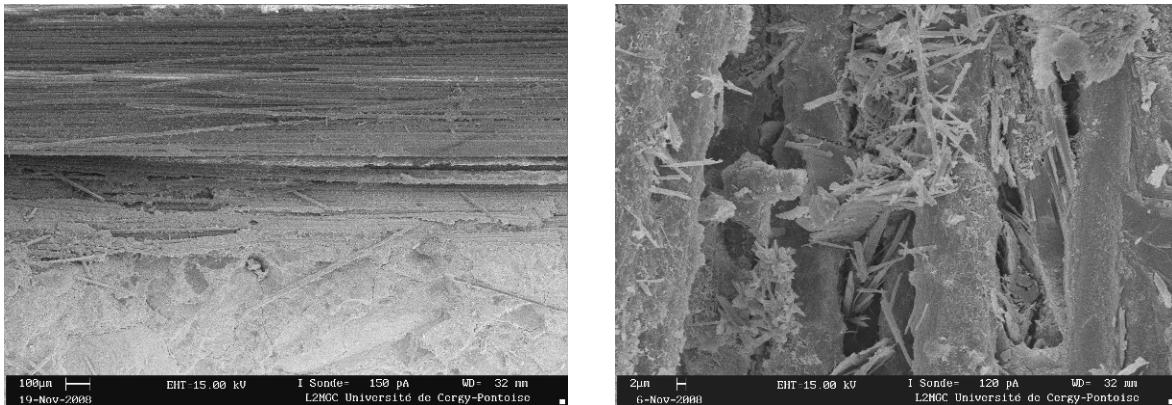
5.1 Specimens preparation

The SEM observations were performed with the aim to characterize the way the impregnation of the yarn by the matrix was made. In particular, specific attention was paid to the homogeneity of the impregnation, and to the existing of different families of filaments, such as core and sleeve filaments. Observation were made after 28 days curing, on longitudinal (parallel to yarn) sections of the micro-concrete specimens. Sections were obtained from split cylinder test performed on 4cm long portions of the cylindrical specimens.

5.2 OC1 yarns

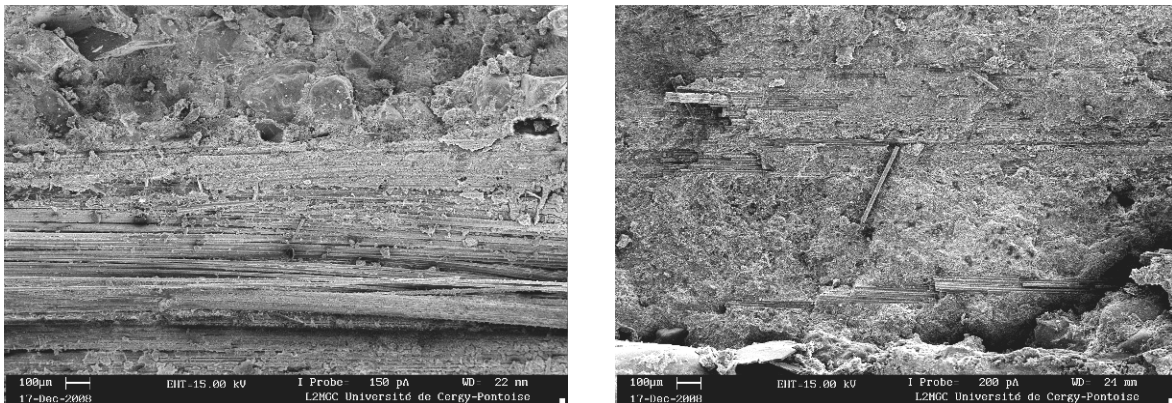


Fig 8. OC1 yarns; longitudinal sections corresponding to N, P and C impregnation.



(a) Near matrix filaments: penetration of cement paste through a thin layer of filaments (b) Core filaments near sleeve filaments: hydrated products are locally observed.

Fig 9. OC1 N yarn; details of the impregnation.



(a) OC1 P: cement matrix penetration in the sleeve filaments. (b) OC1 C: full impregnation of the yarn by the cementitious matrix.

Fig 10. OC1 P and OC1 C yarns; details of the impregnation.

Figure 8 shows the longitudinal sections obtained for OC1 yarn, for the 3 different impregnation levels. The effect of the three processing is here clearly seen. The pre-wetting of the yarn (N) leads to straight parallel filaments with a large portion of them not impregnated (they were removed on figure 8). Only a small portion of the filaments is bonded to the matrix (see figure 9a). The surface of the core filaments is generally free from hydrated products, with the exception of the vicinity of the sleeve filaments where hydrated products exist without constituting a homogeneous layer (figure 9b). Conversely, the pre-impregnation with the cement slurry (C) induces as expected a full impregnation of the yarn, with filaments partially interlocked due to the mechanical action during pre-treatment. The cement matrix that impregnates the yarn has good mechanical properties, which leads to breaking of filaments when processing the split cylinder test (figure 10b).

Partially impregnated yarn (P) shows an intermediate facies, with the main part of the filaments embedded in the matrix. The matrix inside the bundle of filaments appears as weaker than in the case of OC1 C yarn (figure 10a). Just a small proportion of the filaments were not embedded in the matrix, which signifies that the free length of most of the filaments (the distance between two embedded points) is smaller than the length of the sample (4cm).

5.3 OC2 yarns

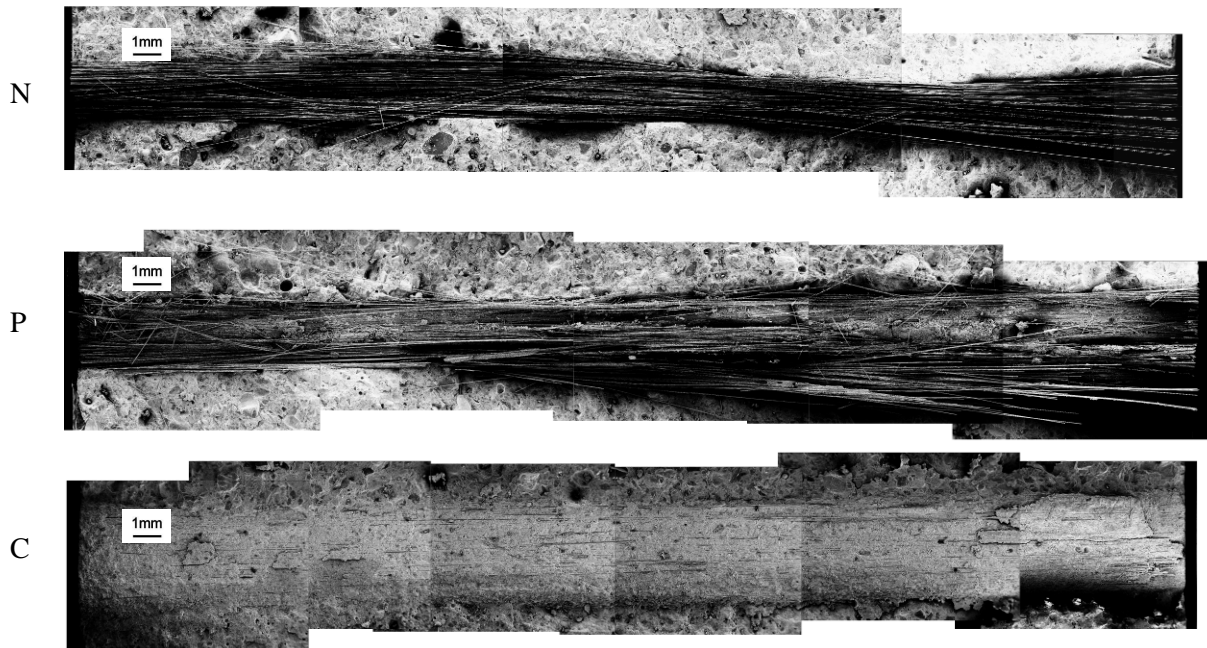
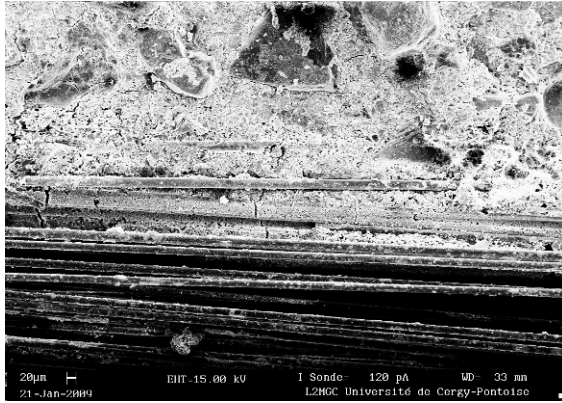


Fig 11. OC2 yarns; longitudinal sections corresponding to N, P and C impregnation.

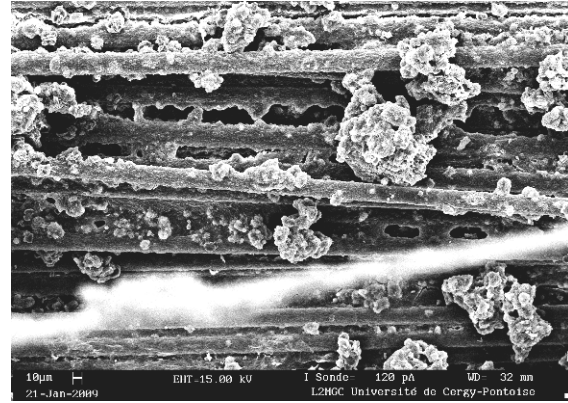
Observations made on OC2 embedded samples show that the impregnation pattern is mainly similar to the one observed for OC1 embedded samples (see figure 11). OC2 N yarn shows parallel mainly non-impregnated filaments, with a thin layer of impregnated filaments (figure 12a). OC2 P yarn appears as very similar to OC2 N. The main differences are the misaligning of filaments and the appearance of hydrated products in-between filaments in the core filaments (see figure 12b). The thickness of the impregnated layer is approximately of the same order than in the case of OC2 N yarn.

As for OC1 yarn, OC2 C shows a completely different organization of the yarn, with a full impregnation of the filaments by the matrix. In this case, because of the specific structure of the yarn (direct roving), the filaments and the matrix are very intimately mixed. No core filaments are detectable and the whole impregnated yarn appears as one homogeneous fibrous body embedded in the micro-concrete (figure 13a). At higher resolution, some areas

appear as largely porous, with cementitious matrix coated fibers separated from each other (figure 13b).

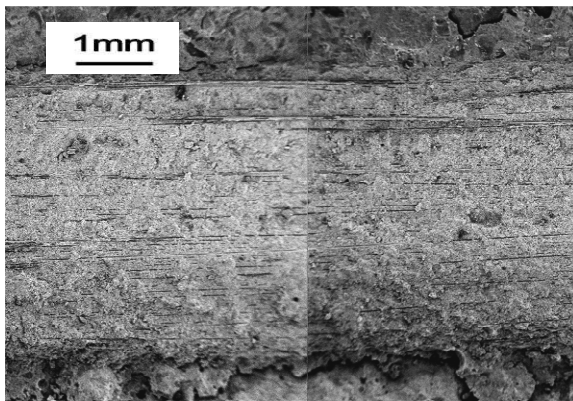


(a) OC2 N: thin layer of impregnated filaments.

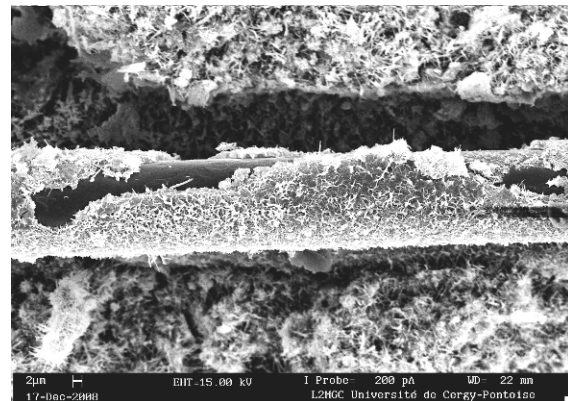


(b) OC2 P: localized observation of hydrated products inside core filaments.

Fig 12. OC2 N and P yarns; details of the impregnation.



(a) Homogeneous impregnation of the filaments.



(b) Coating of fibers by hydrated products.

Fig 13. OC2 C yarn; details of the impregnation.

5.4 SG1 yarns

Figure 14 shows the impregnation of the SG1 yarns by the cementitious matrix, for the three studied different impregnation levels. As for the other yarns, the non-impregnated configuration (SG1 N) leads to a poorly impregnated yarn, with numerous core filaments not in contact with the body of the matrix (figure 15a).

SG1 P yarn is similar to SG1 N yarn: large portion of the filaments are uncovered by the cementitious matrix. However, in some place the matrix has penetrated the yarn, which leads to pieces of cement paste in which filaments are embedded (figure 15b).

SG1 C yarn is much more impregnated than SG1 N and P. Contrary to other type of yarns, it appears as not fully impregnated: portions of filaments remain free of contact with the matrix. It seems that the adhesion of the cementitious matrix to the filament was less important than for OC1 and OC2 yarns, which has led to decohesive failure when splitting the sample in two parts before the SEM observation (figure 16).

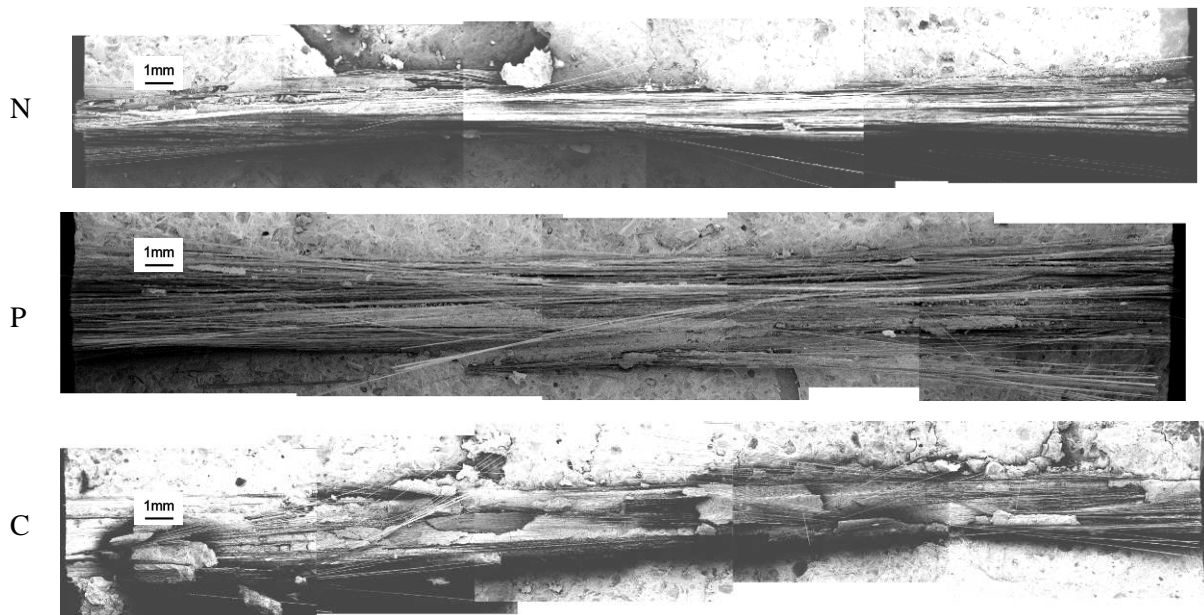
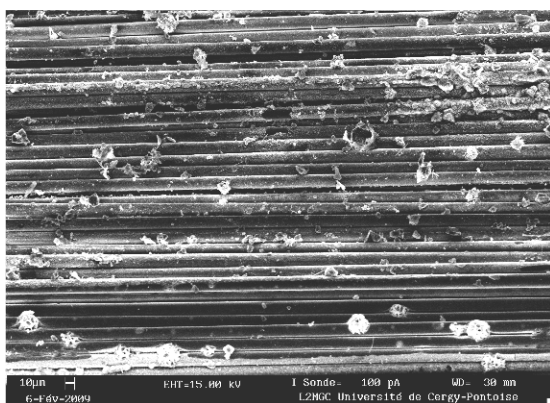
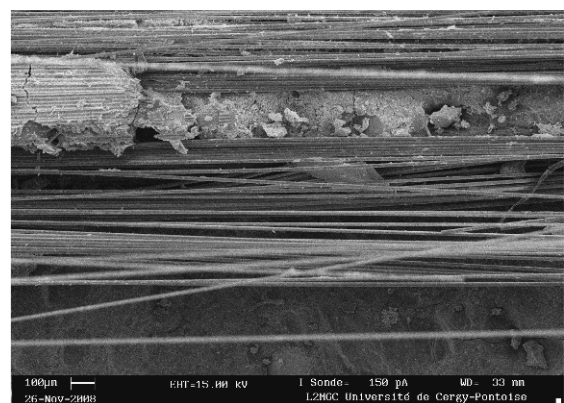


Fig 14. SG1 yarns; longitudinal sections corresponding to N, P and C impregnation.



(a) SG1 N: very low impregnation of the yarn.



(b) SG1 P: partial embedding of the filaments.

Fig 15. SG1 N and P yarns; detail of the impregnation.

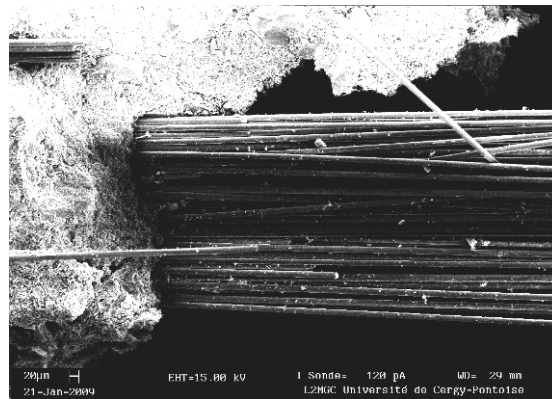


Fig 16. SG1 C yarn; detail of the impregnation.

5.5 Impregnation of the yarns

The penetration depth of the cementitious matrix inside the yarn was visually estimated from the SEM observation for the N and P configurations. Table 5 gives for each type of yarns and impregnation levels the diameter of the impregnated yarn and the minimum, average and maximum values of the penetration depth of the cementitious matrix in the yarn. An impregnation index (named i_Y) was calculated as the ratio between the impregnated area and the total area of the cross section of the yarn, with the following assumption: cylindrical yarn, constant penetration depth of the matrix over the perimeter. We obtain:

$$i_Y = 1 - \left(\frac{R-p}{R} \right)^2 \quad (2)$$

With R radius of the impregnated yarn

p penetration depth of the cementitious matrix

Table 5 : Impregnation characterization of the yarns.

Configuration	Diameter of the impregnated yarn (μm)	Observed penetration depth (μm)			i_Y
		Min.	Average	Max.	
OC1 N	3520	250	375	500	38%
OC1 P	3260	600	700	800	67%
OC1 C	4190				100%
OC2 N	2690	160	170	180	24%
OC2 P	3390	160	170	180	19%
OC2 C	4260				100%
SG1 N	3190	100	125	150	15%
SG1 P	4270	300	325	350	28%
SG1 C	3220				100%

In accordance with the SEM observation, we assumed the full impregnation of the yarn for C configurations, due to the process used. Figure 17 gives the values of i_Y . It should be notice that the impregnation of OC2 dry yarn (P configuration) is not enhanced compared to OC2 wet yarn (N configuration). This can be attributed to the specific conformation of this yarn, which is a direct assembly of filaments.

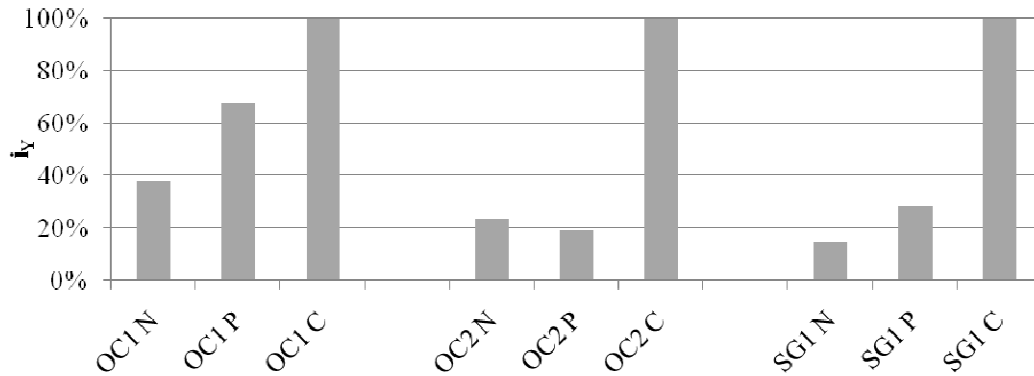


Fig 17. Impregnation index i_Y vs. type of yarn and level of impregnation.

6 Analysis and discussion

6.1 Relationship between flow test and yarn pores volume

Figure 18 shows the relationship between the flow rate and the 0.3-3 μ m pores volume for the three tested yarns and the three impregnation levels. N and P yarns show the same tendency of the flow rate to increase hugely when the porosity index $v_{0.3-3}$ decrease slightly. This is consistent with the non-impregnation of the yarn and with the good alignment and compaction of the filaments (due to the capillarity forces induced by the process), which results in inter-filaments voids made from thin linear pores delimited by filaments with respect to the geometry shown in figure 3. As glass is non-porous and the filaments arrangement is compact, the cumulative pore volume is low. The flow of water is easy due to the fact that inter-filaments pores are linear and parallel to the pressure gradient. The sizing, which directly influences the water / filament contact angle, may explain the influence of the type of yarn on the flow rate.

In the case of C yarns, the pore volume is higher, but the flow rate is the lowest observed. This can be a consequence of the impregnation by the cementitious matrix, which introduce a porous media into the yarn, leading to the increase of the pore volume of the yarn. This porosity is a cement paste type porosity, with tortuous pores which reduces the flow rate, compared to straight pores. In this case, the sizing has no major effect on the flow, as the water is in direct contact with the cement past. This explains the almost stable values of the flow rate observed in this case.

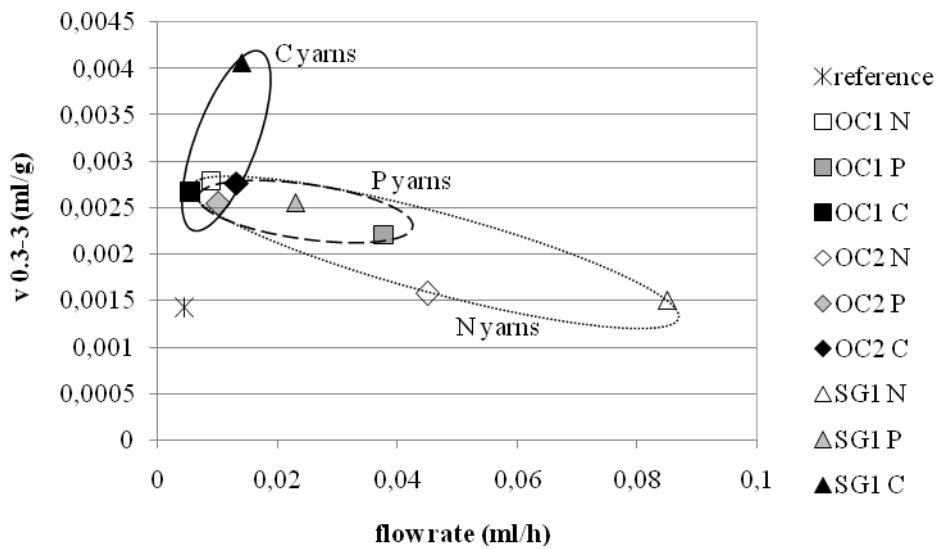


Fig 18. Cumulative pore volume $v_{0.3-3}$ vs. flow rate.

6.2 Relationship to the impregnation index

Figures 19 and 20 give respectively the dependence of the flow rate and yarn pores volume to the impregnation index i_Y . Despite of the poor precision of the measurements, rough tendencies are founded:

- The flow rate is a decreasing function of the impregnation index. The lowest values of the flow rate (about 0.01ml/h) correspond to the full impregnation of the yarn and are not influenced by the type of yarns, probably because the flow take place in the pore structure of the cement past, has explained before. Flow rate for lower impregnation rate are influenced by the type of yarn.
- The cumulative pore volume $v_{0.3-3}$ is an increasing function of the impregnation index, except for OC1 which gives almost constant values. This should be connected to the increasing disorder in the filaments arrangement induced by the penetration of the cementitious matrix, especially in the case of C yarns.

These results link the impregnation to the physical properties measured by the mean of flow test and mercury intrusion porosity. Therefore, these measurements can be used to evaluate the level of impregnation of a yarn. However, the relationships between these different parameters appear as slightly complex. In particular, the flow rate dependency to the pore volume of the yarn is hard to explain, because it is connected to the pore volume of the yarn and to the diameters of the pores, but also to the type of material in contact with water. This last can be different from one configuration to the other: mainly glass when the yarn is not impregnated, it turns to cement past with the increase of the penetration of the cement past in the yarn.

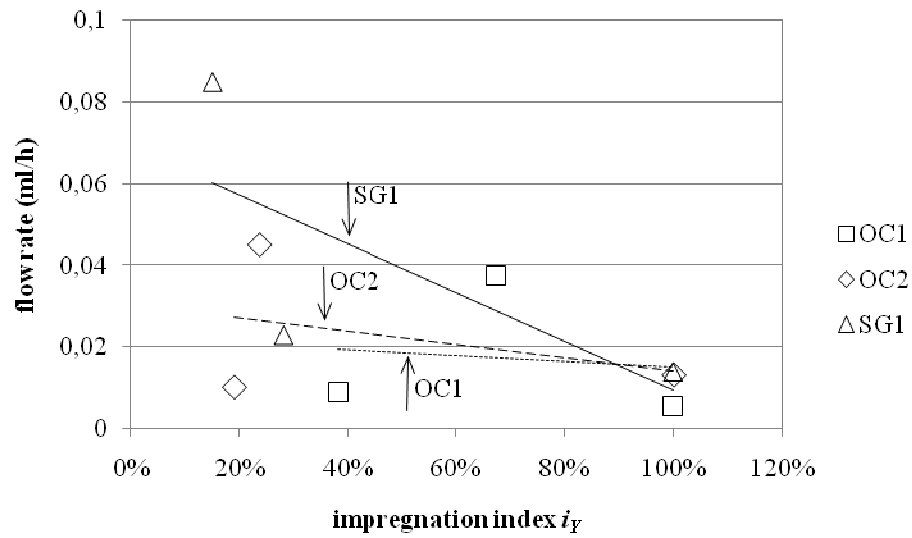


Fig 19. Flow rate vs. impregnation index.

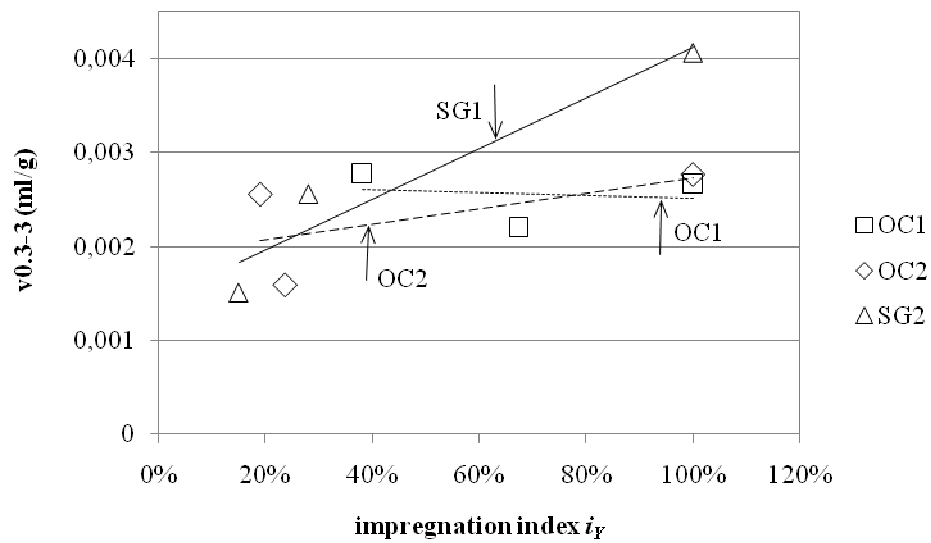


Fig 20. Cumulative pore volume $v_{0.3-3}$ vs. impregnation index.

7 Conclusion

The study presented in the previous pages had two goals. The first was to characterize three different embedded yarns with two dedicated tests able to give quantitative information on the impregnation state of the yarn. The second was to link the physical properties measured with these tests to the level of impregnation of the yarns determined from SEM observation.

The first testing method used (comparative mercury intrusion porosity) allows to estimate the inter-filaments porosity of the yarn. It gives interesting results, even if the accuracy is not very important. In particular, it allows to discriminate the different levels of impregnation and the type of yarns.

The second testing method used (flow test) has a better accuracy. It shows a high sensitivity to the introduction of cement paste into the yarn, but is less sensible to a change in the impregnation level as soon as impregnation is not reduced to almost nothing.

The comparison between the level of impregnation, estimated from the SEM observation, and the results of the two testing methods allow to determined rough relationship between this two families of data. It is shown that these relationships are dependent of the type of yarns. The impregnation level can therefore be estimated from the two methodologies, provided that preparatory measurements are made to characterize the compoment of the yarn regardless to the impregnation process.

8 References

- [1] JESSE, F.; CURBACH, M.: The present and the future of textile reinforced concrete. In: *5th International Conference on Fibre Reinforced Plastics for Reinforced Concrete Structures, July 16-18, 2001, Cambridge, UK*, pp. 593-608.
- [2] WONG, C. M.: *Use of Short fibres in structural concrete to enhance mechanical properties*, University of Southern Queensland, Faculty of Engineering and Surveying, 2004 – Dissertation.
- [3] BENTUR, A.; MINDESS, S.: *Fibre Reinforced Cementitious Composites*, New York: Elsevier Sciences Publishing Ltd., 1990, 449p.
- [4] OHNO, S.; HANNANT, D.J.: Modelling the stress-strain response of continuous fiber reinforced cement composites, *ACI Materials Journal* (91), 1994, pp. 306-312.
- [5] LANGLOIS V.: *Etude du comportement mécanique des matériaux cimentaires à renforts synthétiques longs ou continues*, Université de Cergy-Pontoise, France, 2004 - Ph.D.
- [6] BANHOLZER, B.: *Bond behaviour of a multi-filament yarn embedded in a cementitious matrix*, RWTH Aachen University, Germany, 2004 - Ph.D.
- [7] HEGGER, J.; BRUCKERMANN, O.; WILL, N.: Bond characteristics of multi-filament yarns in a cementitious matrix: Pull-out tests and their numerical simulation, In: *Techtextil-Symposium 2003. 12th International Symposium for Technical Textile, Nonwovens and Textile Reinforced Materials*, April 9, 2003, Frankfurt/ Main, Germany, Lecture No. 4.24.
- [8] LANGLOIS V., BEAUCOUR A.L., CABRILLAC R., FIORIO B., GOUVENOT D.: Study and model of the bond of carbon yarn embedded in a cementitious matrix. In: *3rd International Congress Composites in Construction*, july 11-13, 2005, Lyon, France.

- [9] WINSLOW, D.N.; DIAMOND, S.: A mercury porosimetry study of the evolution of porosity in portland cement, *J. Mater.* (5), 1970, pp. 564–585.
- [10] FELDMAN, R.F.; BEAUDOIN, J.J.: Pretreatment of hardened hydrated cement pastes for mercury intrusion measurements, *Cement and Concrete Research* (21), 1991, pp. 297–308.
- [11] COOK, R.A.; HOVER, K.C.: Mercury porosimetry of hardened cement pastes, *Cement and Concrete Research* (29), 1999, pp. 933–943.
- [12] BEAUDOIN, J.J.: Porosity measurement of some hydrated cementitious systems by high pressure mercury intrusion-microstructural limitations, *Cement and Concrete Research* (9), 1979, pp. 771-781.
- [13] BAROGHEL-BOUNY, V. : *Caractérisation des pâtes de ciment et des bétons méthodes, analyse, interprétations*. Laboratoire Central des Ponts etChaussées (LCPC), Paris, France, 1994 – Ph.D.
- [14] DIAMOND, S.; BONEN D.: Microstructure of hardened cement paste—A new interpretation. *J Amer Cer Soc* (76), 1993, pp. 2993–2999.