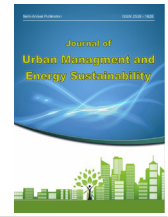
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CASE STUDY RESEARCH PAPER

Analysis of the Relationship between Water Absorption, Permeable Voids and Permeability in Roller-Compacted Concrete and Its Effect on the Watertightness of Horizontal Joints

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ABSTRACT

Roller-compacted concrete (RCC) is widely used in dams because it can be placed rapidly, but its layer-by-layer placement creates horizontal joints that may become preferential seepage paths. How the pore-related properties of RCC relate to its permeability, and how bedding-mortar quality and placement interval govern joint watertightness, is rarely examined together. This study investigated the relationships among water absorption, permeable voids, sorptivity and the water permeability coefficient of RCC and of horizontal joints. Thirty mixtures combined three concrete cement contents, three bedding-mortar cement contents and three placement intervals, after 90 days of water curing. Absorption and permeable voids were measured according to ASTM C642, sorptivity according to ASTM C1585, and permeability under 1–5 bar water pressure using Darcy's law at steady flow. Raising the cement content from 120 to 200 kg/m³ reduced final water absorption from 4.5% to 2.8% and lowered the permeability of unjointed concrete, and higher permeable-void content was accompanied by higher absorption. The richest mortar reduced joint permeability by 41–85% relative to the leanest one, yet jointed specimens remained more permeable than monolithic concrete. Permeability increased with placement interval, most sharply between 12 and 48 h. The sorptivity index correlated strongly with the permeability coefficient. Joint watertightness in RCC dams therefore depends jointly on pore structure, bedding-mortar richness and placement interval, and sorptivity is a simple screening indicator of joint permeability.

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INTRODUCTION

Roller-compacted concrete (RCC) dams, as a type of gravity dam, have attracted attention in large dam-construction projects because of their high speed of construction, lower cost and suitable mechanical properties. This type of concrete is placed in numerous layers using mechanical compaction and requires no conventional formwork. Proper compaction of RCC produces a dense structure and reduces porosity, and can therefore directly affect its durability and permeability (Tajdini et al., 2024). Alongside the desirable properties of RCC, the conditions of its layered placement are particularly important. Placing concrete in successive layers forms horizontal surfaces at the junctions between layers. These zones may differ structurally and functionally from the concrete mass and act as potential paths for the passage of water. Controlling permeability at horizontal joints is therefore one of the important issues in the performance of RCC dams.

One of the factors affecting the behaviour of concrete against water is its pore structure. The amount of porosity and voids in concrete can affect water absorption and the path of water movement inside the concrete. Reducing the water-to-cement ratio and increasing compaction are factors that play a role in the structure of concrete and its permeability. The type of materials, the cement content and the conditions of layer placement can also affect the physical properties of concrete (Rostami et al., 2023). In RCC, the use of less water and mechanical compaction reduces porosity and increases density. However, controlling compaction and the quality of layer placement is very important, because insufficient compaction can create undesirable porosity and increase permeability. Proper selection of materials and control of the construction process are important factors in achieving concrete with low permeability (Farnam & Nouri, 2015; Tajdini et al., 2024). On the other hand, water penetration in RCC dams is not limited to the concrete mass, and the junction zones between layers must also be considered. The presence of horizontal joints and differences in the condition of the contact surface between two layers can create a zone with properties different from those of the concrete mass. In such conditions, the use of bedding mortar, by improving the bond between two layers, can affect the performance of the joint and its permeability. The water-to-cement ratio is also an important factor in the behaviour of concrete against water penetration; reducing this ratio usually increases density and reduces permeability (Akhoundi et al., 2021). The use of pozzolanic materials and suitable admixtures can also be effective in improving the structure of concrete and reducing permeability (Aboubakr Mohammad, 2017). Given the importance of water penetration for the performance of hydraulic structures, simultaneous examination of water absorption, permeable voids and the permeability coefficient can provide a more accurate understanding of the behaviour of RCC against water. Sorptivity can also provide information on the entry of water into the pore structure of concrete. The aim of this research is to investigate the relationship between water absorption, permeable voids, sorptivity and the permeability coefficient of RCC and to examine the effect of these properties on the watertightness of horizontal joints.

MATERIALS AND METHODS

Roller-compacted concrete and its dense structure

Roller-compacted concrete (RCC) is one of the methods used in the construction of concrete dams and has attracted attention in large dam projects because of its high speed of placement, lower construction costs and the possibility of compaction with roller equipment. After being spread in relatively thin layers, this concrete is compacted with roller equipment; therefore, in addition to the composition of the materials, the quality of compaction and the conditions of layer placement also play a role in forming its final structure. Reducing the water content, proper compaction and correct selection of materials have been identified as factors in achieving a

dense structure and reducing the permeability of RCC (Droz et al., 2023; Farnam & Nouri, 2015; Tajdini et al., 2024). Since RCC in dams is in direct contact with water and subject to hydraulic pressure, controlling the paths of water entry and passage in its structure is particularly important. Insufficient compaction can leave voids and porous zones in the concrete, and if these spaces are interconnected they create paths for water transport. In contrast, proper compaction, by increasing density and reducing void space, can limit the permeability of concrete (Farnam & Nouri, 2015; Tajdini et al., 2024). Hence, the internal structure of RCC and its water-transport properties are regarded as important indicators for evaluating the performance of this type of concrete in hydraulic structures (Ali & Abbas, 2022; Sarsam et al., 2014).

Porosity, permeable voids and water absorption

The pore structure of concrete is one of the factors affecting its behaviour against the entry and transport of water. In RCC, this structure is influenced not only by the properties of the materials but also by the proportions of the mixture and the degree of compaction. The water-to-cement ratio, the cement content, the selection of aggregates and the use of pozzolanic materials are among the factors that can affect the internal structure of concrete and hence its durability and permeability (Aboubakr Mohammad, 2017; Akhoundi et al., 2021). The use of less water and proper compaction have also been associated with higher density and lower permeability (Droz et al., 2023; Tajdini et al., 2024). Among the voids in concrete, those accessible to water are particularly important. The percentage of permeable voids represents the part of the void space that water can access and, in this respect, can be used as an indicator of the state of the porous structure of concrete. An increase in the space accessible to water can increase the capacity of the concrete structure to take up and retain water; therefore, examining permeable voids together with water absorption can provide more information on the behaviour of concrete against moisture penetration. Water absorption is also an indicator related to the pore structure of concrete and shows the amount of water entering the pores near the surface. The characteristics of the mix design and the degree of compaction can affect water absorption, and for this reason the simultaneous use of water absorption and permeable voids makes it possible to examine the relationship between the space accessible to water and the absorption behaviour of concrete. Studies on RCC have also identified control of the mixture composition, the water-to-cementitious materials ratio and compaction conditions as factors affecting the physical properties and durability of concrete (Aboubakr Mohammad, 2017; Ettaghaei et al., 2023; Tajdini et al., 2024).

Permeability of RCC and water-transport indicators

Permeability expresses the ability of a fluid to pass through the porous structure of concrete and is of fundamental importance in hydraulic structures. In RCC, permeability depends on the properties of the materials, the proportions of the mixture, the pore structure and the degree of compaction. The fewer continuous and passable paths there are in the concrete structure, the more limited water transport will be. From this perspective, reducing porosity and achieving a dense structure are important factors in controlling the permeability of RCC (Farnam & Nouri, 2015; Tajdini et al., 2024). The relationship between internal structure and water-transport behaviour has also received attention in studies on RCC. Selvam et al. (2023) examined the relationship between compaction mechanisms and the internal structure of RCC, and Sarsam et al. (2014) addressed properties related to the durability of this type of concrete. Studies on RCC also emphasize the importance of controlling the mixture composition and the properties of the materials in reducing permeability and improving durability (Aboubakr Mohammad, 2017; Ali & Abbas, 2022). Conceptually, water absorption, permeable voids and the permeability coefficient are three different but

related indicators of the behaviour of concrete against water. Water absorption relates mainly to the entry of water from the surface and its access to the pores, whereas permeability expresses the ability of water to pass through the concrete structure under a pressure difference. Permeable voids represent the part of the void space accessible to water. Simultaneous examination of these indicators can therefore provide a more complete picture of water-transport behaviour in RCC.

Horizontal joints in RCC and the interface zone

One of the basic features of the construction of RCC dams is the placement of concrete layer by layer. As a result, the contact zone between two layers may differ from monolithic concrete in its structure and water-transport behaviour. Construction details and the way layers are bonded are important issues in the performance of RCC structures, and the conditions under which successive layers are placed can affect the quality of their bond (Ettaghaei et al., 2023; Tajdini, Barazandeh Taj et al., 2023; Tajdini, Goudarzi et al., 2023). The interface zone between two layers of concrete is important because it can act as part of a possible path for water transport. If the bonding conditions are inadequate, discontinuities and voids in this zone can facilitate the passage of water. Hence, assessing the permeability of layered concrete solely on the basis of the properties of monolithic concrete is not sufficient, and the condition of the layer junction must also be considered. One of the methods used to improve bonding conditions is to place mortar between two layers of concrete. By filling part of the spaces at the contact surface and improving the bond, the mortar can affect the behaviour of the interface zone. The cement content of the mortar is also a variable that can change its properties and therefore the water-transport behaviour at the joint. Examining the effect of mortar cement content on joint permeability can therefore be important for understanding the factors that govern the watertightness of horizontal joints in RCC. Another important factor is the time interval between the placement of two layers. As the interval increases, the conditions of contact between the new layer and the previous layer change, and the continuity and quality of the junction zone may be affected. Sources on the construction of RCC dams also emphasize the importance of the timing of layer placement and the details of their bonding (Ettaghaei et al., 2023; Tajdini, Goudarzi, et al., 2023).

The watertightness of horizontal joints can be regarded as the result of the interaction between the properties of the parent concrete, the pore structure, the properties of the mortar and the conditions of layer placement. In this research, water absorption, permeable voids and the permeability of concrete and horizontal joints were examined simultaneously.

Methedology

Overall research design and experimental programme

This research was carried out as an experimental laboratory study focusing on the water-transport behaviour of RCC and of the horizontal joints between its layers. The test framework was designed so that, in addition to examining properties related to the internal structure of the concrete, the effects of the concrete mix design, the properties of the bedding mortar and the time interval between successive layers on water-penetration behaviour could be studied simultaneously. To this end, 30 RCC mixtures were prepared and evaluated by varying three main variables: the cement content of the concrete, the cement content of the bedding mortar and the time interval before placing the second layer. These variables were chosen because of their role in changing the structure of the cement paste, the porosity, the quality of the interface zone and, ultimately, the behaviour of concrete against the entry and passage of water.

In the mixtures examined, three levels of concrete cement content, 120, 160 and 200 kg/m^3, were considered, designated C1, C2 and C3, respectively. The 90-day target compressive

strengths of these three mixtures were set at 17, 22 and 28 MPa, respectively. Type II cement and class F fly ash were used in all mixtures, with fly ash replacing 30 percent of the cement by volume. The water content used in the initial design was reported as 100 kg/m³, and, in determining the water required by the aggregates, given a maximum aggregate size of 37.5 mm, 107 kg/m³ was adopted in the final calculated design. A type D water-reducing admixture was used to improve workability. In addition to creating a defined range of variation in the amount of cementitious materials, the three levels of concrete cement content made it possible to examine the corresponding changes in the water-to-cementitious materials ratio and pore structure of the concrete. In this research, the water-to-cementitious materials ratios of mixtures C1, C2 and C3 were about 0.89, 0.67 and 0.54, respectively. The change in cement content in this experimental programme was therefore not treated merely as a quantitative variable; through the change in the water-to-cementitious materials ratio, its relationship with the density of the internal structure, water absorption and permeability could also be examined.

To simulate different conditions of placing successive layers of RCC, three time intervals of 2, 12 and 48 hours between placing the first and second layers were considered. In the present research, the 2-hour interval was taken as shorter than the initial setting time, the 12-hour interval as representative of construction conditions, and the 48-hour interval as longer than the final setting time. The setting times of the mixtures were determined by the penetration resistance test according to ASTM C403. This choice of intervals made it possible to examine the change in joint behaviour from conditions close to the initial bond between layers to conditions in which a cold joint is likely to form.

In addition to varying the concrete cement content and the time of placing the second layer, three levels of bedding-mortar cement content, 250, 400 and 550 kg/m³, designated M1, M2 and M3, respectively, were considered to evaluate the role of the interlayer in controlling the passage of water. The water-to-cement ratio of the mortar was varied in line with the cement content, and the values reported for M1, M2 and M3 were about 0.92, 0.57 and 0.42, respectively. Thus, in addition to changing the properties of the parent concrete, the experimental matrix made it possible to examine the role of the quality and density of the mortar layer in the hydraulic behaviour of the joint.

Materials and mix design

Type II cement, class F fly ash, aggregates with a maximum size of 37.5 mm, water and a type D water-reducing admixture were used in the design of the RCC. The specific gravities of cement and fly ash were reported as 3.16 and 2.41, respectively. To achieve the desired grading, the volume of sand was set at about 45 percent of the total aggregate volume, and the combination of fine and coarse aggregates was based on the grading curve determined in the mix-design process. In the mix-design process, the amount of cementitious materials was first determined according to the target compressive strength. Accordingly, mixture C1 with a cement content of 120 kg/m³ was designed to achieve a compressive strength of 17 MPa, mixture C2 with 160 kg/m³ for a target strength of 22 MPa and mixture C3 with 200 kg/m³ for a target strength of 28 MPa at 90 days. The target Vebe time was in the range of 15 to 25 seconds, which was consistent with the very dry nature of RCC and the need to achieve adequate compaction.

For each mixture, the mix proportions were determined using volumetric calculations including the volumes of cementitious materials, water, air and aggregate and the mortar-to-paste ratio. In the design process, the mortar volume was calculated as the sum of the volumes of cement, fly ash, water, air and aggregates smaller than 4.75 mm, and the mortar-to-paste ratio was also checked. In mixture C3, for example, the amounts of coarse and fine aggregate, cementitious mate-

rials, water, air and other components were determined on the basis of volumetric calculations.

Design and fabrication of jointed specimens

The specimens examined in this research were made in two layers to simulate a horizontal joint between two layers of RCC. To make the specimens, the aggregates, cement, fly ash and water were introduced into the mixer in the specified order and mixed until adequate uniformity was achieved. Compaction of the RCC was a key step in specimen fabrication, and an electro-pneumatic compaction hammer was used according to ASTM C1435 to achieve the desired compaction. Proper compaction of RCC is very important, because the amount of residual voids can affect water-transport behaviour in concrete.

For the specimens used in the permeability and shear strength tests, cubic moulds measuring 15 × 15 × 15 cm were used. Before the second layer was placed, the surface of the first layer was cleaned and prepared by green cutting to provide the contact-surface conditions required for the intended joint. The second layer was placed on the lower layer after one of the specified time intervals, i.e., 2, 12 or 48 hours, and bedding mortar with one of the three cement contents M1, M2 or M3 was placed at the junction. In the specimen designation, the letter C denotes the concrete cement content, the letter M the mortar cement content and the letter T the time interval before placing the second layer; for example, C2M3T12 denotes a specimen made with concrete mixture C2, mortar M3 and a 12-hour interval. The experimental programme therefore comprised all 27 combinations of the three concrete cement contents (120, 160 and 200 kg/m³), the three mortars and the three placement intervals, plus the three unjointed mixtures C1–C3 (30 mixtures in total). For each mixture, three specimens were prepared for compressive strength, two for direct tensile strength, three for shear strength and two for the permeability test. In total, 300 specimens were made in the main experimental phase. Although the present article focuses on hydraulic behaviour and water penetration, the results of the other tests are not reported here.

Curing of specimens and Water absorption and permeable voids test

After casting, the specimens remained in the moulds for 24 hours and, after demoulding, were placed in water for further curing. The specimens were cured for 90 days in water at 23 ± 2 °C. The age of 90 days was chosen in view of the nature of the RCC studied and the aim of examining the more stable behaviour of the concrete structure after the curing period.

All specimens used to evaluate properties related to water penetration entered the preparation and testing stage after the 90-day curing period. The comparison between mixtures in terms of water absorption, permeable voids and permeability was therefore made under identical curing conditions, and the effect of differences in curing conditions on the comparison of the main test variables was controlled as far as possible. To evaluate relative porosity and the amount of void space accessible to water, the water absorption and permeable voids test was carried out. In this test, cylindrical specimens were prepared and dried after 90 days of curing in water, and their masses were measured in the required conditions. The percentage of permeable voids was then calculated from the oven-dry mass, the saturated surface-dry mass and the volume of the specimen. The test was performed according to ASTM C642-82.

This test is of particular importance in the present research, because the aim of the article is not merely to determine water absorption or porosity independently but to examine the relationship between these parameters and water-transport behaviour in concrete. The results showed that an increase in the percentage of permeable voids is accompanied by an increase in water absorption. These two indicators were then used for comparison with the sorptivity and permeability results.

Sorptivity test and Water permeability test under pressure

To examine the rate of water entry into the surface structure of the concrete and to evaluate capillary absorption behaviour, the sorptivity test was carried out according to ASTM C1585. Cubic specimens measuring 10 × 10 cm, after preparation and drying, were placed under test conditions such that only 10 percent of the specimen height was immersed in water. The masses of the specimens were recorded at specified time intervals, and the change in mass due to water uptake was used to determine the rate of absorption.

In this test, the absorption was calculated in millimetres and its relationship with the square root of time was examined. Thus, in addition to the amount of absorption, the time course of water entry was also considered. The sorptivity index was used to compare the behaviour of water entry from the surface with the permeability coefficient, and the changes in these two indicators were compared across the various mixtures. A permeability apparatus was used to determine the water permeability coefficient of specimens with a horizontal joint. Cubic specimens measuring 15 × 15 × 15 cm were prepared for testing after 90 days of curing. To simulate conditions closer to the performance of joints in RCC hydraulic structures, the relevant surfaces of the specimens were sealed with an impermeable coating so that the water path was controlled in the defined test direction. Water pressure in the range of 1 to 5 bar was then applied to the specimens.

At the beginning of the test, the flow rate varied noticeably and, as the test continued, moved towards a steady state. In the RCC specimens, the flow rate increased in the early stages of the test and then decreased over time, reaching an approximately steady state about two days after the start of the test. In accordance with the research method, once the flow had reached a steady state, the flow rate was used to calculate the permeability coefficient, and, to improve accuracy, the results of two replicate specimens were taken into account in determining the permeability coefficient.

The permeability coefficient was calculated from Darcy's law using the following equation:

$$K=(M^*L)/(A^*h)$$

In this equation, K is the water permeability coefficient (m/s), M is the flow rate (cm^3/s), L is the length of the specimen in the direction of water flow, A is the cross-sectional area perpendicular to the flow and h is the hydraulic head.

Using the steady flow to calculate the permeability coefficient allowed the specimens to be compared on the basis of a single quantitative indicator. Within this framework, the permeability coefficients of the different specimens were compared as the concrete cement content, the mortar cement content and the time interval before placing the second layer varied. The relationship between this coefficient and the sorptivity index and permeable voids was also examined to determine whether the changes in permeability are consistent with changes in the indicators related to pore structure.

Independent variables and test levels and Data analysis framework

In the experimental programme, the concrete cement content was considered at three levels of 120, 160 and 200 kg/m^3. The mortar cement content was examined at three levels of 250, 400 and 550 kg/m^3 and the time interval between placing layers at three levels of 2, 12 and 48 hours. The combination of these variables formed the basis for preparing the specimens and examining water absorption, permeable voids and water permeability in RCC specimens and horizontal joints. The data in this article were analysed by direct comparison of the hydraulic responses of the specimens and by examining the relationships between the different water-transport indicators. First, the changes in water absorption and permeable voids were examined for the different mixtures, and then the relationship between these two parameters was evaluated. Next, the time course of the water flow rate and the permeability coefficients of unjointed and jointed

specimens were examined. Finally, the effect of the mortar cement content on joint permeability and the relationship between the permeability coefficient and the sorptivity index were studied. In this article, the different water-transport indicators were examined simultaneously so that the trends in water absorption, permeable voids, sorptivity and permeability could be compared with each other. The results also show that the sorptivity index and the permeability coefficient followed a similar trend across the mixtures, with the sorptivity index generally increasing as permeability increased. Next, the results of water absorption, permeable voids, sorptivity and permeability were compared with each other, and the changes in the behaviour of the concrete and horizontal joints against the passage of water were examined. In this way, in addition to determining the individual values of each parameter, the research method made it possible to analyse the role of pore structure and joint conditions in the watertightness of RCC.

FINDINGS AND DISCUSSION

Water absorption and permeable voids

Water absorption of mixtures C1, C2 and C3 was examined at three times: 30 minutes, 7 hours and 50 hours. The absorption after 30 minutes was taken as the initial absorption and the value recorded after 50 hours as the final absorption. The results showed that the initial water absorption of mixtures C1, C2 and C3 was 3.3, 2.3 and 1.8 percent, respectively, and their final absorption was 4.5, 3.5 and 2.8 percent, respectively.

According to the CEB classification, water absorption values below 3 percent fall in the good range, values of 3 to 5 percent in the average range and values above 5 percent in the poor range. Accordingly, at the initial-absorption stage, mixture C1 with 3.3 percent fell in the average range and mixtures C2 and C3 with 2.3 and 1.8 percent in the good range. At the final-absorption stage, the water absorption of mixture C1 was 4.5 percent and that of mixture C2 3.5 percent, both in the average range, whereas mixture C3 with 2.8 percent was in the good range. Comparison of the three mixtures showed that, as the cement content increased from C1 to C3, water absorption decreased at both the initial and final stages. This change can be analysed in the context of the differences between the mixtures and the simultaneous change in mix properties and pore structure; therefore, on the basis of this test, the independent effect of the water-to-cementitious materials ratio cannot be separated from that of the cement content. Nevertheless, the results show that the mixtures with higher cement content exhibited lower water absorption under the conditions examined.

Examination of the relationship between water absorption and permeable voids also showed that the characteristics of the pore structure are related to water absorption. An increase in the pore space accessible for the entry and transport of water can be accompanied by an increase in water absorption. Hence, simultaneous examination of water absorption and permeable voids together with the permeability coefficient can provide a more complete picture of the behaviour of RCC against water transport. Since water absorption values change over time, evaluating initial and final absorption together with pore-structure indicators can be used to compare the behaviour of different RCC mixtures. These results also show the need to consider both pore-structure characteristics and water-transport indicators when examining the permeability of RCC and of horizontal-joint zones. (Fig. 1)

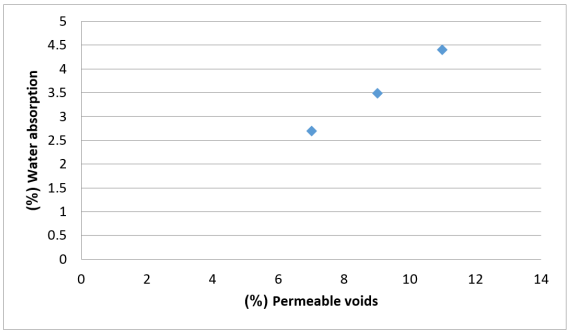


Figure 1: Relationship between water absorption and permeable voids

Water flow behaviour and permeability coefficient

In the permeability test, the water flow rate increased rapidly at the beginning of the test and then gradually approached equilibrium. In the RCC specimens, the flow rate reached equilibrium after about two days. The results of two replicate specimens were used to determine the permeability coefficient. This procedure allowed a more accurate examination of the permeability of the concrete. In the unjointed specimens, as the cement content increased from C1 to C3, the permeability coefficient decreased considerably. A decrease in the water-to-cementitious materials ratio was also accompanied by a decrease in permeability. The permeability of mortars M1, M2 and M3 was also lower than that of the leanest RCC (C1); only M2 and M3 were less permeable than C2, and none was less permeable than C3 (Fig. 2). This difference was attributed to the denser structure of the mortar and its greater cohesion.

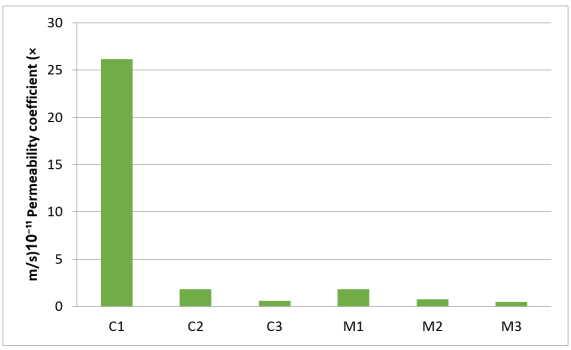


Figure 2: Permeability coefficient of unjointed specimens

Effect of mortar on joint permeability

The interface zone between two layers of concrete in the composite specimens was regarded as one of the important possible paths for water transport. The use of mortar between two layers, by improving the condition of the junction zone, can affect water-transport behaviour and joint permeability. The results showed that the permeability coefficient of joints filled with mortar M3 was about 41–85 percent (64 percent on average, Table 1) lower than that of joints with mortar M1. Increasing the mortar cement content was accompanied by a decrease in the joint permeability coefficient. This trend can be related to the change in the condition of the interface zone and the reduction of passable water paths at the junction.

In the C3T2 specimens, too, the use of a richer mortar clearly reduced the permeability of the jointed specimens. Nevertheless, the permeability coefficient of the unjointed C3 specimens still differed from that of the jointed specimens. This result shows that the interface zone between the mortar and the surfaces of the two layers can still play a role in water-transport behaviour in jointed specimens. (Fig. 3)

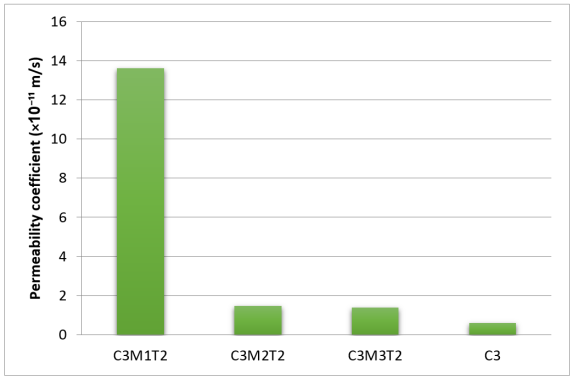


Figure 3: Effect of mortar cement content on joint permeability

Relationship between permeability coefficient and sorptivity index

The results showed a direct relationship between the permeability coefficient and the sorptivity index, such that in many mixtures an increase in the permeability coefficient was accompanied by an increase in the sorptivity index (Pearson r = 0.97, R^2 = 0.94, n = 27; Table 1 and Fig. 4). For example, in mixture C1M1, as the interval between layers increased from 2 to 12 and 48 hours, the permeability coefficient increased from 40.1 to 58.9 and 95.1, and the sorptivity index rose from 0.388 to 0.5075 and 0.7.

This concordance shows that the sorptivity index and the permeability coefficient, despite the difference in how they assess the entry and passage of water, show similar trends in many

mixtures. An increase in the sorptivity index can therefore be accompanied by an increase in the water-transport capacity of the concrete structure. (Tab. 1 and Fig. 4)

Table 1: Permeability coefficient and sorptivity index of the mixtures

Mixture	Permeability coefficient ($\times 10^{-11}$ m/s)	Sorptivity index	Mixture	Permeability coefficient ($\times 10^{-11}$ m/s)	Sorptivity index
C1M1T2	40.1	0.388	C2M3T2	3.57	0.079
C1M1T12	58.9	0.5075	C2M3T12	6.54	0.010
C1M1T48	95.1	0.7	C2M3T48	13.08	0.160
C1M2T2	32.68	0.26	C3M1T2	13.62	0.18
C1M2T12	37.269	0.34	C3M1T12	31.04	0.227
C1M2T48	80.1	0.52	C3M1T48	38.48	0.388
C1M3T2	25.06	0.23	C3M2T2	1.46	0.037
C1M3T12	31.034	0.24	C3M2T12	2.73	0.073
C1M3T48	59.012	0.49	C3M2T48	15.84	0.205
C2M1T2	37.34	0.4	C3M3T2	1.38	0.04
C2M1T12	49.1	0.49	C3M3T12	2.11	0.064
C2M1T48	56.29	0.49	C3M3T48	8.68	0.125
C2M2T2	4.37	0.12	–	–	–
C2M2T12	7.1	0.110	–	–	–
C2M2T48	34.49	0.29	–	–	–

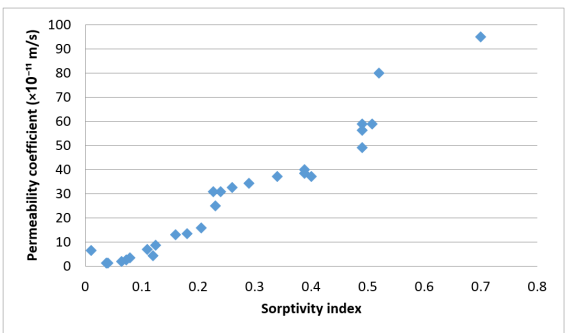


Figure 4: Relationship between permeability coefficient ($\times 10^{-11}$ m/s) and sorptivity index

Effect of the time interval between layers

The results showed that permeability increases as the time interval between placing layers increases. The changes in permeability between 12 and 48 hours were more pronounced than between 2 and 12 hours (in seven of the nine concrete–mortar series; Table 1). The lowest permeability was observed at the 2-hour interval. As the interval increased to 12 hours, permeability increased, and at 48 hours a greater increase was observed. This trend shows the importance of the time at which the second layer is placed for joint performance. Increasing the interval between layers changes the condition of the contact surface and increases joint permeability.

Effect of concrete cement content and Relationship between pore structure and joint watertightness

Increasing the concrete cement content reduced permeability. In the unjointed specimens, mixtures with higher cement content had lower permeability coefficients. This behaviour was accompanied by a decrease in the water-to-cement ratio and in the volume of voids. In the mixtures with higher cement content and lower water-to-cement ratio, water absorption and permeable voids were also at their lowest. The results of the water absorption, permeable

voids, sorptivity and permeability tests showed that the structural characteristics of the concrete are related to its behaviour against water. An increase in permeable voids was accompanied by an increase in water absorption. In many mixtures, an increase in the sorptivity index was also accompanied by an increase in the permeability coefficient. In the jointed specimens, this relationship became more important, because the interface zone between two layers acted as an important path for the passage of water. The use of mortar with a higher cement content was able to reduce joint permeability, but even in specimens with higher cement content, the difference between jointed and unjointed specimens remained.

Hence, simultaneous control of the pore structure of the concrete and the quality of the joint interface zone is important for reducing water penetration.

RESULTS AND CONCLUSION

The results of the water absorption and permeable voids test showed a direct relationship between the volume of permeable voids and water absorption. An increase in permeable voids increased water absorption, and a decrease in void volume was accompanied by a decrease in water absorption. Increasing the cement content and decreasing the water-to-cement ratio reduced the void volume and water absorption. In the mixtures with higher cement content, the concrete structure was denser and better behaviour against water entry was observed. In the water permeability test, the flow rate increased at the beginning of the test and then reached equilibrium. In RCC, the water flow approached equilibrium after about two days.

Increasing the concrete cement content reduced the permeability coefficient. This trend was clearly observed in the unjointed specimens and showed that changes in the internal structure of the concrete and a reduction in voids can be effective in reducing permeability. The use of bedding mortar also affected joint permeability. The permeability coefficient of joints with mortar M3 was about 41–85 percent (64 percent on average) lower than that of joints with mortar M1. The results showed that, as the mortar cement content increased, the permeability of jointed specimens decreased. This trend can be attributed to changes in the properties of the mortar and the performance of the joint zone. Despite the reduction in permeability due to the use of mortar, the permeability coefficient of the unjointed C3 specimens still differed from that of the jointed specimens. The interface zone between the mortar and the surfaces of the two layers therefore remains an important factor in water leakage.

Increasing the time interval between placing layers also increased permeability. The largest changes were observed between 12 and 48 hours, and the 2-hour interval resulted in the lowest permeability. A relationship was also observed between the sorptivity index and the permeability coefficient. As the permeability coefficient increased, the sorptivity index also increased in many mixtures. This trend showed the concordance of the changes in the sorptivity index and the permeability coefficient in the mixtures examined. Overall, the results showed that reducing the permeability of RCC and improving the watertightness of horizontal joints require simultaneous attention to the pore structure of the concrete, water absorption, the mortar cement content and the time interval between layers.

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