Factors Affecting the Permeability of Roller Compacted Concretes

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Abstract

Nowadays, the roller compacted concrete (RCC), as a new material in dam construction industry, has been seriously attracted the dam constructing companies and great research institutes. One of the main problems of this material is its permeability, which requires heavily injection after completing the construction in great dams, or application of less permeable concrete in upstream and downstream faces. In the mix design of this concrete, for decreasing the voids and secondary reactions, other non-cohesive materials can be used. In this research, permeability and its control, in the concrete dam body and in the joints, have been investigated. The experimental works, carried out, on RCC specimens with different mix designs, and addition of different percentages of pozzolans. Test results show that, by increasing the specific gravity and compressive strength of the concrete mixtures, the permeability decreases and also application of pozzolans in concrete will lead to less permeability in RCC dams.

Keywords: Roller Compacted Concrete (RCC), Mix design, Pozzolan, Permeability

1. Introduction

Dam construction with RCC method is a new technology which has been developed during recent years and has been transferred from developed countries to the developing countries. The main reason of this development is economic considerations, application of local materials and its great construction rate. RCC transportation, placing, and compacting is similar to the earthfill dams, and also will gain the properties of hardened concrete. Normal aggregate, cement & pozzolans are used in its mix. Increasing the use of pozzolans in such concrete influences its long term properties and its durability. Application of RCC in dam construction leads to higher permeability problems and this has to be taken into account design procedure [1].

As cementitious materials are not able to fill all the voids between materials, some voids are always remained in concrete. In some cases, for more workability it is necessary to add water to the mix, which in more than that needed for hydration. This leads to formation of more voids in the mix. Its mechanism is related to water-cement reactions, which by completion of these reactions, their absolute volume becomes less. This is the reason that the cement mixture with any water ratio couldn't fill all the material voids.

So, there would be some voids in the concrete after hardening the cement mixture, and also there would be some air voids, which has been confined during mixing.

The voids in the concrete are related to each other by water, therefore the concrete is naturally permeable. As a result of this and, under severe pressure, water can penetrate into concrete. The absorption, seepage and penetration of water, and specially other harmful liquids, reduces the durability of concrete. Application of appropriate materials, sufficient compaction, and good curing, low permeable concrete can be achieved. It should be noted that the some voids are produced during hardening period, and evaporation of water creates capillary pores in the concrete body. On the other hand, hydration of cement can fill the pores by cement gel and decrease the permeability of concrete. However, it should be noted that all voids will not be filled entirely. Impermeability should be considered more importantly than the compressive strength of the concrete in hydraulic structures. These structures should be protected against penetration of liquids. This is necessary to avoid freezing of water in these voids, and remaining the sedimented salts in the voids.

2. Permeability of Concrete

Water permeability tests are carried out by two methods: "water penetration" and "water discharge". In each test, cylindrical specimens are used. At first, the specimen is placed on a steel cell and both sides are tightly closed. Then under-pressure water is applied to the specimen by a vertical pipe, which a gauge and an air-compressor are attached to it. The penetrated water is measured by the attached gauge. In the second method, i.e. water discharge method, it is necessary to avoid evaporation. It should be noted that in this method, at first, because of the absorption, outlet water is less than inlet water, but finally these two values should become equal. Under-pressure water easily absorbs air, and then releases this air in the concrete specimen, therefore its pressure deceased. In other words, the water flow in the specimen reduces; as a result, reasonable solutions should be found for preventing air-release in the specimen. The results show that the seepage discharge can be obtained by Darcy's equation:

$$\frac{Q}{A} = K_c \frac{H}{L} \tag{1}$$

Where:

Q: Seepage discharge (cubic meter per second)
A: Cross sectional of specimen (square meter)
$\frac{H}{L}$: Head pressure to the length of the specimen
K_c: Concrete permeability coefficient.

3. Effective factors on concrete seepage

One of the main problems of RCC dams is the seepage in such structures, which has been discussed widely during the construction of willow-Creek dam.

Considering seepage in dams makes it clear that seepage is a common problem in such structures and almost all of them are facing it. Therefore, the RCC dams are not excepted of this rule, too. The measured seepage in such dams is in the range of 0 - 170 lit/ sec.

The seepage problem in RCC dams caused by the following sources:

1) Foundation
2) Joint between layers
3) Concrete permeability
4) Thermal cracks

3-1. Foundation

This problem has no relation with dam type. In fact, it is similar in RCC dams and other concrete dams. It can be controlled by injection and drainage methods.

3-2. Joint between layers

A large amount of seepage through dam body is through the joint between two adjacent concrete layers. In RCC dams, concrete is transported to the construction site by special equipment, distributed by bulldozers, and compacted by rollers. In the middle of each layer, stoppage the construction operation causes seepage problem through them. One of the reasons for this problem is the segregation of aggregates in the layers, which causes uncontiniouty of the layers and therefore formation of weak zones in the RCC body. It should be noted that segregation in RCC dams is a serious problem, therefore it is necessary to think about special considerations, like type of aggregates, the cement content, transportation system, and so on, to avoid it. Another reason for seepage is the long period of concrete hardening or the long period between the construction of the two layers, creates cold joints, due to loss of water, and atmospheric influence like temperature and wind. Therefore, it will create week layers in the dam body.
Decreasing of construction joints, by increasing thickness of each layer, causes less permeability of the layers. As an instance, if instead of 15 cm layers, 30 cm layers are used, the number of joints is reduced to half, and the seepage water volume through the layers is also reduced.

3-3. Permeability

Permeability is one of the main problems in RCC dams. It is related to parameters, such as Particle – size distribution, percentage of fine aggregate, degree of compaction, etc. Thus, if a RCC concrete with appropriate particles is mixed, placed, and compacted, it will result in less permeability than normal concrete.
Test results on different specimens, show that the permeability of concrete varies between 0.3048×10^{-10} - 0.3048×10^{-8} m/sec. Investigation by Peker showed that the RCC permeability varies between 0.3048×10^{-8} - 0.3048×10^{-4} m/sec.

3-4. Thermal cracks

These cracks have been found in two dams, Galesville and Copperfield, and have caused serious problem. Although it is difficult to determine the percentage of seepage water, but it obviously results in large amount of seepage through the dam. The main reasons for these cracks are tensile stresses in the dam body as a result of concrete shrinkage and also stress concentration, because of nonhomogeneous shape of the valley and the foundation of dam. Potential causes of these cracks are the same in all of dams, and the differences between dams are because of site temperature during the construction, changes in climate, strength parameters, deflection of RCC dams, and the shape of cross section of the dam.

4. Experimental program

4-1. RCC Materials

The materials used in this study were aggregates (gravel and sand), cement, pozzolans(Jajrood trass), and water.
Gravel: Crushed gravel with maximum size of 20 mm, in accordance with British standard (B.S. 882) was used. The results of particle-size distribution are shown in Table 1-a:

Table 1-a: particle-size distribution of coarse aggregate

Sieve No.(inch)	1	3:4	1:2	3:8	3:16	pan
Mass retained(g)	0	250	1030	1580	2080	60
Mass passing(g)	5000	4750	3720	2140	60	-
Percentage passing	100	95	74.4	42.8	0.5	-

Sand: Natural sand with the particle size distribution shown in Table 1-b was used.

Table 1-b: particle-size distribution of fine aggregate

Sieve size(mm)	9.5	4.75	2.36	1.18	#600	#300	#150	pan
Mass retained(g)	0	256	563	708	261	142	30	40
Mass passing(g)	2000	1744	1181	473	212	70	40	-
Percentage passing	100	87.2	59	23.65	10.6	3.5	2.0	-

Cement: Type II Portland cement from Abyec Co. was used throughout this investigation. Chemical analysis of the cement is presented in Table 2.

Table 2: chemical properties of type II cement

composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Loss of ignition	Eq. Na_2O	C_3S	C_2S	C_3A	C_4AF	Free CaO
percentage	20.1	5	3.10	61.4	2.7	0.3	0.8	17	3.9	0.83	54	17	8	9	-
standard limit	Min 20	Max 6	Max 6	-	Max 6	-	-	Max 3	Max 3	-	-	-	Max 8	-	-

Pozzolans: for replacing a part of cement with pozzolans, Jajrood Trass was used. Chemical analysis of trass is shown in Table 3. Jajrood trass is one of natural Pozzolans of Iran and is made from volcanic tuff. Generally, tuff is one of pyroclastic stones, which has been preformed from volcanic minerals. Jajrood trass is a green tuff which is obtained from Damavand Mountain's mines.

Pozzolans are very useful materials for mass concrete and can control and reduce the heat of hydration. The replacement level of pozzolans with cement should be clearly determined. The density of pozzolans are usually lower than cement, so their replacement by mass will increase the volume of total cementitious materials.

Table 3: chemical properties of trass pozzolan

composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	SO_3	Loss of ignition
percentage	76.80	12.87	1.11	2.63	1.23	0.96	2.03	0.11	-	2.00

Water: Tehran tap water was used in this test program.

4-2. Test Procedures

Crushed coarse aggregate was used in all RCC concrete mixtures. 15 cm concrete cubes were prepared for permeability and compressive strength tests. Some specimens were tested along the joints while some others kept for permeability testing perpendicular to the direction of joints, A few 10x10 cylindrical specimens were made for permeability testing with special permeameter.

In these tests, as mentioned before, the particle size distribution was in accordance with BS 882 standard, and moisture percent and cement content was chosen based on previous test results [22].

According to previous results, the optimum content of pozzolan was 20% of the weight of the cement, and the optimum moisture was 9% of the total weight of the aggregates and cement. The water/cement ratio was 1.2, and specific gravity of concrete, with optimum moisture was 2300 kg/m^3. Sand to total aggregate ratio by weight was kept at 0.5 [22].

The mix design for one cubic meter of concrete is presented in Table 4. Six series of mixtures, with cement contents of 75, 100, 120, 130, 140, 150, kg/m^3, was made. In the second group, the pozzolanic effect was considered. These six series of mixtures was made at the same cementitious material content with 20% replaced with pozzolan.
Half of the molds were filled with RCC concrete and compacted. Then they were cured and kept in 17 °C for 8 hours. After that, the second half was poured. Therefore, the joints' hardening degree (i.e. product of the temperature and the time) was about 136 centigrade hour.
The normal range of hardening-degree is 120-460 °C-hr. Therefore, by choosing the above range, there is no need to adjust continuity of layers, by special equipments and materials.

Table 4: Mix properties of materials (Kg/m^3)

Mix No.	Weight of materials				
	Water	Aggregate		Cementitious materials	
		Fine	Coarse	Pozzolan	Cement
1	90	1067.5	1067.5	-	75
2	120	1040	1040	-	100
3	144	1018	1018	-	120
4	156	1007	1007	-	130
5	168	996	996	-	140
6	180	985	985	-	150
7	90	1067.5	1067.5	15	60
8	120	1040	1040	20	80
9	144	1018	1018	24	96
10	156	1007	1007	26	104
11	168	996	996	28	112
12	180	985	985	30	120

4-3. Gas Permeability Test

For this test, the gas permeameter manufactured in the department was used. Permeability is measured by gas transmitting through the specimen and measuring the output flow. The necessary parameters for calculating the permeability of concrete specimens are:

n: Transmitted air discharge, in $\frac{cm^3}{\sec}$,
P_1: Air pressure on the specimen, in bars,
P_2: Laboratory pressure (usually considered as to 1 bar),
L: Length of specimens, in meter,
A: Cross sectional area of each specimen, in square meters,
Using above mentioned parameters, permeability coefficient of concrete specimens is obtained from equation (2):

$$K = \frac{2 \times P_2 \times \upsilon \times L \times 2.02 \times 10^{-10}}{A \times (P_1^2 - P_2^2)} \qquad (2)$$

The gas permeameter was used to determine the water permeability through concrete. Cylindrical specimens were used for this test. After 42 days of curing, the specimens were kept in oven for 48 hours. For applying uniaxial test on them, their sides must be isolated by paraphines.

5. Results and Discussions

Test results of RCC specimens, with different cement contents, are presented in Tables 5, 6 & 7 and Figures 1-4:

Table 5: The permeability results of RCC specimens

TYPE OF TEST		permeability results					
Permeability variation along the direction of joint **(with pozzolan)**	Cementitious materials Content (Kg/m^3)	75	100	120	130	140	150
	Water discharge x10^{-7} (m^3/s)	52	31.1	17.5	12.8	8.07	6.40
	Permeability coefficient x10^{-7} K(m/s)	10.8	6.48	3.6	2.67	1.81	1.33
Permeability variation along the direction of concrete placement **(with pozzolan)**	Cementitious materials Content (Kg/m^3)	75	100	120	130	140	150
	Water discharge x10^{-7} (m^3/s)	68.3	6.20	8.40	4.73	3.67	2.50
	Permeability coefficientx10^{-8} K(m/s)	14.2	12.8	11.3	9.86	7.64	5.21
Permeability variation along the direction of joint **(without pozzolan)**	Cementitious materials Content (Kg/m^3)	75	100	120	130	140	150
	Water discharge x10^{-6} (m^3/s)	64.0	20.0	8.31	4.91	4.21	2.81
	Permeability coefficientx10^{-6} K(m/s)	133	41.7	17.3	10.2	8.77	5.85
Permeability variation along the direction of concrete placement **(without pozzolan)**	Cementitious materials Content (Kg/m^3)	75	100	120	130	140	150
	Water discharge x10^{-6} (m^3/s)	82.0	78.8	56.6	34.6	17.5	6.60
	Permeability coefficientx10^{-6} K(m/s)	17.0	16.4	11.8	7.20	3.64	1.8

Table 6: The compressive strength results of RCC specimens (without pozzolan)

Mix. No.	Permeability coefficient X10^{-5} (m/s)	Compressive Strength (Kg/cm^2)	Gravel To sand ratio	Cement content (Kg/m^3)	Dry density (Kg/m^3)	Optimum moisture content (%)	Wet density (Kg/m^3)
1-75	1.7	56.1	1	75	2095	9	2284
1-100	1.64	80.2	1	100	2139	9	2331
1-120	1.18	106.4	1	120	2158	9	2352
1-130	0.72	135.2	1	130	2178	9	2374
1-140	0.634	165.2	1	140	2215	9	2385
1-150	0.18	170.4	1	150	2240	9	2402

Table 7: The compressive strength results of RCC specimens (with pozzolan)

Mix No.	permeability coefficient X10^{-7} (m/s)	Compressive Strength (Kg/cm^2)	Gravel To sand ratio	Pozzolan content (Kg/m^3)	Cement content (Kg/m^3)	Dry density (Kg/m^3)	Optimum moisture content (%)	Wet density (Kg/m^3)
2-75	1.42	51.1	1	15	60	2065	9	2251
2-100	1.29	72.3	1	20	80	2095	9	2284
2-120	1.13	94.4	1	24	96	2130	9	2322
2-130	0.986	114.6	1	26	104	2156	9	2350
2-140	0.764	146.0	1	28	112	2203	9	2401
2-150	0.521	158.6	1	30	120	2220	9	2420

It can be see that:

By increasing the cement content, the permeability coefficient and the passing discharge of concrete specimens decrease.

Figure 1 shows that the increase of 10 Kg/m^3 cement in the mixtures will lead to 30% reduction in the permeability. However, the increment of 10 Kg/m^3 cementitious materials has resulted in 50% reduction in permeability.

Figure 2 depicted that the increase of cement content or cementitious materials content by 10 kg/m^3, will lead to approximately 30% decrease of permeability along the direction of joints in concrete mixtures.

The addition of pozzolan has a great influence on the permeability of concrete mixtures, this is clearly shown in Figure 3 and 4.

As expected the addition of cementitious materials will improve the compressive strength of concrete mixtures. More results are needed to correlate the permeability of concrete to their compressive strength.

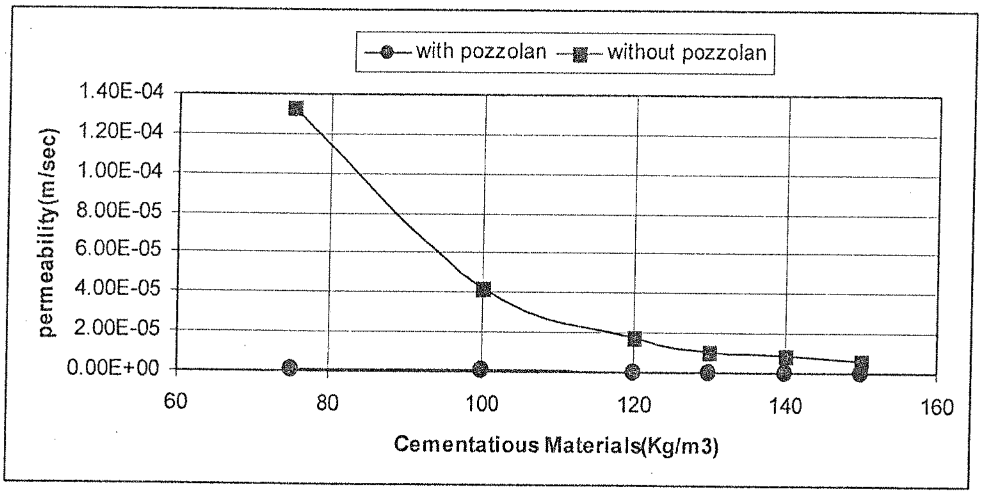

Fig.1- Permeability variation along the direction of joint

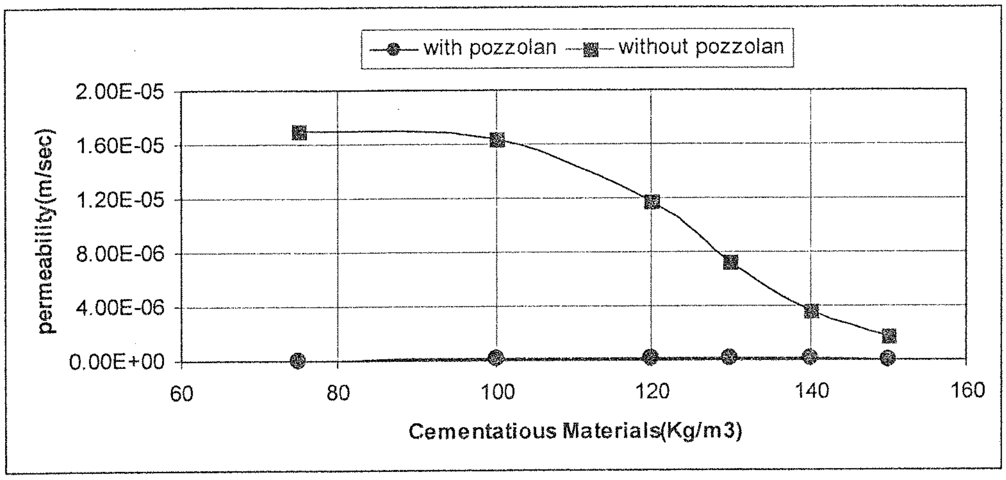

Fig.2- Permeability variation along the direction of concrete placement

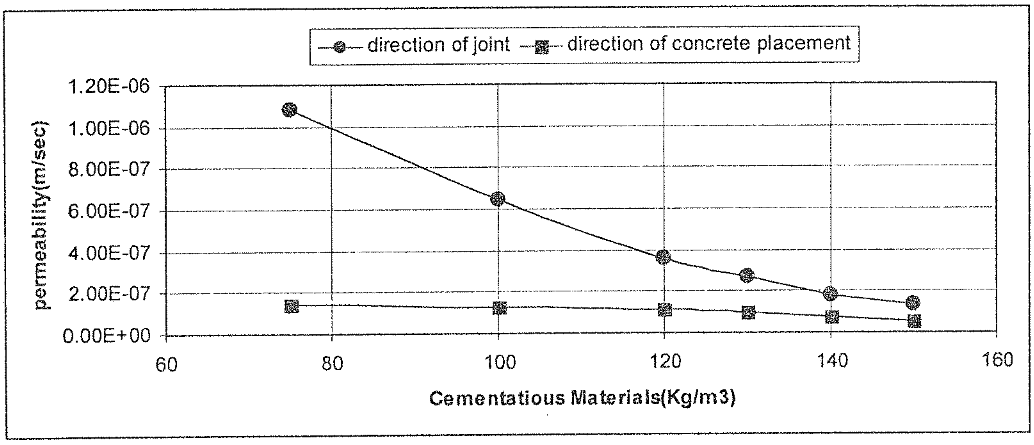

Fig.3- Permeability variation along the direction of joint and concrete placement (with pozzolan)

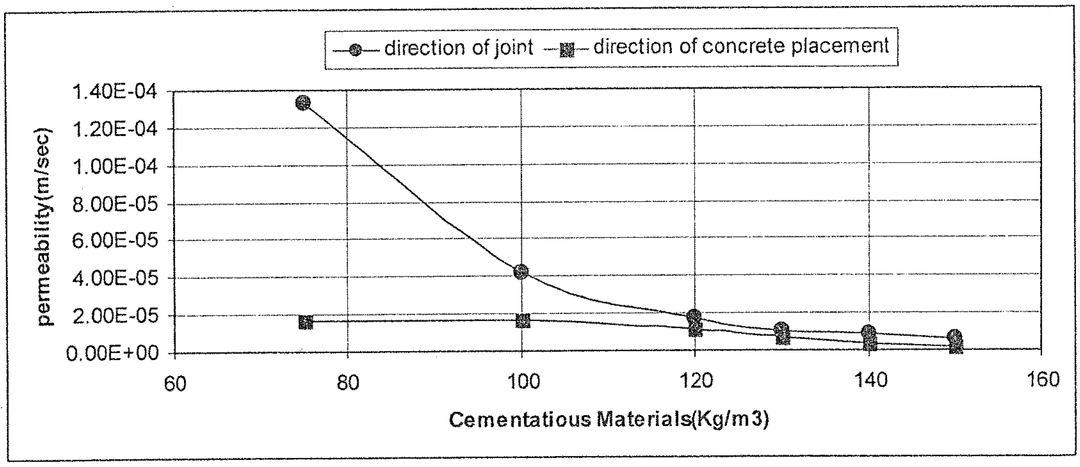

Fig.4- Permeability variation along the direction of joint and concrete placement (without pozzolan)

6. Conclusions

From the results obtained in this investigation, the following conclusions can be drawn:

1) Increasing the cement content will lead to decreasing permeability.
2) Permeability along the direction of joints is more than permeability through the direction of concrete placement.
3) The addition of pozzolans can decrease the permeability significantly.
4) Increasing specific gravity and compressive strength will decrease permeability of concrete.
5) It must be noted that during construction of RCC layers, increasing the layers thickness and these decreasing the number of joints reduce the permeability of concrete.

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