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Key words: *concrete, permeability, porosity, compressive strength, density, absorption*

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CORRELATION BETWEEN PERMEABILITY AND POROSITY WITH OTHER PROPERTIES OF CONCRETE

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Most of concrete properties such as strength, permeability, density and absorption are significantly affected by the porosity of its internal microstructure. Many researchers studied the relationships between permeability, porosity and other properties of concrete, but in the author's opinion, the subject still needs more researching works. The purpose of this research is to investigate the possible correlations between concrete porosity and permeability with other properties such as compressive strength, absorption and density. Helium Gas Pores meter was used to measure porosity and Nitrogen Gas Permeate device was used to measure permeability. The investigated variables were the aggregate to cement ratio (A/C) and water to cement ratio (W/C). Based on regression analysis of test results, mathematical relationships between tested properties were suggested. The higher correlations were observed for mixes with constant water to cement ratio and variable aggregate to cement ratio.

Key words: concrete, permeability, porosity, compressive strength, density, absorption

INTRODUCTION

Most of concrete properties such as strength, permeability, density and absorption are significantly affected by the porosity of its internal structure. The permeability is a measure of the movement of fluids through the porous media. It is a characteristic that affects the performance of the concrete as the concrete durability is highly dependent on its ability to prevent the ingress of aggressive chemical species. The penetration of aggressive liquids will depend upon the degrees of porosity and permeability of concrete [1]. Concrete porosity determines mainly its permeability. If the porosity decreases the permeability of concrete will be decreases as well. In general, the ratio of water to cement and the degree of hydration determine the overall porosity of the capillary. It reduces by reducing the water to cement ratio and increasing the degree of hydration [2]. Nayme and Illston [3] stated that the total porosity is not the unique function of permeability and the permeability is clearly different from that caused by the variation of water to cement ratio. This may suggest that the flow space in hardened cement past is confined to distinct flow channel, and the permeability depends on the continuity characteristics of the pore rather than on pore volume. Watson and Okeya [4] proposed a relationship between water cement ratio and permeability as follows:

A) If there is no admixture in the hardened cement past:
$K = K_0 \ \exp\{A(W/C)\}$

B) If there is 4% by cement weight superplasticiser admixture:
$K = K_1 \ (W/C) + B$

Okpala [5] suggested two relationships:

A) between permeability and water cement ratio (W/C) of cement paste:
$K = K_1 \exp a_1 \ (W/C)$

B) between permeability and total volume of aggregate
$K = K_2 \ \exp a_a \ (A_r)$

Where: K = permeability coefficient

K_0, K_1, K_2, a_a, a_1, A, B = Constant for different types of cement

A_r = total volume of aggregate

The compressive strength of concrete is one of the most important factor used in the design of concrete structures and it is also becoming a major consideration used to judge the concrete quality, and its fitness. Jaya et al. [6] suggested linear relationships between porosity and compressive strength and quadratic between permeability and compressive for concrete containing rice hush ash with different grinding time as shown in Table 1. The best correlations between porosity and permeability coefficients with compressive strength were found after 28 days.

Table 1: Jaya et al. relations between permeability, porosity and compressive strength

Age	Equation	R^2
Porosity versus compressive strength		
7 days	y = -0.226x + 19.97	0.93
28 days	y = -0.2004x + 20.447	0.98
Permeability versus compressive strength		
7 days	y = 0.018x2 – 1.1715x + 20.135	0.9221
28 days	y = 0.007x2 – 0.6167x + 13.747	0.9415

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Lain C. [7] developed a mathematical model to characterize the relationship between compressive strength and porosity for porous concrete by analyzing empirical results and theoretical derivations. Chen et al. [8] showed that the ratio between compressive strength and indirect tensile (splitting tensile and flexural) strength of cement mortar is not constant, but it is a porosity dependent. The ratio decreases with increase porosity values of cement mortar. Singh [9] suggested relationships between permeability, compressive strength and split tensile strength for steel fiber reinforced concrete SFRC as well as plain concrete PCC. Elawady et al. [10] pointed out that there is a strong correlation between compressive strength, permeability, and sorption and the three measured concrete properties had similar tendency for both concretes in the absence and presence of silica. Zhao et al. [11] proposed an extended Bhattacharjee model [12] to examine the relationship between compressive strength and pore structure. Porosity, mean diameter, and hydration degree were taken into consideration, which clearly explain the relationship between pore structure and strength of cement mortar. Bu and Zitan [13] developed a statistical model to relate the compressive strength to relevant pore structure features. Pratap et al. [14] carried out an experimental investigation on water permeability, porosity and compressive strength of high performance concrete and based on the obtained results, relations were formulated between permeability versus compressive strength and permeability versus porosity. Zhang and Zong [15] found that both of surface water absorption and internal water absorption had no clear relationship with compressive strength, which indicated that the strength cannot be simply evaluated by water absorption. Permeability mainly depended on the surface water absorption of concrete, and there was a significant linear correlation between permeability and surface water absorption. However, internal water absorption presented little relationships to permeability.

Relationships between permeability, porosity and other concrete properties can be of great use, especially for liquid transport and storage projects, as it can be used for finding the porosity and permeability values through compressive strength, absorption and dry density tests available in most concrete technology laboratories. It was shown that many researchers studied these relationships, but in the author's opinion, the subject still needs more researching works. The purpose of this research is to investigate the possible correlations between concrete porosity and permeability with compressive strength, absorption and density. Helium Gas Pores meter was used to measure porosity and Nitrogen Gas Permeate device was used to measure permeability.

EXPERIMENTAL PROGRAM

An experimental program was implemented including several laboratory tests on concrete properties such as permeability, porosity compressive strength, absorption and density. Two groups of concrete mixes were tested, in which the variables were the ratio of water to cement (W/C) and the ratio of aggregate to cement (A/C). In the first group, the ratios of cement: fine aggregate: coarse aggregate were (1: 2: 2), (1:2:3), (1:2:4} and (1:2:5.5), respectively with constant water to cement ratio (0.50), while, in the second group the ratio of cement: fine aggregate: coarse aggregate was (1:2:3), respectively, with variable water to cement ratios (0.35, 0.45, 0.50, 0.55, 0.60, and 0.65). Material weights were calculated per cubic meter using the volumetric equation to be as shown in Table 2.

Table 2: Materials used and mix proportions

Mix No.	Aggregate Cement ratio (A/C)	Water Cement ratio (W/C)	Aggregate kg/m^3	Cement kg/m^3	Water kg/m^3
First group					
1	4	0.50	1745	436	216
2	5	0.50	1875	375	188
3	6	0.50	1967	328	164
4	7.5	0.50	2075	276	138
Second group					
1	5	0.35	1982	396	139
2	5	0.50	1875	375	188
3	5	0.45	1907	382	172
4	5	0.55	184 0	368	203
5	5	0.60	1804	361	217
6	5	0.65	1772	354	230

Materials

Cement is the Portland cement type I per specification ASTM C 150 [16].

Fine aggregate is locally available sand with maximum size 5 mm. The sieve analysis was carried out and the results showed that it was within the permissible limits according to BS882: 1992[17].

Coarse aggregate is a local irregular shape with maximum size 20 mm. The sieve analysis was carried out and the results showed that it was within the permissible limits according to the British specifications BS882: 1992 [17]. Table 3 shows the sieve analysis of fine and coarse aggregates.

Table 3: Sieve analysis of fine and coarse aggregates

Fine aggregate			Coarse aggregate		
Sieve size (mm)	Cumulative passing (%)	BS882: 1992	Sieve size (mm)	Cumulative passing (%)	BS882: 1992
2.36	85.50	80-100	20	100	90-100
1.18	73.05	70-100	14	65	30-80
600 μm	63.00	55-100	10	32.83	30-60
300 μm	25.00	5-70	5	6.05	0-10
150 μm	0.40	0-15	-	-	-

Water: Drinking water free of salts, impurities and organic matter was used for mixing and treatment.

All materials in the concrete mixture were weighed separately depending on the mixing ratios identified. The mixes were produced in a concrete mechanical mixer with a capacity of 150 liters. First, the aggregates and 75% of the total water were loaded gradually and mixed for two minutes. Then, the cement and rest of the total water were added and mixed for three minutes more. Finally, the 150 mm ×150 mm ×150 mm mold is formed and divided into three layers of compaction. All specimens were kept in molds for 24 hours and then cured by immersion in water at laboratory temperature until test time at 28 days age.

Laboratory Tests

Porosity Test

The porosity is measured using Helium Gas Pores meter apparatus shown in Figure 1 on cylindrical specimens with diameter of 3.79 cm and length 5.45 cm as follows:

Figure 1: Helium Gas Pores meter

1. The cubes were placed in the drilling machine to extract the specimens according to the requirements of the testing apparatus.
2. The specimens are dried inside the oven at 105C and weighing daily until the weight is stabilized (± 5g).
3. The specimens are washed using solvents (toluene and methanol). Toluene is used for organic substances such as oils and Methanol is used to dissolve salts.
4. The test device shall be calibrated by testing on pieces of disks to find the constants (a, b). To ensure calibration of the device, the correction factor R2 shall be close to 1.
5. The size of the specimens is calculated using the mercury pump shown in Figure 2. The pump reading is taken after the first drop of mercury in the container.
6. The specimen is then placed inside the porosity meter and the gas pressure P inside the in the specimen is measured from which the size of granules is calculated.

Figure 2: measurement of specimen size

7. The size of the voids is calculated using the equation: Size of voids = Total size of specimen - Granular size
8. Porosity is calculated from the following formula:

$$Porosity = \frac{void\ size}{total\ size} \times 100$$

Permeability Test

The gas permeability is a measure of the flow of gas through a porous material caused by a pressure head and prepends on the open porosity prevailing in this material. For this reason it is important to take into account the moisture content of the concrete since the gas pressure in the pores is not sufficient to move the water and the pores will remain blocked not being able to let the gas pass. The tests is performed using a Nitrogen Gas Permeate device as shown in Figure (3) as follows:

1. Test specimens for permeability testing are prepared in the same way as porosity tests in steps 1, 2 and 3 in the same dimensions.
2. The specimen shall be placed in the holder, which is a metal cylinder with a cylindrical rubber tube inside. The external pressure valve is then opened by 200 Psi, so that the rubber tube is pressed on the specimen to ensure that gas will pass through the sample only.
3. The gas valve is then opened and the gas passes through the specimen.
4. Read the pressure difference in Psi.
5. The flow rate Q is taken in cm3 / sec.
6. The temperature reading is taken by a centigrade unit.
7. The permeability coefficient is calculated from the following equation:

$$K_g = \frac{2000 * \mu N_2 * Q * l}{A * \Delta p}$$

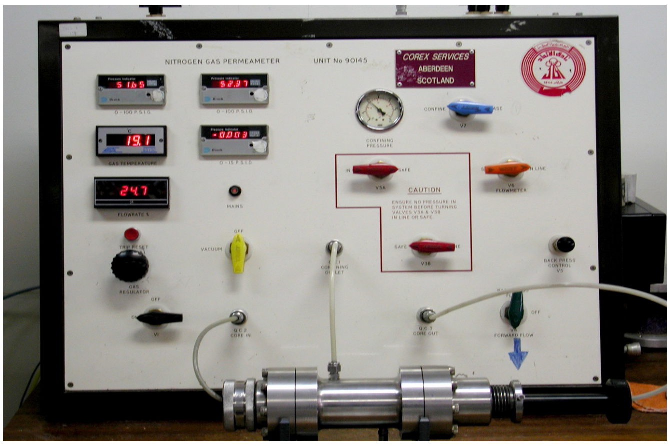

Figure 3: Nitrogen Gas Permeate device

Where:

K_g = gas permeability coefficient in Darcy unit

μN_2 = viscosity of nitrogen gas in (CP)

$\mu N_2 = 0.0165815 + 4.8 \times 10^{-5}\, T$

T = temperature in centigrade unit

Q = flow rate (cm^3 / sec)

L = sample length (cm)

A = Sample section area (cm^2)

ΔP = pressure difference in (psi)

Then the water permeability (K_W) can be found from the following formula:

$K_w = 0.68 \times K_g^{1.06}$

And water permeability in cm2 unit can be found from the following formula:

$K_w\,(cm^2) = K_w\,(md) \times 9.8692 \times 10^{-12}$

Density Test

Density test has been done as per ASTM C 642 [18].

Absorption Test

Absorption test has been done as per ASTM C 642 [18]

Compressive Strength Test

Compressive strength test has been done as per B.S.1881, Part 116, 1989 [19].

RESULTS AND DISCUSSION

Table 4 shows test results of measurement, porosity and permeability, compressive strength, density and absorption of concrete specimens, while tables 5 and 6 show the variations of the tested properties with respect to the variation of water to cement ratio (W/C) and aggregate to cement ratio (A/C). All experimental results are the average value of three repeated tests.

Table 4: Test results

Mix No.	Aggregate Cement ratio (A/C)	Water Cement ratio (W/C)	Compressive Strength (fcu) (MPa)	Coefficient of Permeability (Kw) (md)	Porosity %	Density kN/m^3	Absorption (Ab) %
First group							
1	4	0.50	40.95	0.226	15.245	023.	2.37
2	5	0.50	35.54	0.230	14.946	23.4	2.45
3	6	0.50	34.47	0.236	14.336	623.	2.46
4	7.5	0.50	24.14	0.242	12.268	823.	2.42
Second group							
1	5	0.35	46.33	0.073	13.790	22.82	2.35
2	5	0.45	42.53	0.107	14.260	22.87	2.41
3	5	0.50	35.54	0.230	14.946	23.4	2.45
4	5	0.55	31.84	0.269	16.026	0323.	2.46
5	5	0.60	29.47	1.051	16.433	22.9	2.55
6	5	0.65	24.88	1.381	17.498	22.8	2.58

Table 5: Variation of tested properties for first group

A/C	Permeability variation %	Porosity variation %	Compressive strength variation %	Absorption variation %	Density variation %
4	0.00	0.00	0.00	0.00	0.00
5	1.77	- 5.56	- 13.21	1.70	3.37
6	4.42	-5.96	- 15.82	2.61	3.80
7.5	7.08	- 19.53	- 41.05	3.48	2.19

Table 6: Variation of tested properties for second group

W/C	Permeability variation %	Porosity variation %	Compressive strength variation %	Absorption variation %	Density variation %
0.35	0.00	0.00	0.00	0.00	0.00
0.45	46.6	3.30	- 19.17	2.55	0.22
0.50	223.3	8.38	- 36.91	4.26	3.41
0.55	268.5	16.21	- 43.48	4.68	0.70
0.60	1339.7	19.17	- 47.68	8.51	0.35
0.65	1791.8	26.89	- 55.83	9.78	0.00

Permeability, compressive strength, and absorption depend on the pore structure, but with different trends. Porosity is influenced mainly by the water to cement ratio and degree of hydration [20]. From Table 5 and 6, it was observed that permeability is the property showed the higher variation with the ratio of water to cement followed by compressive strength, porosity, and then absorption, and when the ratio of aggregates to cement was changed, the compression strength showed the higher variation followed by porosity and then permeability, while their effect on absorption and density is relatively small. This may be related to the grain size distribution of the aggregates, the amount of cement paste used, the interconnectivity of the pores, degree of compaction, and the micro cracks due to shrinkage in the interfacial transition zone between aggregate and cement paste [21]. Test results showed that, when (A/C) ratio was increased from 4 to 5, from 5 to 6, and from 6 to 7.5 the permeability increased by 1.77%, 2.60%, and 2.54%, respectively, the compressive strength decreased by 13.21%, 3.01%, and 29.97%, respectively, the porosity increased by 1.96%, 4.08%, and 14.43% respectively, and the absorption increased by 3.38%, 0.41%, 0.41, and – 1.63%, respectively. Test results also showed that, when (W/C) ratio was increased from 0.35 to 0.45, from 0.45 to 50, from 0.50 to 0.55, from 0.55 to 0.60, and from 0.60 to 0.65, the permeability increased by 46.57%, 114.45%, 16.96%, 290.71% and 31.39%, respectively, the compressive strength decreased by 8.2%, 16.74%, 10.41%, 7.44% and 15.57%, respectively, the porosity increased by 3.41%, 4.81%, 7.23%, 2.54%, and 6.48 respectively, and the absorption increased by 2.55%, 1.66%, 0.41%, 3.66%, and 1.18%, respectively.

Based on the test results and using Microsoft Excel, many relationships were suggested as shown in table 7 and Figures from 4 to 18 and they were chosen to be as simple as possible and showing their trends:

Table 7: Suggested relationships between permeability, porosity and other properties

No.	Equation	R^2	Reference
1	$K_w = 2\times10^{-5} (f_{cu})^2 + 6\times10^{-4} (f_{cu}) + 0.2411$	0.9200	Figure 4
2	$K_w = 35.338e^{-0.133 (f_{cu})}$	0.8926	Figure 5
3	$K_w = 7.3019e^{-0.095 (f_{cu})}$	0.6057	Figure 6
4	$Poros = -0.0006(f_{cu})^2 + 0.6096(f_{cu}) + 1.3893$	0.9808	Figure 7
5	$Poros = -0.1609(f_{cu}) + 21.335$	0.9587	Figure 8
6	$Poros = -5.527\ln(f_{cu}) + 34.893$	0.8194	Figure 9
7	$K_w = -0.0027(Poros)^2 + 0.0695(Poros) - 0.2015$	0.9998	Figure 10
8	$K_w = 0.0952(Poros)^2 - 2.6076(Poros) + 17.909$	0.8865	Figure 11
9	$K_w = 0.0926(Poros)^2 + 2.5243(Poros) - 17.365$	0.8844	Figure 12
10	$K_w = 34.226(Ab)^2 - 163.4(Ab) + 195.14$	0.9808	Figure 13
11	$Poros = 82.123(Ab)^2 - 390.37(Ab) + 478.02$	0.6110	Figure 14
12	$K_w = 0.0047(A/C) + 0.2072$	0.9934	Figure 15
13	$Poros = -0.2847(A/C)^2 + 2.0184(A/C) + 11.129$	0.9988	Figure 16
14	$K_w = 0.0013e^{10.156(W/C)}$	0.9143	Figure 17
15	$Poros = 21.194(W/C)^2 - 9.3383(W/C) + 14.304$	0.9816	Figure 18

Permeability and compressive strength relationship

The relationships between permeability and compressive strength of concrete are illustrated in Figs. 4, 5 and 6. It can be observed that the permeability increased as the compressive strength reduced. Quite good relationships between permeability and compressive strength of concrete have been suggested, as regression analysis provided correlation coefficients (R^2) of 0.92, 0.8926, and 0.6057. These relationships may be considered acceptable when taking into account the large scattering in the permeability test results due to the large variations in the radius, tortuosity and continuity of capillaries in the microstructure of the porous solid.

Porosity and compressive strength relationship

Test results showed that, the compressive strength increased as the porosity decreased. Lower porosity with sufficient cement paste content, resulting from lower values of (W/C) and (A/C) ratios, leads to higher strength values of concrete. The magnitude of this effect depends greatly on sizes, shape, and distribution of pores [13] and [22]. Figs 7, 8, and 9 showed the relations between porosity and compressive strength.The porosity showed higher relationships with compressive strength in comparison with that between permeability and compressive strength as the correlation coefficient values were 0.9808, 0.9587 and 0.8194.

Permeability and porosity relationship

Figs 10 to 12 show the relation between permeability and porosity. The permeability coefficient increased with the increase in the porosity. The analysis of test results showed a considerably high relationship between permeability and the porosity of concrete as the regression analysis provided correlation coefficient (R^2) of 0.9998, 0.8865 and 0.8844. The considerable difference in the correlation coefficients can be attributed to the significant increase in the permeability values compared to that of the total porosity when (W/C) ratios were increased and to a lesser degree when increasing the (A/C) ratios in the mixtures.

Permeability and porosity relationship with absorption

Relationship between permeability and absorption was shown in Fig 13. It can be seen that, the permeability coefficient increased with the increase in water absorption, and there was a high relationship between permeability and absorption as the regression analysis of the results provided correlation coefficient (R^2) of 0.9808. Fig 14 showed a lower relationship between porosity and absorption as the correlation coefficient (R^2) was 0.611. The higher correlation coefficient between permeability and absorption may be attributed to the fact that both permeability and absorption depend on the connectivity of capillary pores.

Permeability and porosity relationship with (W/C) and (A/C) ratios

Figs 15 to 18 show the Permeability and porosity relationship with (W/C) and (A/C) ratios. From these figures it can be seen that both permeability and porosity increased with the increase of (W/C) and (W/C) ratios. Test results showed a considerably high relationships between permeability and (A/C) ratio and between permeability and (W/C) ratio as the regression analysis provided correlation coefficients (R^2) of 0.9934 and 0.9143, respectively. Better relationships between porosity and (A/C) ratio and between porosity and (W/C) ratio were obtained as the regression analysis provided correlation coefficients (R^2) of 0.9988 and 0.9816, respectively.

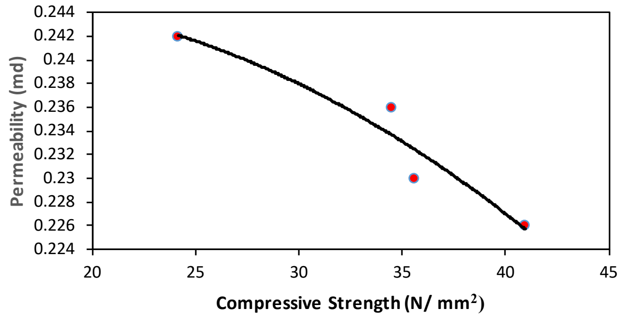

Figure 4: Variation of permeability with compressive strength when W/C constant & A/C variable

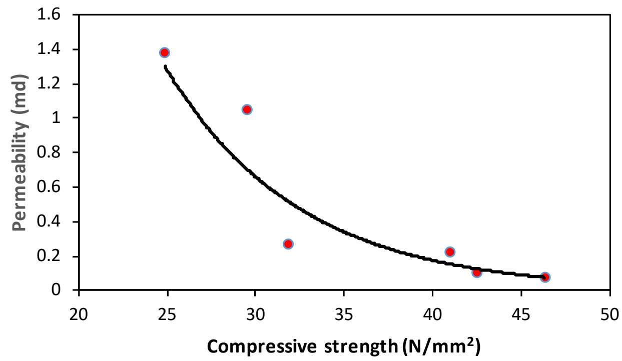

Figure 5: Variation of permeability with compressive strength when A/C constant & W/C variable

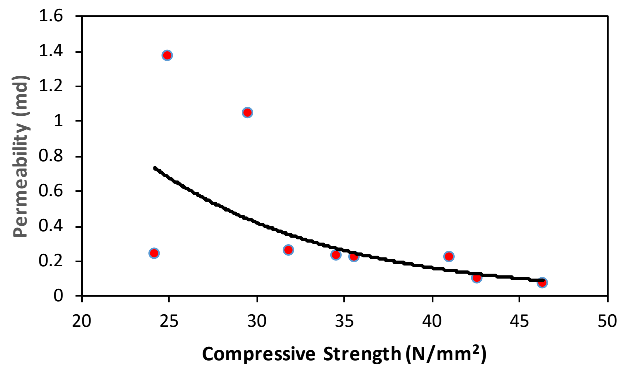

Figure 6: Variation of permeability with compressive strength when A/C & W/C are variables

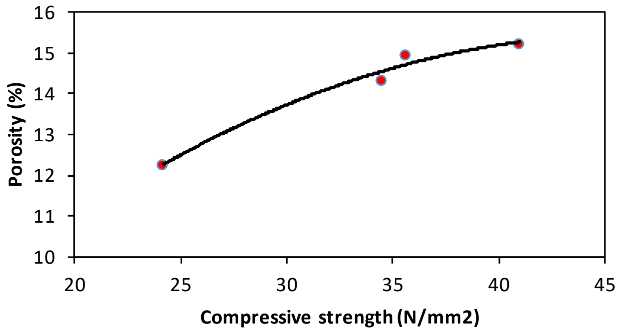

Figure 7: Variation of porosity with compressive strength when W/C constant & A/C variable

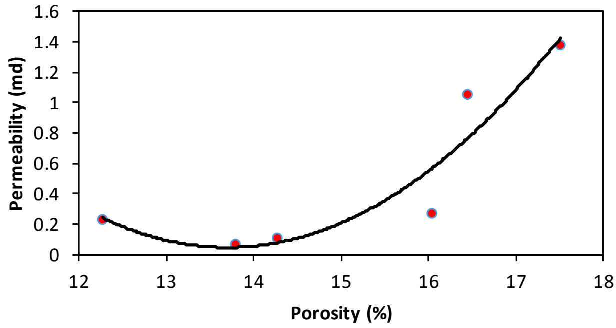

Figure 11: Variation of permeability with porosity when A/C constant & W/C variable

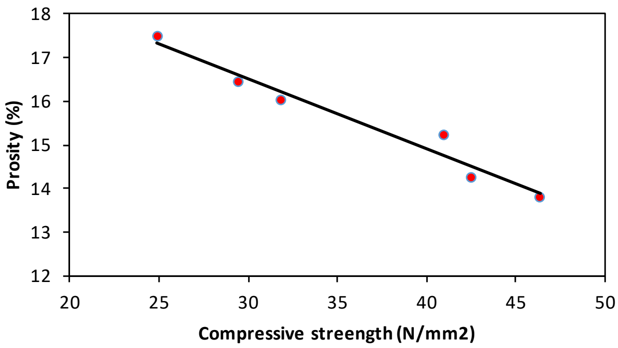

Figure 8: Variation of porosity with compressive strength when A/C constant & W/C variable

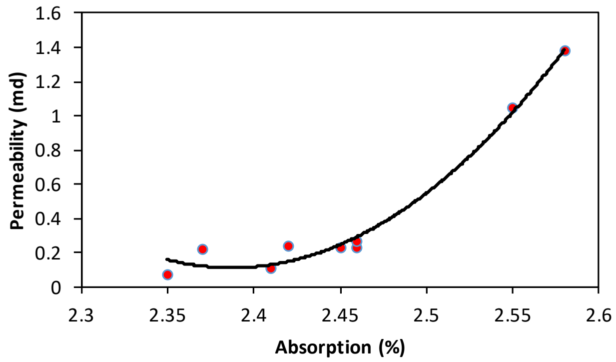

Figure 12: Variation of permeability with porosity when A/C constant & W/C variable

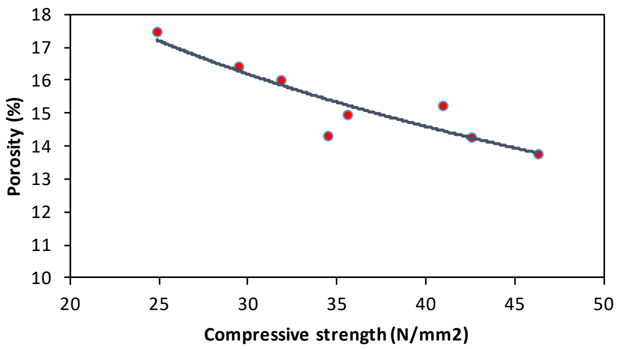

Figure 9: Variation of porosity with compressive strength when A/C & W/C are variables

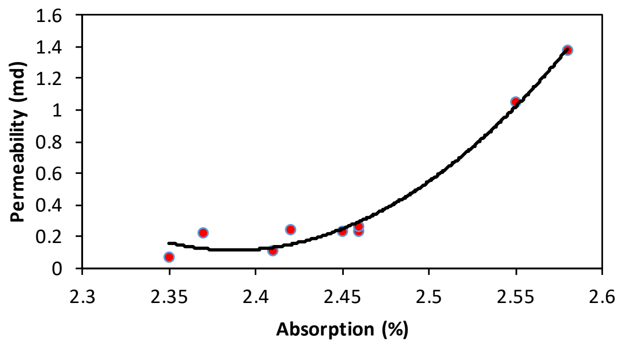

Figure 13: Variation of permeability with absorption

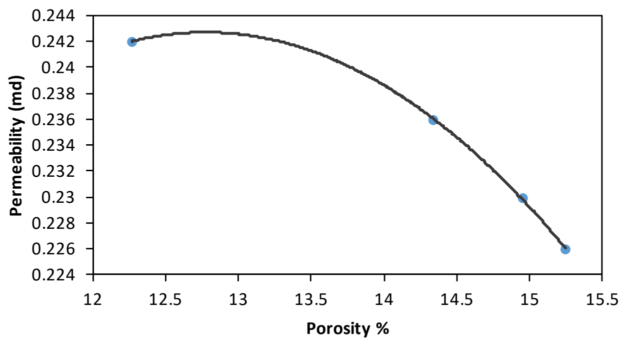

Figure 10: Variation of permeability with porosity when W/C constant & A/C variable

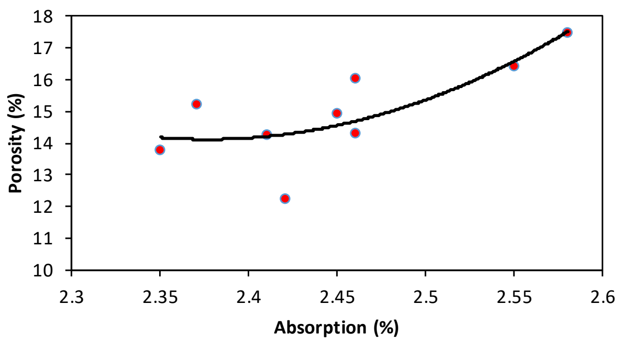

Figure 14: Variation of porosity with absorption

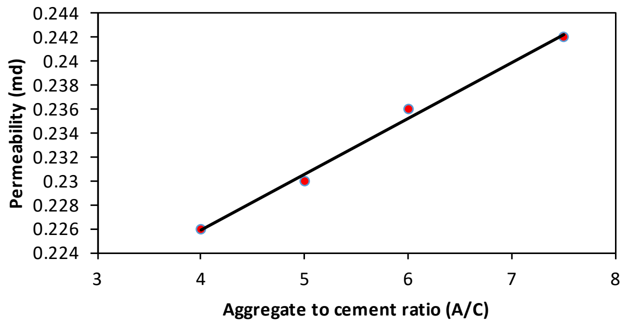

Figure 15: Variation of permeability with aggregate to cement ratio (A/C)

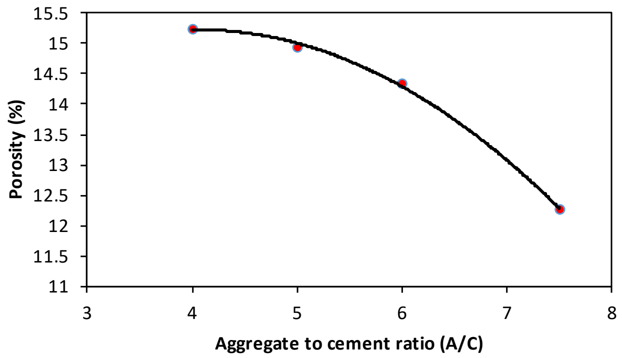

Figure 16: Variation of porosity with aggregate to cement ratio (A/C)

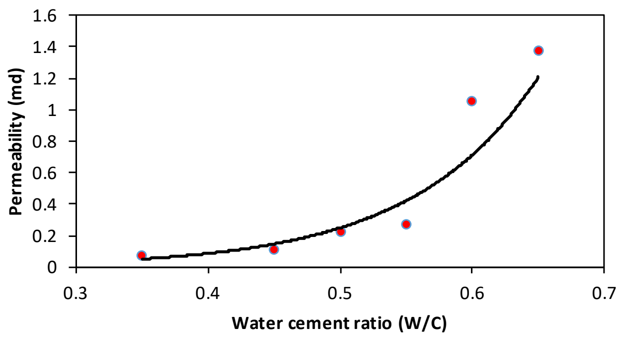

Figure 17: Variation of permeability with water to cement ratio (W/C)

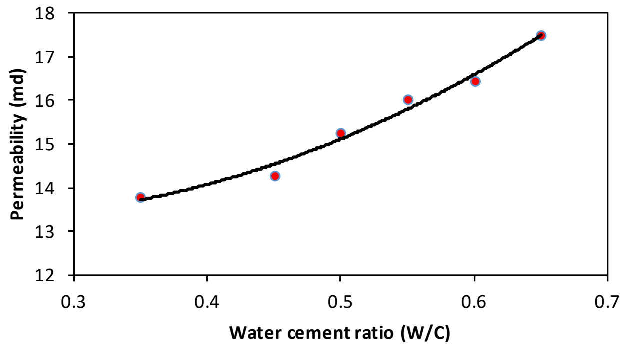

Figure 18: Variation of porosity with water to cement ratio (W/C)

CONCLUSIONS

1. Permeability, compressive strength, and absorption depend on the pore structure, but with different trends. Permeability is the property showed the higher variation with the ratio of water to cement followed by compressive strength, porosity and then absorption, as when (W/C) ratio was increased from 0.35 to 0.45, permeability increased by 1791.80%, compressive strength decreased by 55.83%, porosity increased by 26.89%, absorption increased by 9.78%, and no change was recorded in dry density.
2. The compression strength is property showed the higher variation with the aggregate to cement ratio followed by porosity and then permeability, while their effect on absorption and density is relatively small. Test results showed that when (A/C) ratio was increased from 4 to 7.5, compressive strength decreased by 41.05%, porosity decreased by 19.53% , permeability increased by 7.08%, absorption increased by dry density increased by 2.19%.
3. Based on the test results and using Microsoft Excel, many relationships were suggested between permeability and other properties of concrete which significantly affected by water to cement ratio and aggregate to cement ratio The higher relationships were observed between permeability, porosity and other properties of concrete for mixes with constant water to cement ratio and variable aggregate to cement ratio followed by when the aggregate to cement ratio was constant and the water to cement ratio was variable, while lower relationships were observed when both water to cement ratio and aggregate to cement ratios were variable.
4. The porosity showed higher relationships with compressive strength in comparison with that between permeability and compressive strength as the correlation coefficient (R^2) values were 0.9808, 0.9587 and 0.8194 for porosity and compressive strength relationships in comparison with 0.92, 0.8926, and 0.6057 for permeability and compressive strength.
5. A higher relationship between permeability and absorption was obtained as the regression analysis of the results provided correlation coefficient (R^2) of 0.9808 in comparison with that between porosity and absorption as the correlation coefficient (R^2) was 0.611 and this may be attributed to the fact that both permeability and absorption depends on the interconnectivity of capillary pores.
6. The best relationships were obtained between permeability and porosity with water to cement ratio and aggregate to cement ratio as the average correlation coefficient (R^2) was 0.972.

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