permeability of cement based materials is presented in Fig. 6 (19) which shows that the permeability of cement paste, mortar and concrete can be reduced by an order of magnitude, simply by lowering the w/c from 0.70 to 0.50. For a given w/c, mortars and concretes generally have a higher permeability because of the paste aggregate interface which offers a preferential path for water movements in concretes and mortars.

Superplasticizers can be used to produce low w/c concretes or high-performance concretes, that generally have a very low water permeability. Figure 7, presents the water permeability of a group of superplasticized low w/c concretes made with ordinary or blended Portland cements (silica fume and fly ash). The detailed composition of these concretes can be obtained in the original paper (20). For the lowest water/binder ratios (w/b) (≤ 0.33), the permeabilities reach a very low value (< 5 x 10-14 m/s) and, from a practical point of view, it is a general agreement that with that level of permeability, concrete can be considered as impervious to water (6). The results of Figure 7 also show that a very low w/b is not the only way to obtain a highly impervious concrete. When superplasticizers are used in combination with a mineral admixture, such as silica fume or fly ash, the permeability of concrete can be low (< 10×10^{-14} m/s) even for a usual w/b of 0.45. In Figure 7, concretes containing fly ash or silica fume have the lowest permeabilities obtained in the range of 35 MPa to 50 MPa.

A concrete with a low water permeability is generally a more durable concrete because many deterioration processes only take place when external water is available in the mass of concrete. For example, the formation of corrosion products around the reinforcing steels depends on the availability of OH ions which are formed by the electrochemical process between water, oxygen and the electrons liberated by the anodic reaction. The better protection against corrosion of concretes with a low water permeability can also be explained by their lower degree of saturation which increases the electrical resistivity of the electrolyte.

Other types of expansive products in cement paste such as silica gel formed by the alkali-aggregate reactions or ettringite formed by the sulfate-related reactions in concrete contain a very large number of water molecules and their rate of formation is a direct function of the availability of external water. Most of the destruction processes associated with freeze-thaw cycles, and particularly the salt scaling resistance, depend on the saturation level of the cement paste. Pastes with a low permeability usually have a lower saturation level near the surface and a better resistance to salt scaling (16,21). The penetration of aggressive ions such Cl is generally much slower in concretes with a low water permeability since these ions mainly penetrate the concrete through the liquid phase.

Air permeability

Figure 8 shows the relation between air permeability of concrete, the w/c and the length of the curing period (22). As for water permeability, air permeability of low w/c concretes is lower because of the finer and more discontinuous network of capillary pores of the hardened cement paste. The positive effect of a low w/c on the air permeability is particularly noticeable during the first 7 days of the initial moist curing. At 1d and 4d the air permeability is reduced by an order of magnitude when the w/c is lowered from 0.70 to 0.40. Obviously, air permeability is also a function of the length of the curing period. Moist conditions reduce air permeability by sustaining the formation of additional hydration products that fill and divide the capillary pores. It is mainly the first 7 days of curing that produce the most important reduction of the air permeability. It should be pointed out that air permeability is far less sensitive to the length of the curing period for low w/c concretes (w/c = 0.40). This has important practical consequences since air permeability of low w/c concretes should be less affected by unfavorable initial curing conditions.

Compressive strength can be a relatively good indicator of air permeability of concrete because both properties are closely linked to the quality of the paste matrix and of the paste-aggregate interface. Figure 9 presents the relationship between oxygen permeability and compressive strength of a fairly wide group of concretes made with or without complementary cementitious materials (silica fume, fly ash) and with w/b ranging from 0.26 to 0.80. The detailed composition of these concretes can be found in the original paper (23). From these results, concretes with a high compressive strength (or a low w/b) clearly have a much lower oxygen permeability. However, permeability becomes less affected and seems to reach a minimum value for w/b lower than approximately 0.30 or when the compressive strength is higher than about 60 MPa.

Air permeability is a major parameter in the durability of reinforced concrete because it controls the availability of both oxygen and CO_2 in the "covercrete" protecting the reinforcing bars. A low air permeability is beneficial because it should reduce the oxygen supply at the cathode where OH ions are produced and that eventually react to form expansive products. A low air permeability will also reduce the availability of CO_2 and the risk of carbonation, which can accelerate the corrosion process by destroying the protective passive oxide film of steel.

Chloride-ion permeability

Chloride permeability is an important property that governs many aspects of the durability of concrete structures (corrosion of reinforcing steel, deicing salt resistance). The AASHTO 277 procedure *Rapid determination of the chloride permeability of concrete* (24) is one of the most commonly used test method to assess the chloride permeability of concrete. The chloride permeability is estimated by measuring the total charge (in coulomb) passing through a concrete specimen (diam. 95 x 50 mm) maintained under a constant electrical tension of 60V during 6 hours. However, this relatively simple test procedure only gives an estimation of chloride permeability by using an indirect measurement mainly based on the conductivity of concrete. Despite this drawback, the AASHTO 277 test method can provide useful information on the protection of concrete against corrosion of reinforcing steel since it gives a relatively good assessment of the mobility of the chloride ions and of the conductivity of the cement paste (25).

As for the other types of concrete permeabilities, the w/c is a key factor controlling the rapid chloride permeability (Figure 10). This type of permeability measurement is particularly sensitive to low values of w/c (26). As shown in Figure 10, the total charge passed through the specimen is relatively less affected for w/c higher that 0.50, but for lower w/c, the total charge drops rapidly and becomes almost negligible for a w/c of approximately of 0.25. Even if it is always a good practice to maintain favorable curing conditions for the longest possible period to reduce the rapid chloride permeability, it must be pointed out that low w/c concretes (< 0.40) are far less affected by short or unfavorable curing conditions (Figure 10).

A general relationship between rapid chloride permeability and compressive strength is shown in Figure 11, which presents some results obtained with a relatively wide family of concretes made with w/b ranging from 0.25 to 0.45 and with various dosages of mineral admixtures (silica fume and fly ash) (20). The rapid chloride permeability of concretes with a compressive strength of less than 50 MPa is somewhat variable, depending on the w/b ratio and on the dosage of silica fume or fly ash. For that range of compressive strengths, concretes with fly ash or silica fume generally have a lower chloride permeability (20). For high-strength (f'c > 50 MPa), or for low w/b ratio concretes (< 0.33), the total charge after 6 h is generally under 1000 coulomb, which is very low according to the reference scale proposed by Whiting (27). From the results of Figure 11, it appears clearly that the use of a superplasticizer to reduce the w/b ratio will not only produce concrete with a higher compressive strength but will also produce concrete with a significantly lower chloride permeability.

While the rapid permeability test is not a direct measurement of the chloride-ion permeability, it can give valuable information on the corrosion protection of concrete, since the result is a direct function of the electrical conductivity of concrete (25). A concrete with a low rapid chloride permeability should offer a better protection against corrosion because of its low electrical conductivity that limits the corrosion current and the mobility of OH^- and Cl^- in cement paste.

CONCLUSIONS

Superplasticizers offer a simple and economical way of enhancing the general durability of many types of concrete structures. When used as high range water reducer, they allow the production of highly workable concretes with w/c ratios well below the usual value of 0.45. These more dense concretes not only have a much higher compressive strength but they also have a significantly improved durability. Literature data on to the durability of concrete show that, very often, this is the best and most inexpensive way to protect the concrete against any aggressive agents (6). If the strength of the resultant concrete exceeds the design strength, the designer will have to learn how to take advantage of the enhanced strength provided by these concretes of higher performance.

The essence of the better durability of low w/c superplasticizer concretes is their lower and finer capillary porosity. The more discontinuous network of pores produces a cement paste with a very low permeability against almost all types of potentially external aggressive agents (water, oxygen, CO_2, chloride ions). A quick review of the main destruction mechanisms and of the parameters that control the durability of concrete exposed to a severe environment reveal that a lower permeability generally reduces the extent of the destruction processes.

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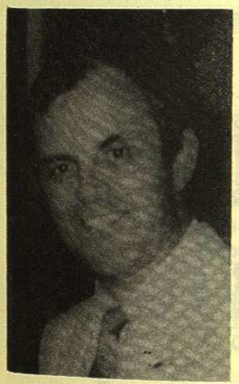

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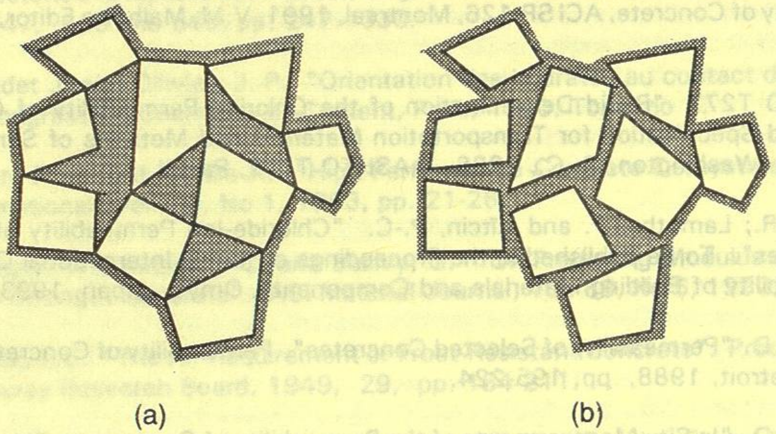

Fig. 1- Schematic representation of a suspension of cement grains in water. (a)-Flocculated state. (b)-Deflocculated state.

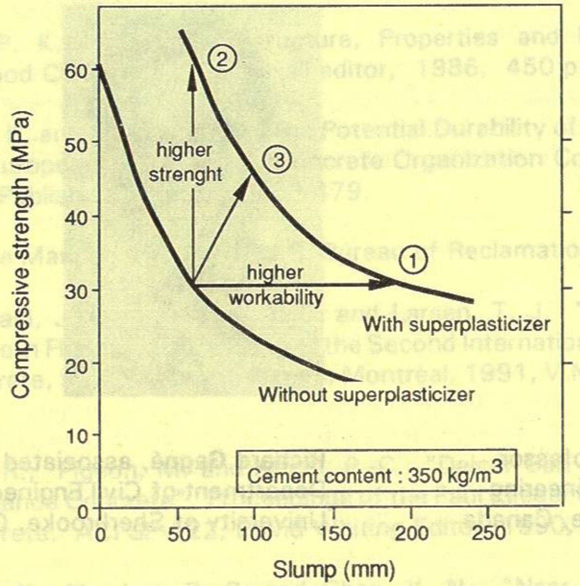

Fig. 2 - Typical effect of a superplasticizer addition on some properties of fresh and hardened concrete.

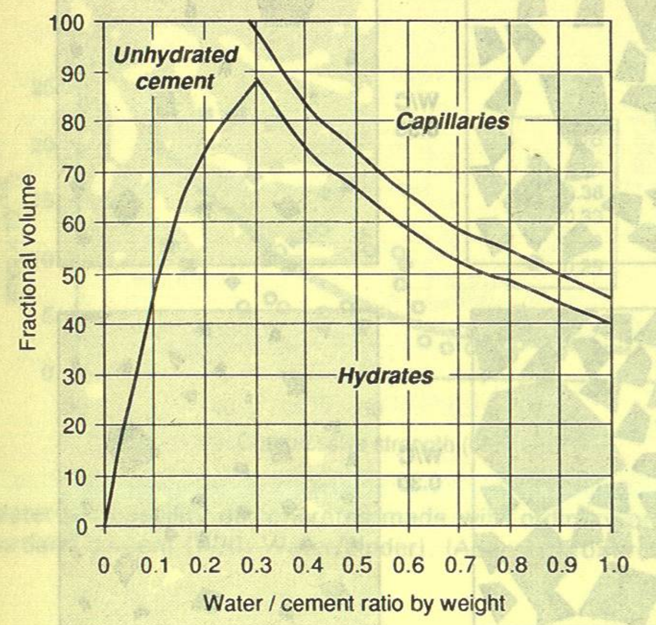

Fig. 3- Theoretical physical composition of a cement paste continuously stored in water (assuming a maturity facto of 8%).

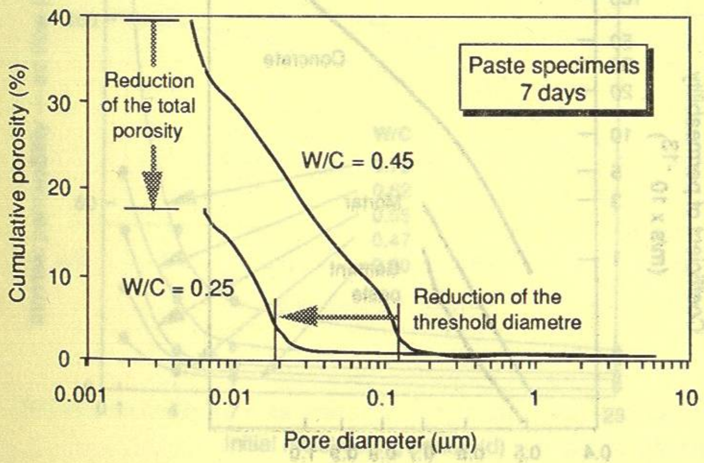

Fig. 4- Mercury intrusion curves of paste specimens after 7 days of curing in water.

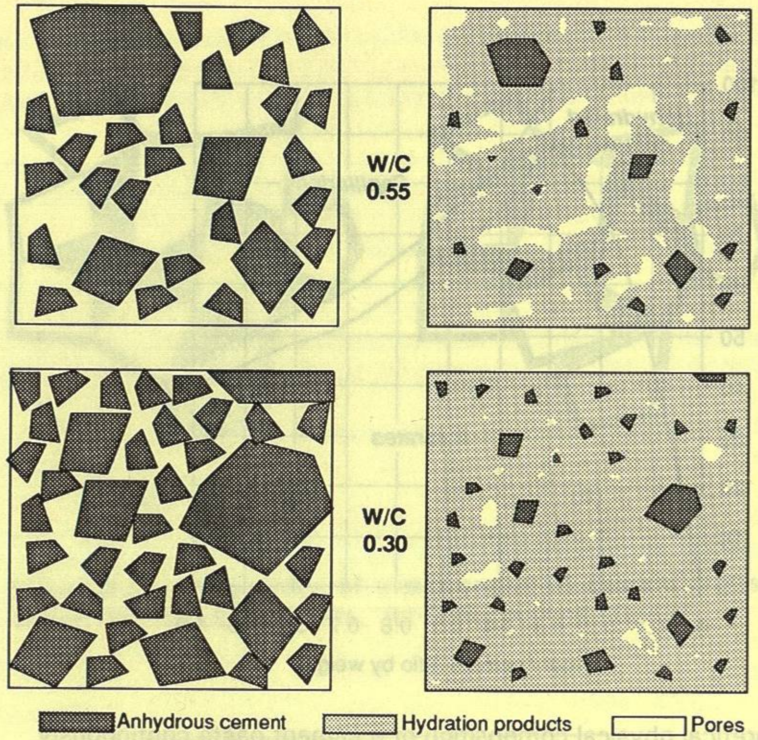

Fig. 5- Schematic representation of the physical composition of two cement pastes with a w/c of 0.55 and 0.30.

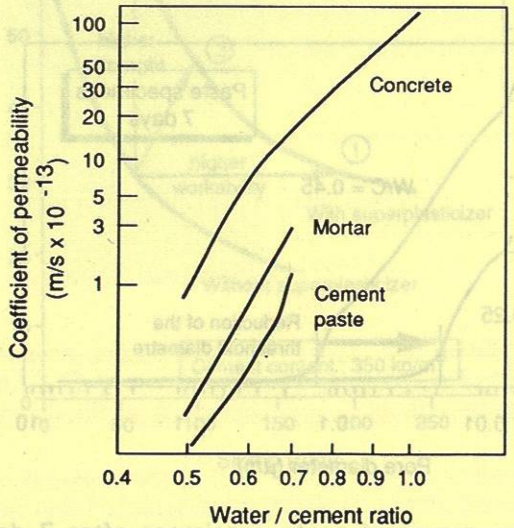

Fig. 6- Water permeability of cement paste, mortar and concrete as a function of w/c. (Adapted from ref. 19).

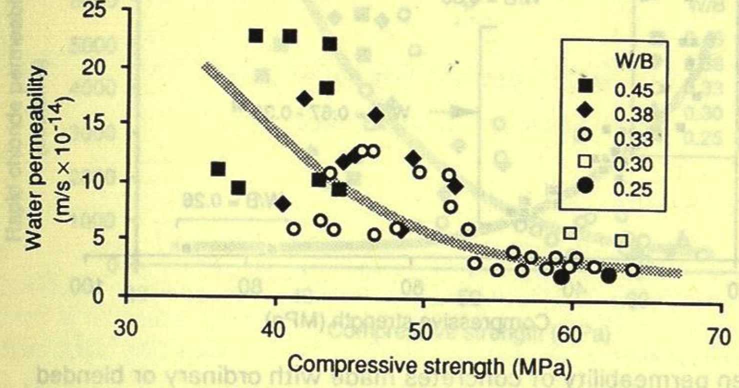

Fig. 7- Water permeability of concretes made with ordinary or blended Portland cement (W/B: Water/Binder). (Adapted from ref. 20).

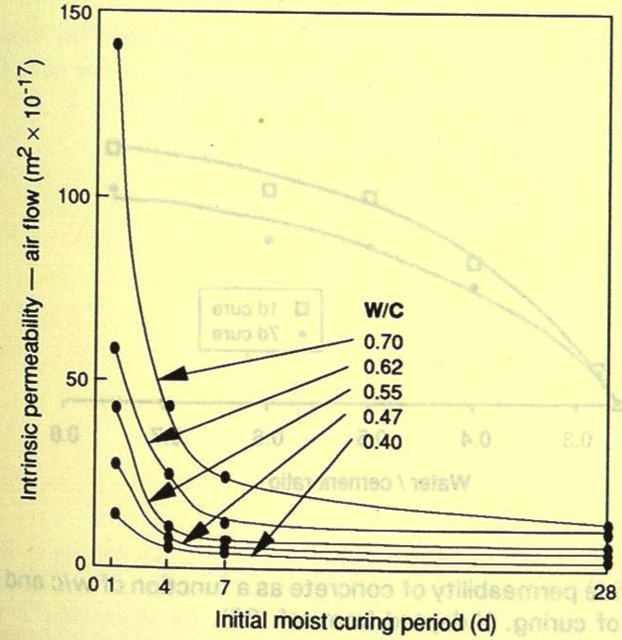

Fig. 8- Intrinsic air permeability of concrete as a function of w/c/ and the length of curing period. (Adapted from ref. 22)

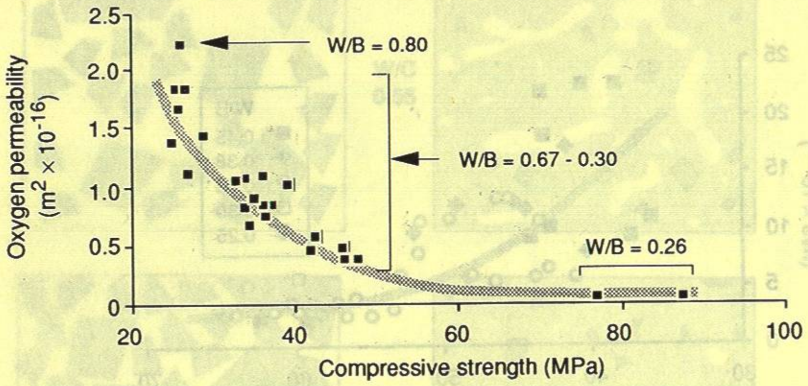

Fig. 9- Oxygen permeability of concretes made with ordinary or blended Portland Cement (W/B: Water/Binder). (Adapted from ref. 23).

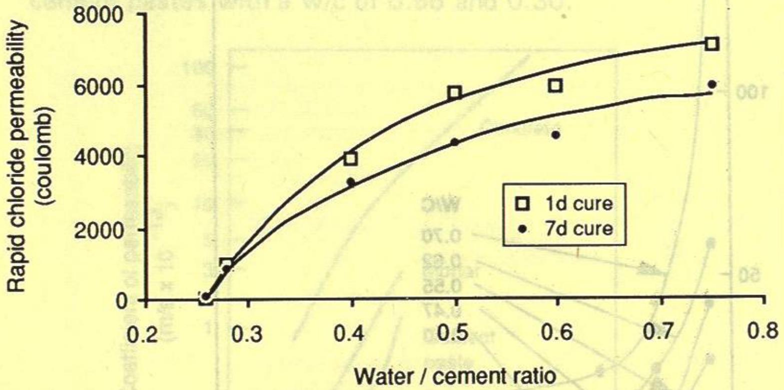

Fig. 10- Rapid chloride permeability of concrete as a function of w/c and the length of curing. (Adapted from ref. 26).

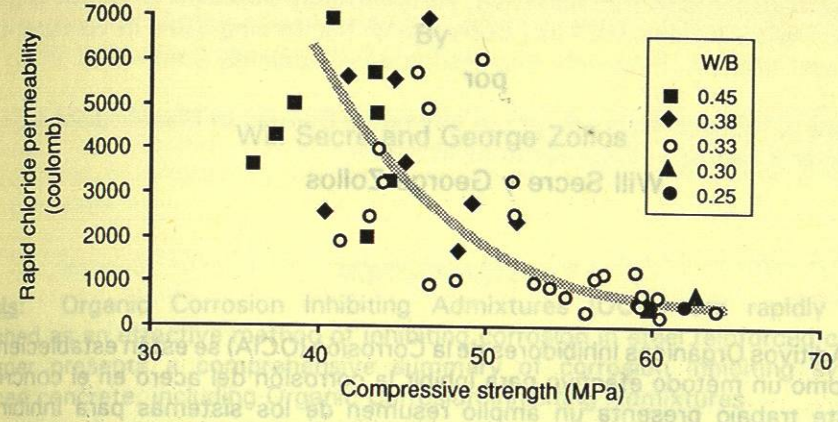

Fig. 11- Rapid chloride permeability of concretes made with ordinary or blended Portland cement (W/B: Water/Blinder). (Adapted from ref. 20).