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PERMEABILITY AND POROSITY CHARACTERISTICS OF STEEL FIBER REINFORCED CONCRETE

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ABSTRACT

Steel fibres have gained popularity in recent decades for use in concrete at relatively low volume fractions. They are mainly used to enhance toughness, flexural strength and resistance to shrinkage-induced cracking. However, little information is available about the effects of fibers on permeability and porosity, which play an important role in long –term durability of concrete materials.

This paper presents the results of an experimental study that was carried out to examine the influences of steel fiber addition on the permeability and porosity of a concrete prepared mainly from local materials. The test results are discussed in this paper, the interpretation of the test results is reported as well as conclusions regarding the effects of steel fibers on the water and gas permeability of concrete.

Keywords: porosity, permeability, voids, steel fiber concrete

1. INTRODUCTION

Permeability of concrete generally refers to the rate at which water or other aggressive substance (sulphates, chlorides ions, etc.) can penetrate concrete. It plays an important role in the long-term durability of concrete [1]. Low permeability is an important requirement for hydraulic structures and in some cases water tightness of concrete may be considered to be more significant than strength although, other conditions being equal, concrete of low permeability will normally also be strong and durable. A concrete, which readily absorbs water, may be susceptible to deterioration. Resistance to deterioration is determined largely by the ability of the cover zone concrete to resist the ingress of deleterious agents from the environment.

Concrete is inherently a porous material. This arises from the use of water in excess of that required for the purpose of hydration in order to make the mix sufficiently workable, and the difficulty of removing all the entrapped air voids from the concrete during compaction. If the voids are interconnected, concrete becomes pervious; although with normal care concrete is sufficiently impermeable for most purposes.

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Steel fibres have gained popularity in recent years and are used in concrete mainly to improve flexural and toughness strength and to reduce shrinkage cracking [2, 3]. The arrest of shrinkage cracks in young concrete by fibres can lead to reduced permeability of steel fibre reinforced concrete when compared with plain concrete [4]. But, little information is available about the effect of fibre addition on both porosity and permeability of concrete.

The main aim of this experimental study is to examine the influence of fibre length and fibre content on the porosity and permeability of a concrete prepared mainly from local materials. The work reported herein is based on laboratory experiments carried out in accordance with the ASTM standards [5] for the porosity property, while gas and water Permeability were measured using the test rigs illustrated in Figure 1and 2.

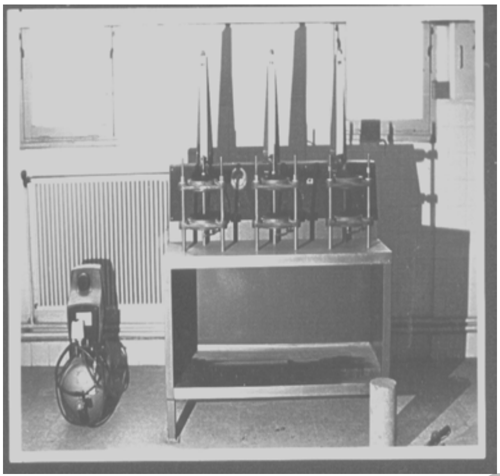

Figure 1. Water Permeability test rig

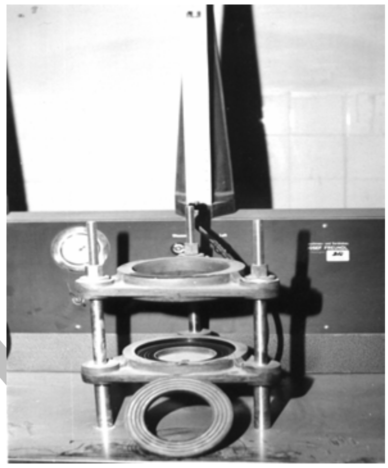

Figure 2. General view of the cell

2. MATERIALS AND METHODS

2.1 Basic Ingredients.

The basic ingredients used to make the steel fibre reinforced concrete were:

- *Portland cement*: Type CPJ45, comes from AIN TOUTA factory in ALGERIA. It conforms to NF. P. 15.301. The chemical composition and physical properties of the cement are given in Table 1 and 2.

Table 1. Physical and mechanical test results

Blaine fineness m^2/kg	Autoclave expansion, percent	Setting time (vicat)		Compressive strength, MPa	Shrinkage µm/ml
		Initial	Final		
324	0.01	105	220	45MPa (28 days)	800

Table 2. Chemical composition (%, by weight) of CPJ cement

Constituent, %	SiO_2	Al_2O_3	Fe_2O_3	CaO	Mg O	CaO free	SO_3	P.F	Insoluble
CPJ 45	19.48	5.06	3.72	61.95	0.85	1.63	1.1	3.44	1.26

- *Coarse aggregate:* A local aggregate obtained by crushing limestone rock from the quarry of COSIDER situated in the EL-EUCH region was used. The aggregate has two fractions 3/8 and 8/15 cm. Its physical properties are given in Table 3 and 4.

Table 3. Some characteristics of the sand and gravel used in the tests

Materials	Density	Porous/ dense	Compactness	Porosity	Sand equivalent
Sand	2.56	1.64/1.83	36.42/70.76	36.58/29.24	75.4/77.2
Gravel 3/8	2.68	1.28	47.46	52.24	----
Gravel 8/15	2.68	1.32	49.25	50.75	----

Table 4. Some physical and mechanical and morphological properties of the gravel used

Gravel Grading	Superficial tidiness (P)	$CaCO_3$ (%)	Flattening Coef	Los Angles (LA)	MDE
3/8	1.5	85	18	20	16
8/15	1.28	83	13	23	17

- *Dune sand:* this is a clean, siliceous and fine sand of fraction 0/5 cm taken from BOUSAADA region. Its characteristics are presented in Table 3 and 5.

Table 5. Chemical composition (%, by weight) of the sand of dune used.

Constituent,%	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	CaO free	SO_3	P.F	Insoluble
Sand of dune	86.04	1.35	0.86	6.63	0.08	----	---	5.00	---

- *Steel fibers:* all fibers used in this study were steel fibers having 1.2 mm diameter, 10 to 30 mm length. The average fiber density was 7.89. The fiber content varied from 0.5 to 2% by volume. Its characteristics are regrouped in Table 6.

Table 6. Some physical and mechanical properties of steel fibres

Density	Tensile strength MPa	Elasticity modulus MPa	Dilatation Coef (μ/m)	Fire resistance (°)
7.8	1000 to 3000	2.10^5	11	1500

2.2. Mix Proportioning

Concrete mixes were designed to provide a slump of (60±10mm) for ease of handling, placing and finishing. The air content of all mixes was 3 ± 0.5 %. The concrete mix proportion used (class 350 dan/m^3) were determined by the absolute volume method "SCRAMTAIEV METHOD" [6] and were as follows:

Cement: 350 kg/m^3, Sand: 758 kg/m^3, Gravel: 1073 kg/m^3

Total water: 215 l/ m^3 (this quantity takes into account the degree of aggregates absorption)

3. SPECIMEN PREPARATION AND CONDITIONNING

3.1 Mixing, Casting and Curing

A total of nine plains (three for porosity tests, three for gas permeability tests and three for water permeability tests) and forty five fibre reinforced mixes were prepared. Materials were mixed in a linear-cum-flow mixer type 'O' which had a capacity of 0.043 cubic metres and a power driven rotating pan and paddle. This mixer was sturdy enough for fibrous mixes, and a good uniformity of fibre distribution was achieved. The mixer was first loaded with the coarse aggregate and a portion of the mixing water. After starting the mixer the sand, cement and the rest of water were added and mixed for 5 min. The fibres, in the case of fibrous mixes, were added following the addition of all mix ingredients.

Three 16×32 cm cylinders were cast from each mix. They were cast in cylindrical steel moulds and compacted on a vibrating table. Specimens were placed under plastic sheet membrane for 24 hours in an ambient temperature. Following removal from the moulds, they were individually sealed in plastic bags and stored at room maintained at 24°C and 65% relative humidity until testing at ages of 7, 14 and 28 days for porosity tests and only at age of 28 days for permeability tests. But, before testing, the cylinders were removed from the plastic bags, and cut (in the case of porosity and gas permeability tests), using specimen cutting machine, into 50 mm-thick slices, having removed a 10mm thick slice from the top and the bottom.

4. POROSITY AND PERMEABILITY TESTS

4.1 Porosity Test in Hardened Concrete

The porosity of steel fibre reinforced concrete, as well as plain concrete, is an important characteristic, which determines to a large extent the mechanical properties of the concrete.

High porosity is detrimental to the strength and permeability of a concrete, particularly if the pores are of large diameter and connected.

To determine the porosity of hardened concrete ASTM C642 requires reporting of :

- Bulk density dry,
- Bulk density after immersion
- Bulk density after immersion and boiling
- Absorption after immersion
- Absorption after immersion and boiling,
- Volume of permeable voids was evaluated by using the following formula:

$$T.V = (1 - y_1/y) \times 100 \quad (1)$$

Where T.V = Volume of permeable pore space in concrete, percent
y_1 = Concrete bulk dry specific gravity
y = Concrete apparent specific gravity

4.2 Water Permeability Test in Hardened Concrete

Water permeability was measured using the apparatus illustrated in Figure 1. This apparatus, designed by Contralab Engineering Company, has been used in many laboratories. It consists of a metal stand with three permeability cells with a unit pressure regulator a range from 0 to 30 bars, and a graduated glass gauge.

Each cell comprises top and bottom steel plates which are bolted together by three steel shafts fixed on the stand (Figure 2). The base plate is mild steel with a 20mm diameter hole drilled to form the water inlet. The top is also steel but with a circular window, through which the top face of the test specimen can be observed.

After putting the test specimen in the cell and making the water pressure on, the flow test is normally measured by observing the rate of flow of water through the calibrated glass tube.

Generally, for concrete complete penetration of the specimen may take several days or more. In our case, the specimens are removed from the test after one week, and the permeability coefficient calculated from the depth of water penetration.

5.3. Water Permeability Coefficient

The test, in this case, consists in making an amount of water, under a predetermined pressure, flows through a cylindrical concrete specimen and then measure the flow.

- To measure the coefficient of water permeability by flow, the DARCY'S Law [7] can be applied as the flow is continuous:

$$K_{1D} = Q.X / A.h \quad (2)$$

Where Q is the volume flow rate given in (m^3/s), A is the cross-sectional area of the test specimen in (m^2), h is the head of water given in (m), X is the specimen thickness in the direction of thickness (m), K is the permeability coefficient.

- To measure the water coefficient by penetration, VALENTA'S Law [8] can be applied if the material is less permeable:

$$K_{1V} = \chi^2_{P}.V /2.h.t \quad (3)$$

Where K_{1V} : Water permeability coefficient (m/s)

χ^2_P : depth of penetration (m)

V: Volume of voids filled by water in the penetrated zone.

t : Time to penetrate to depth χ_P (s)

h : Applied pressure (eg: 1 bar = 10m)

The two coefficients calculated from equation 2 and 3 are derived for a specific fluid flowing through a specific porous medium. To compare the permeability of concretes obtained from tests using different liquids it is necessary to define the "intrinsic permeability" K_i, which should depend only on the pore structure of the concrete:

$$K_{1c}= Q\,\chi\,\eta /A\,(P_1- P_2) \quad (4)$$

Where K_{1c} = intrinsic permeability of concrete (m^2)

η = viscosity of liquid

P_1 = upstream pressure (N/m^2)

P_2 = downstream pressure (N/m^2)

$P_1 - P_2$ = pressure differential = $h\,\rho\,g$, P = density (kg / m^3) and g = 9.81 m/s

Substituting for $P_1 - P_2$ in equation 4.

$$K_{1c} = Q\,\chi\,\eta / A\,h\,\rho\,g \quad (5)$$

Then $K_{1c} = K_{1D}\,\eta / \rho\,g$; for water $\rho = 1000 kg/m^3$, hence

$$K_{1c} = K_{1D}.\,10^{-3}/1000.\,9.61 = 1.02.\,10^{-7}\,.\,K_{1D}$$

For water, therefore, the intrinsic permeability coefficient in units of m^2 is approximately10^{-7} times the Darcy coefficient in units of m/s.

4.4 Gas Permeability Test

The test rig used to measure gas permeability is illustrated in Figure.3. It is an apparatus which measures bubble flow and it made up mainly of:

- A pressure unit automatically-controlled, leading to cell entry
- Glass tubes of different volumes (1.5-5-15-150ml)

The test cell is made up of 5 parts: an aluminium receiver, two milled plates being used for recuperating oxygen crossing the concrete disc, a polyurethane membrane surrounding the disc of concrete and a lid (Figure 4).

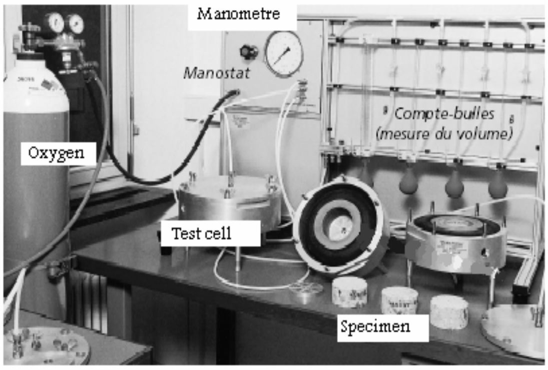

Figure 3. Gas permeability test rig

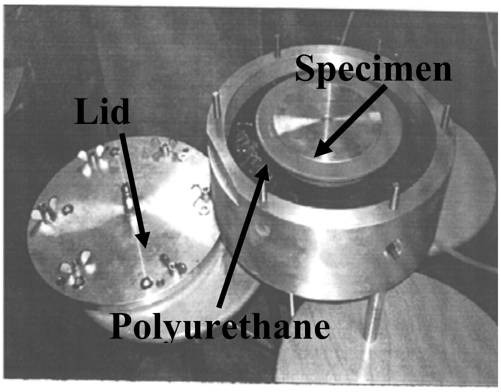

Figure 4. General view of the cell

4.5 Gas Permeability Coefficient

The principle is the same one as for water, a gas overpressure is applied to one of the test disc and a flow is measured at the exit. Thus, The permeability coefficient obtained using a gas normally defined by the Hagen-Poiseuille ‘s formula:

$$Kg = 2.\ Q.x.P_0.\ \mu./A\ (P^2 – P_a^2) \qquad (5)$$

Where K_g is the intrinsic permeability coefficient of gas in units of m^2, μ is the dynamic viscosity of liquid, P is the downstream pressure, P_0 is the pressure at which the flow is measured (generally =Pa), Pa is upstream pressure, Q, A, x are as defined previously. Here, it very important to mention that the flow rate is measured at downstream face. If the flow rate is measured through the upstream face, then P replaces P_a in the numerator.

5. TEST RESULTS

5.1 Porosity Test Results and Discussion

Porosity in hardened concrete (nine unreinforced concrete specimens and twenty seven steel fibres reinforced concrete specimens) was determined according To ASTM C642 standard method. The results given in this paper are the average values obtained from three specimens per mix.

A relationship between porosity and curing age, fibre content, fibre length and slice position was established using data calculated by equation 1.

In this investigation, pores distribution throughout the plain and reinforced concrete specimens were evaluated after slicing each cylindrical specimen into six cylindrical slices as illustrated in Figures 5 and 7.

The porosity percentage decreases from 6.38 % in the top slice to 4.46 % in the bottom slice, which is the most compacted part of the specimen. This indicates that pores content are not uniformly distributed throughout the specimen (see Figure 7).

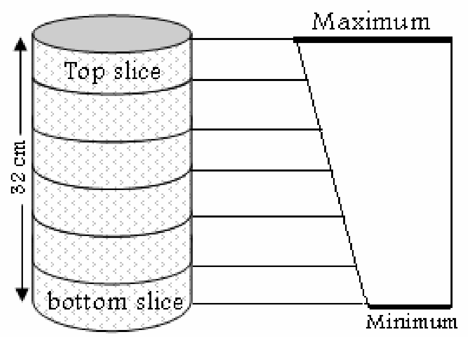

Figure 5. Pores distribution throughout the specimen

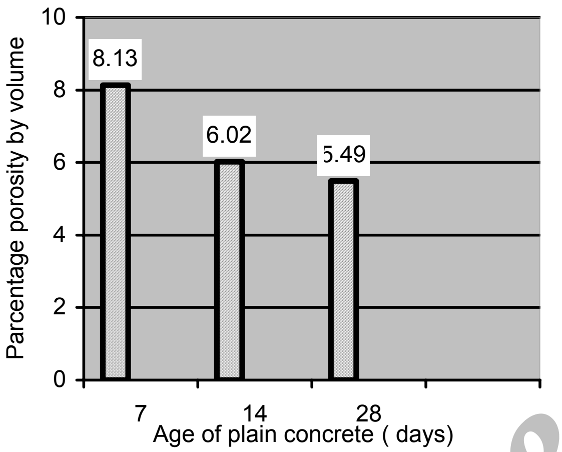

Figure 6. Relationship between pores percent and cure age (Average values of the whole specimen)

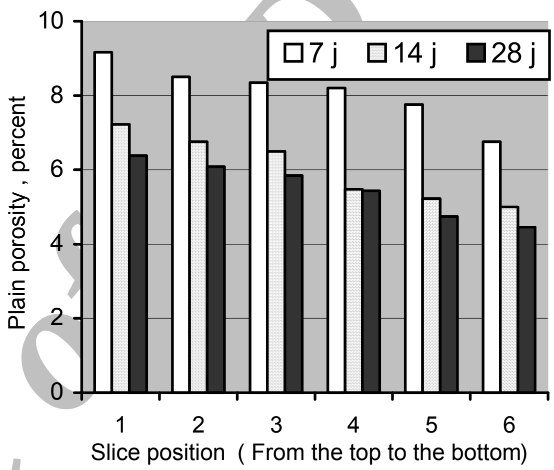

Figure 7. Relationship between pores and cure age at different positions

The 28 days porosity values for plain concrete specimens cured in the laboratory are shown in Figure 6. These values were in the range of 4.46 percent (in the bottom slice) to 6.38 percent (in the top slice). It can be also seen from Figure 6 that porosity decrease with an increasing curing age. The 7 days porosity percent was 8.13. But the porosity was only an average of 5.49 at 28 days. This can be explained by the hydration process in which the capillary pores and air voids are partially or completely filled with the hydration products and the possibility of water flow is gradually reduced. This fact is also confirmed by other researchers [4, 9] who reported that the duration and quality of curing of the fresh mix determine the process of hydration and the volume of hydration products, which may eventually fill the capillary pores and reduce their permeability.

Generally, it can be seen from Figure 6 that the value of porosity is lower after 28 days at ambient temperature, because the pores accrete. On the contrary, concrete with steel fibers exhibits lower porosity values compared with plain concrete at the same slice when tested in the same direction. With fiber amount which varied in the range of 0.5 to 2 % percent by volume (L_f =10mm), the porosity varied from 5.5 to 3.82 %, as it can been seen from Figure 8, whereas with a fiber length of 20 mm, the porosity increased with an increasing fiber content.

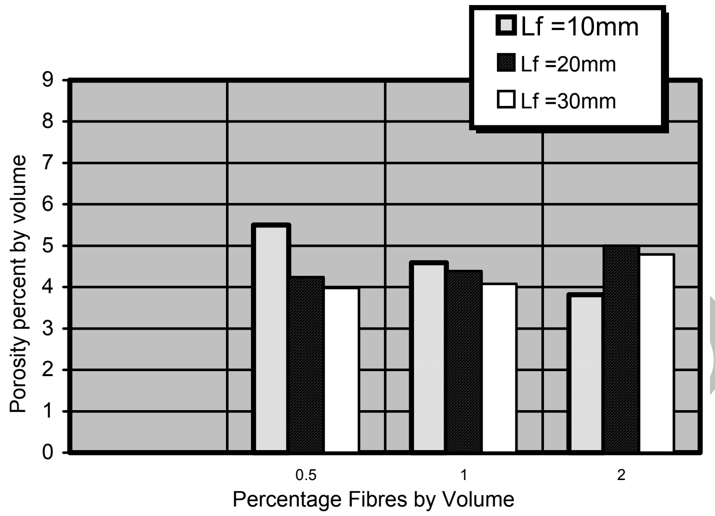

Figure 8. Relationship between porosity and fibre content with three different lengths

The addition of fibers, with a length of 30mm, did not affect the porosity when the amount ranged from 0.5 to 1 % but, beyond the 1 % there was a slight increase in porosity. The slight decrease reported in the porosity of specimens reinforced with steel fibers compared to the plain concrete can be explained by the fact that reinforced concrete specimens needed a long duration of vibration, which can affect the pores sizes and distribution. It is important to mention that many studies have reported that fibers addition did not significantly increase the amount of pores above those calculated for plain concrete [9,10].

5.2 Water permeability results and discussion

Generally in the cases of a concrete as a composite high porosity does not necessary mean high permeability. Indeed only the interconnected of these pores is significant for permeability. The results given in this paper are average values obtained from three specimens per mix and were derived from penetration measurements using the Valenta equation 3. All results are reported in Figure 9 and 10.

Steel fibre addition to concrete clearly increases water permeability coefficient whatever fibre amounts or fibre length as it can be seen from Figure 9 and 10.

The water permeability coefficient of a plain concrete was around 4.02×10^{-19} m^2, while it can be seen that all three fibre lengths, at 0.5% by volume addition, caused water permeability coefficient to range from 6.71×10^{-19} m^2 for L_f =10mm to 23.36×10^{-19} m^2 for L_f =20mm and 65.49×10^{-19} m^2 for L_f = 30mm. At 1 % fibre content, water permeability coefficients were 21.87×10^{-19} m^2, 51.39×10^{-19} m^2 and 39.21×10^{-19} m^2 for 10 mm, 20 mm and 30 mm fibres respectively. But, at 2% fibre content this coefficient varied from 38.83×10^{-19} m^2 $L_f = 10$mm to 33.18×10^{-19} m^2 for $L_f = 30$mm.

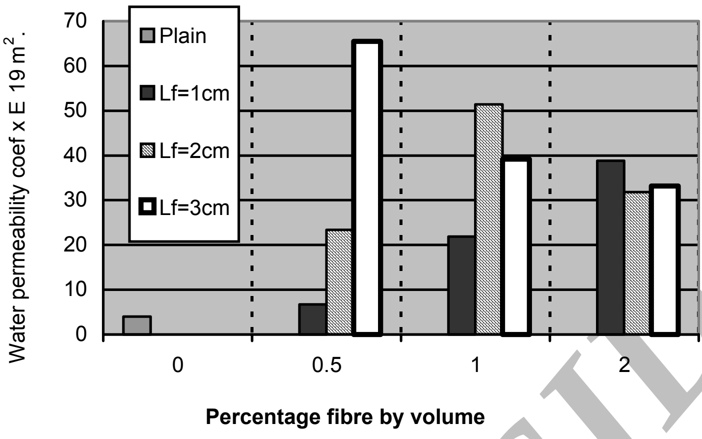

Figure 9. Relationship between Kw and fibre content

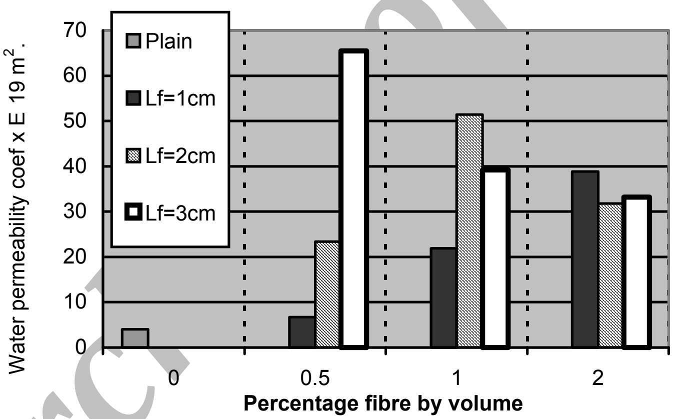

Figure 10. Relationship between Kw and fibre content

Generally water permeability tests are very complicated conduct and the results given in this paper can be explained by the fact that the presence of fibres, whatever their length or their content facilitated the interconnection between pores which were reduced according to the porosity results. The fibre acted as a bridge between pores so that the flow rate was increased and the water permeability coefficient was subsequently also increased.

5.3. Gas Permeability Results and Discussion.

The permeability was determined by using equation 3 of Hagen-Poiseuille. Tests were carried out on a ordinary concrete disc with thickness of 65 mm, having undergoes a 28 days of curing as mentioned before. A pressure of 5 bars was selected on the pressure gauge of the permeameter and fluid movement was observed in the tubes for 5 minutes. This enabled us to check that oxygen does not pass by the disc edges when the tire is inflated.

Typical results of a plain concrete specimen as an example are given in Table 7, while some results, which represent steel fibres reinforced concrete specimens, are given in Table 8.

Table 7. typical results of plain concrete

P (bars)	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**
T1	33	39	29	39	44	32
T2	34	40	30	40	44	32
T3	34	39	30	39	44	32
T4	35	40	30	40	44	32
T5	34	40	30	40	44	32
T moy (s)	34	39.6	29.8	39.6	44	32
V (ml)	1.5	4	5	10	15	15
Pa (bars)	1.02	1.02	1.02	1.02	1.02	1.02
P^2- Pa^2	1.27	3.04	5.31	8.08	11.35	15.12
Q(m^3/s). E-07	0.4411	1.01	1.6779	2.5253	3.409	4.6875
Ki (m^2). E-17	4.081	3.9035	3.7121	3.6716	3.5286	3.6421
K (m^2)	3.7565					

The average value of permeability coefficient K_g for plain concrete is 3.6950×10^{-17}, while that of concrete reinforced with 1 % by volume of steel fibres is 4.0916×10^{-17}

This means that steel fibres increased gas permeability coefficient. To explain such increase in the gas permeability coefficient of steel fibre reinforced concrete, it may be assumed that permeability is determined more by matrix properties [9, 10, and 11] than the fibres. In particular, the matrix-fibre interface has the largest content of pores and micro cracks that effect overall permeability. Also, it is very important to mention here that fibres act as ties between pores so that interconnections are created which allow gas flow to penetrate more easily inside the concrete structure.

Table 8. typical results of steel fibre reinforced concrete

P (bars)	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**
T1	42	31	54	36	34	32
T2	43	30	52	35	35	31
T3	42	30	53	35	34	31
T4	43	30	53	35	34	31
T5	42	30	53	35	34	31
T moy (s)	42.5	30.2	53	35.2	34.2	31.2
V (ml)	3	5	15	15	20	25
Pa (bars)	1.02	1.02	1.02	1.02	1.02	1.02
P^2- Pa^2	1.27	3.04	5.31	8.08	11.35	15.12
Q(m^3/s). E-07	0.70755	1.6556	2.8302	4.2614	5.848	8.0128
Ki (m^2). E-17	6.545	6.3981	6.2615	6.1958	6.053	6.2258
K (m^2) . E-17	6.2799					

All results were obtained at the time of a rise in pressure followed by a descent. The final result is an average of each pressure of the calculated permeability. In the large majority of the cases, the average value obtained in the downward phase in the pressure is the same as that measured of the rising phase.

All results of the gas flow (Q_g) can be plotted against pressure variation. Figure 11 is a typical example that confirms the influence of fibre addition on gas permeability in concrete. It can be seen from Figure 11 and from all the data obtained that all curves are very close to being approximately straight lines which indicates correct operation of the equipment and the ability of oxygen to cross the material tested.

5. SUMMARY AND CONCLUSIONS

At 0.5, 1 and 2 percent volume fraction, the effects of steel fibres, with three different lengths, on water and gas permeability of concrete were investigated experimentally. Results of this investigation indicate that high porosity does not mean high permeability. The main factor which governs the permeability is the interconnections interconnectivity.

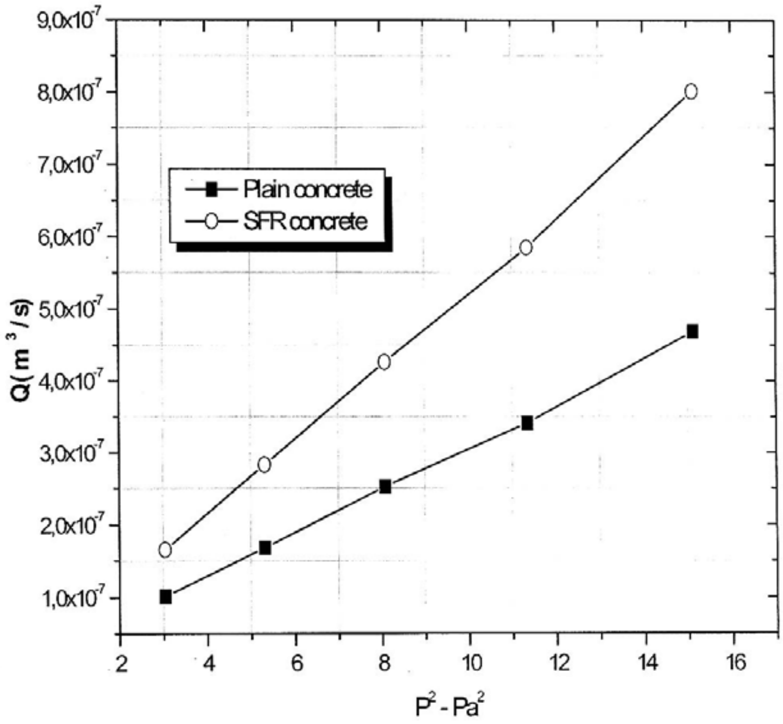

Figure 11. Relationship between gas flow and P^2-Pa^2

The porosity results presented in the paper indicate that steel fibres can reduce porosity. This reduction may have been caused by the vibration duration, which was longer with steel fibres reinforced concrete specimens than in the plain concrete specimens. More tests will be required to confirm our results and to give more details about this point.

Steel fibre addition to concrete clearly increases water permeability coefficient whatever the fibre amount or fibre length. This increase is also observed with gas permeability coefficients. The fibres acted as bridges between pores so that the flow rate was increased and both water and gas permeability coefficients were subsequently increased.

As a conclusion, it is important to mention that with 1 percent of steel fibre content, the water permeability coefficient was $21.87\times10^{-19}m^2$, while the average value of the gas permeability coefficient K_g was 4.0916×10^{-17}. So, concrete permeability coefficients obtained using water and gases were considerably different, due to the phenomenon of gas slippage.

Further studies are recommended to confirm these results and to establish a relationship between porosity and permeability of steel fibre reinforced concrete.

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