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Low-Permeability Concrete: Water-to-Cement Ratio Optimization for Designing Drinking Water Reservoirs

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Abstract **–***One of the important debates for designing concrete reservoirs of drinking water is making a concrete with low permeability that has attracted the attention of researchers to determine materials and their ratio to achieve this goal. The ratio of water*-to-*cement due to its impact on strength, durability, and permeability of concrete is one of the key design discussions. In this study, by analyzing the experimental results provided by other researchers in terms of durability, strength, and permeability in concrete, the optimum water*-to-*cement ratio is presented to design concrete reservoirs of drinking water. The water*-to-*cement ratio due to its impact on strength, durability, and permeability of concrete is one of the key design discussions. The fundamental question is what should be the best water*-to-*cement ratio to design low permeability concrete reservoirs for drinking water.*

Keywords*-Concrete Reservoirs for Drinking Water, Permeability, Water*-to-C*ement Ratio, Concrete Strength, Concrete Durability.*

INTRODUCTION

For designing concrete reservoirs for drinking water, maintaining the proper strength of concrete should be concerned in addition to the durability and low permeability of concrete. In other words, concrete should be designed that has both low permeability and good strength. In the fields of strength and permeability, many experiments have been carried out by various researchers on concrete, and it has been determined that each depends on different parameters such as water-to-cement ratio, cement to aggregate ratio, grain size, surface texture, shape, strength, hardness of aggregate particles as well as the maximum aggregate size and permeability of aggregates. In this study, the water-to-cement ratio is considered as a factor that has the greatest impact on the strength and permeability of a fully compressed concrete.

LITERATURE REVIEW

A. *Concrete Strength and Water-to-Cement Ratio*

When ordinary aggregates up to a maximum of 40 mm are used, it can be argued that factors such as the ratio of cement to fine-grained aggregates, surface texture, shape, strength, the hardness of aggregate particles and maximum aggregate size are less important than the water-to-cement ratio [16]. But according to Bloem and walker, the strength of concrete depends on the strength of the mortar, the adhesion of the mortar, and the strength of coarser aggregates. [2]

Some Equations have been presented for the strength of concrete and its relation to the water-to-cement ratio, some of them are as follows: Duff Abroms (1919) stated that there is an inverse relationship between strength and the water-to-cement ratio:

$$f_c = \frac{k_1}{k_2^{\frac{w}{c}}} \quad (1)$$

In this Equation, w/c is the water-to-cement ratio, and k1 and k2 are empirical constant parameters. [9]

Rene Feret (1896) also considered concrete strength to be related to water and cement ratio, and introduced Feret's Law as follows:

$$f_c = k\left(\frac{c}{c+w+a}\right)^2 \quad (2)$$

In this Equation; f_c is the strength of the concrete, c is the volume of the cement, w is the volume of water, a is the volume of air, and k is a constant parameter. [9]

B. Concrete Permeability and Water-to-Cement Ratio

There have been several research works on the permeability of concrete and various Equations have been presented including the Darcy law for determining the penetration coefficient, as well as the Equation for converting penetration depth to permeability coefficient provided by Valenta.

The Darcy Act for porous media and capillary flow in saturated concrete is as follows:

$$\frac{dq}{dt}\frac{1}{A} = \frac{k'\rho g}{\mu}\frac{\Delta h}{L} \quad (3)$$

In this Equation: dq/dt is water flow rate, A is theconcrete cross-sectional area, L is thickness, ρ is fluid density (in concrete for water), μ is the fluid dynamic viscosity coefficient, Δh is hydraulic pressure drop from the sample, and g is gravity acceleration based on the SI metric system. Also, k' is the intrinsic permeability of thematerial in square meters and independent of the type of fluid used [16] because the water is always used for designing reservoirs for drinking water:

$$k = \frac{k'\rho g}{\mu} \quad (4)$$

In this case, k is the permeability coefficient in m/s. However, due to the presence of the viscosity parameter in the above Equation, which changes with temperature, it is assumed that k depends on the temperature of the room, and finally, the following Equation is obtained as the flow equation in a slow and steady state:

$$\frac{dq}{dt}\frac{1}{A} = k\frac{\Delta h}{L} \quad (5)$$

The permeability (k) is easily obtained from this Equation [16]

Valenta also has presented an Equation below to convert the penetration depth to the permeability coefficient in good quality concrete with no flow from this type of concrete, while the water penetrates the concrete to a certain depth: [10]

$$k = \frac{e^2 v}{2ht} \quad (6)$$

In this Equation e is thedepth of penetration in meters, h is a height of water in meters, tisthe time of exposure under pressure in seconds, and v is part of the volume of concrete occupied by pores.

The depth of penetration of the water after blasting the sample and viewing its surface is such that the wet concrete is darker after a given time. If e is less than 50 mm, the concrete is impenetrable. [5] V also shows apart pores in concrete such as air bubbles that are filled with water pressure and can be calculated from the amount of increase in concrete mass during the test. Of course, given that only the pore where water penetrates the area is filled with water. These pores should be considered in calculations, and most often this value is between 0.02 and 0.06. [6] The height of the water with pressure is also in the range of 0.1 to 0.7 MPa. [5]

In the case of permeability tests, it can be stated that they have not yet been standardized [1] and the numbers obtained from different standards vary greatly and are not comparable. These standards include Civil United States Institute with the method of 4913-92 [15], in which the water pressure equivalent to 2.76 MPa equal to 282 meters height of liquid is used, and can Canadian and German methods 1048-1991 DIN [3] can be noted, in which the water pressure to cross the sample is very large and can change the natural state of the concrete.

STRENGTH AND PERMEABILITY TESTS OF CONCRETE

As shown in Figure (1), the strength curve to the water-to-cement ratio is approximately one hyperbolic curve. The use of the ratio of cement to water, due to the hyperbolic property displayed with y=k/x, gives a linear relationship when k is equal to 1.

Which is 1.2 to 2.5 in the range of cement, and this relationship was first proposed by Professor W. [16] and then approved by Alexander and Ivanusec [16] as well as Kakizaki et al. [8]. The researchers believe the use of this linear relationship, especially when interpolation is needed is much simpler than using the water-to-cement curve. In Figure 2, data are shown linearly based on thewater-to-cement ratio.

In Figure. 1, it can be stated that in the part of the diagram where the water-to-cement ratio is low, and the compaction is not completely possible, the curve does not follow the similar trend to the rest of figure. By using better compaction tools, the curve gets closer to the main path. But in general, the Figure shows that the lower the water-to-cement ratio, the strength of concrete increases.

Of course, you should also consider specific cases. For example, in mixtures with a very low water-to-cement ratio and a high amount of cement more than 530 kg/m3 especially when large aggregates are used, the strength usually begins to decrease; therefore, less water-to-cement ratio does not improve the strength. [9]

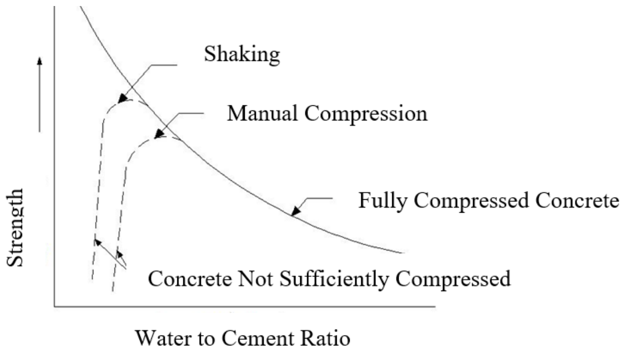

Figure 1 - The Relationship Between the Strength and Water-to-Cement Ratio. [16]

Figure. 2, which is drawn from the cement to water ratio in strength, shows two lines with different slopes. The first line continues to the water-to-cement ratio of 2.6. (Which is equal to water-to-cement ratio of 0.38) In this line, the maximum hydration is usually less 100 %. However, in the second line, when thewater-to-cement ratio is increased to 2.6, usually the maximum hydration reaches 100 %. [7] And the diagram in general shows that the higher water-to-cement ratio, the strength of the concrete also increases. For example, in bridge structures, higher compressive strength can lead to more economical elements, such as fewer beam and pier sizes and therefore lower cost in materials and finally increases the service life of the high bridges [23, 24].

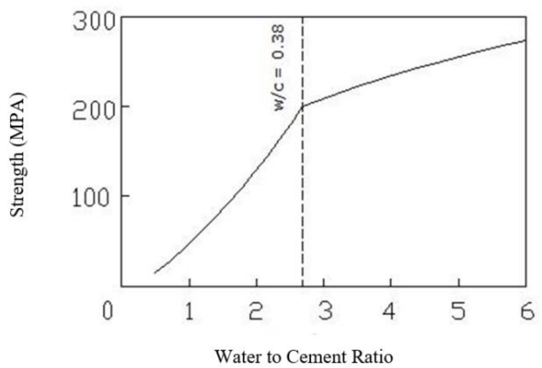

Figure 2 - The Relationship Between Strength of Heat-Curable Dough and Water-to-Cement Ratio with Maximum Hydration Assumption. [16]

Regarding the diagrams and data obtained by other researchers, the most suitable water-to-cement ratio for concrete strength is less than 0.45. However, the use of water-to-cement slightly higher and slightly less than 0.38 is more suitable and common for strength. [16]

The permeability of the concrete depends on several factors, including the distribution, shape, size, and twist of the path,the bonding of the pores, and pre-mature micro-cracks during early hydration. The later was investigated by Assi et al., for cement paste using acoustic emission [17] Despite the high number of pores due to the very fine texture of hardened cement, its permeability is very low, while in aggregates, with a smaller number of pores, permeability is more due to larger pores. [14] As the hydration progresses, the permeability is reduced, so that the cement dough has a permeability by 20 to 100 times that of the gel [14], and the gel gradually occupies some of the initial spaces filled with water. As the hydration progresses, the volume of the gel increases and does not nearly equal to ½ times the amount of non-hydrated cement. In the case of the effective parameter for permeability, it can be stated that size and concentration of the initial grains of the cement are effective in the fresh dough. But in the maturated dough, shape, size, the concentration of the gel and sinusoidal or continuous capillary tubes are effective. [12]

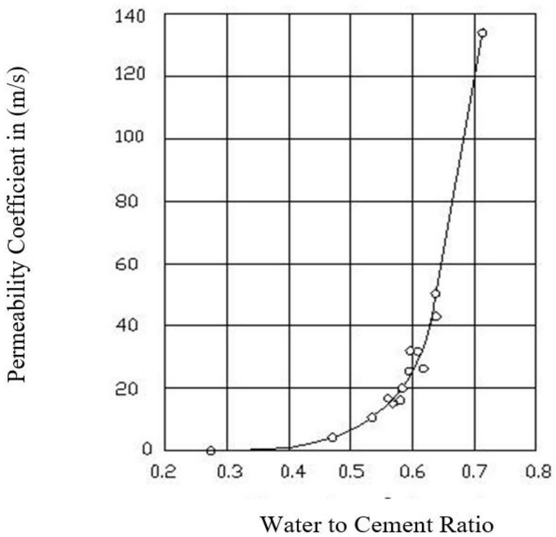

Figure 3 - The Relationship Between Permeability and Water-to-Cement Ratio for Cement Dough with Hydration of 93%. [13]

Powers et al. (1954), in a test on concrete with a water-to-cement ratio of 0.7, showed that the longer the concrete's dough lasted, its permeability decreased, which could be due to increased gel volume and closure of capillary tubes. [13] Bonzel (1966) also stated that the lower the water-to-cement ratio, the lower the permeability would occur more quickly, for example, if the specific permeability for the water-to-cement ratio was 0.6 is 28 days and for the water-to-cement ratio of 0.45 is 7 days; i.e. 0.75 times faster [5]. If the hydration rate is equal in the different dough, the dough with less water to ratio has less permeability. [13]

As shown in the diagram above, this curve has two different parts: the first part indicates water-to-cement ratio to 0.6 and the next part water-to-cement ratio above 0.6. In the first part, the slope of the curve is mild, but in the second part, the slope is steep, so that by decreasing the water-to-cement ratio from 0.7 to 0.3, the permeability coefficient decreases by 3 times.

Whiting (1988) stated that reducing the water-to-cement ratio from 0.75 to 0.26 reduces the permeability coefficient by 4 times and reducing the water-to-cement ratio from 0.75 to 0.45 reduces the permeability coefficient by 2 times. He introduced the permeability coefficient of $10^{10} m/s$ for a water-to-cement ratio of 0.75 as a highly permeable concrete, he also stated that for water-to-cement ratio of 45 % indicates a permeability coefficient of 10-11 to 10-12and showed a low Permeability concrete [2]

In the above curve, it is clear that in the water-to-cement ratio less than 0.4, the capillary tubes are discontinued, but with increasing this ratio, this incidence is less, and the permeability is significantly increased. Other factors also affect the level of permeability, including the increasing the curing time of wet concrete for ratio; if this time is extended from 1 day to 7 days, water-to-cement permeability decreases by 5 times. [2] Another factor that is effective in this field is the type of cement and the type of aggregate. Powers' research (1954) shows that the constant water-to-cement ratio, paste or fine-grained cement produces a much lower permeability than paste or coarse cement [13].

Also, the use of low permeability aggregates is for making a surface with a low permeability against the water and force the water to bypass the aggregates in a longer path that has a good effect on reducing the permeability. But it should also be reminded that hardened cement paste has the greatest impact on the permeability of concrete [14]. Regarding the discussions mentioned earlier, it can be stated that water-to-cement ratio in the range of less than 0.4 is a reasonable permeability.

The permeability of concrete is of great significant for other construction types. For instance, in timber construction, recently cross-laminated timber panels have gained attention as timber panel product that is suitable for floor application [18,19]. In this product, a concrete topping is used to improve the performance of timber floors and they are transferring the load through out-of-plane load carrying [18, 19] connected to the rest of construction using metal connections [20, 21]. Low-Permeability Concrete can be used for repair of in-service timber pile bridge decks and precast components once it increases thedurability of concrete decks [28, 29, 30]. In concrete and steel structures, which are exposed to high humidity and corrosive condition, using low-permeable concrete in frame elements and floors leads to more durability of structure and retains theintegrity of concrete diaphragm and frame elements against lateral load such as earthquake [22, 23, 24]. On the other hand, the permeability of concrete is an important factor in thedesign of concrete dams. The water in the dam reservoir tends to cross through the dam body as well as the foundation of the dam through the soil underneath [25, 26, 27]. In these cases, and many other cases of application of concrete, having a good design mix with appropriate water-to-cement ration is of great reliance.

CONCLUSION

According to the results presented for the strength and permeability of concrete, water-to-cement ratio in the range of 0.35 to 0.4 is suitable for the design of concrete reservoirs of drinking water. However, if full hydration is considered, the best water-to-cement ratio is from 0.38 to 0.4. As the water-to-cement ratio increases to more than 0.4, the permeability rate increases sharply and by decreasing the water-to-cement ratio less than 0.35%, hydration percentage decreases.

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