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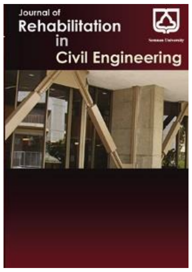

Comparative Study on Water Permeability of Concrete Using Cylindrical Chamber Method and British Standard and Its Relation with Compressive Strength

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ABSTRACT

Since the penetration of fluids (water, oil and chemicals) into concrete, plays a major role in the durability of concrete, this paper describes the effect of compressive strength of concrete on its permeability. Having revised the existing methods developed so far, the results of investigations into the permeability of different mixtures of concrete are presented. The results of the new method (cylindrical chamber method) used for the estimation of the permeability of 5 different strength grades concrete samples after different curing periods were compared with the comparative results obtained using British standard method (BS EN 12390-8:2009). These experiments tend to indicate a very good correlation between the two sets of results. Based on the test results, higher water/cement ratio and shorter curing period result in decreased compressive strength and increased permeability. The correlations between compressive strength and permeability parameters (penetration depth, average penetration flow velocity, permeability coefficient and penetration volume) are also investigated using a regression approach. It is concluded that power and second-order polynomial approximations can predict these correlations with a desirable accuracy.

1. Introduction

Fluid flow through porous media is of great importance in concrete structures. Cementitious materials like concrete are one of the porous materials which are used widely in civil engineering structures like dams, bridges and marine structures.

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Concrete water permeability is a key property which has a significant impact on its durability. Water permeability of concrete controls concrete serviceability during freezing and thawing or heating and cooling [1]. Concrete water permeability is generally measured using permeability cells. A pressure gradient is applied during the test which makes the fluid (water) to penetrate concrete [2, 3]. Recent works using new designed permeability test setups are done to evaluate concrete water permeability [4-9].

In 1988, Soongswang and et al. developed an apparatus to evaluate concrete water permeability [10]. Concrete samples with different water to cement ratios were tested using the developed setup. It was observed that a lower water to cement ratio (higher compressive strength) results in a lower permeability, regardless the curing conditions.

In 1991, Bamforth studied the relationship between water permeability of concrete and its strength [11]. 17 concrete mixes with compressive strength ranging from 16 to 100 N/mm^2 were tested for this purpose. Water permeability coefficient was measured using a test cell. He concluded that there is a semi-logarithmic relationship between water permeability and compressive strength for one day water-cured concrete samples. He also reported that curing history should be known to evaluate water permeability of concrete and compressive strength is not an efficient index to predict the water permeability of concrete.

In 1992, Armaghani and et al. studied water permeability, chloride permeability and corrosion resistance of twenty-two concrete mixtures with different combinations of fly ash and silica fume [12]. Based on their investigation, there is a poor correlation between strength and permeability. Concrete samples with equal compressive strength do not necessarily have equal permeability. They reported that durability specifications should be developed to consider both strength and permeability.

In 1997, Khatri and et al. used the constant flow and penetration depth techniques to evaluate water permeability coefficient [13]. The correlation between the two methods was also investigated. They concluded that the water permeability of concrete decreases when the compressive strength increases. The relation between initial surface absorption and in-situ strength of concrete can also be found in Ref [14].

In 2009, Al-Amoudi and et al. studied the correlation between compressive strength and water permeability, chloride permeability and chloride diffusion coefficient for plain, silica fume and fly ash cement concrete samples after 28 days of water curing [15]. A good correlation between the durability indices and compressive strength was observed using a statistical analysis. This correlation is dependent on the cementitious materials used in the mix design.

In 2013, Kondraivendhan and et al. researched the compressive strength, permeability and hydraulic diffusivity of ordinary Portland cement with or without pozzolana blended concrete [16]. They reported that the estimated permeability increases with increasing water/cement ratio and decreases with increasing curing period. They also estimated compressive strength, permeability and hydraulic diffusivity in terms of pore size distribution parameters (mean distribution radius and porosity).

In 2016, Andrzej and Marta [17] used German’s Water Permeation Test (GWT) to evaluate the permeability of three concrete bridges with two different compressive strength groups. The effect of compressive strength on the ability of concrete structure to resist water pressure was not proved, which means that compressive strength isn't an appropriate index to evaluate water permeability of concrete. They reported that a concrete sample is considered to be water permeable if velocity of water penetration is greater than a specific value.

In 2016, Cui and et al. explored the correlation between compressive strength and permeability of pervious concrete [18]. They reported that the permeability of pervious concrete increases when compressive strength decreases. There is an optimum water/cement value which results in a maximum compressive strength.

In 2017, Ishtiaq Ahmad and Anwar Hossain studied the water permeability of normal strength concrete made from clay bricks and natural stone aggregate [19]. They reported that increased water/cement ratio results in a corresponding increase in water permeability of both stone and brick aggregate concretes and Increase in compressive strength results in a corresponding decrease in water permeability of concrete and vice versa.

As water penetration into concrete effects its durability properties, this paper tends to explore the effect of concrete compressive strength on its permeability. Therefore, concrete samples with water/cement ratios ranging from 0.4 to 0.9 after 3, 7, 28, 49, 75 and 90 curing days were tested using cylindrical chamber method [20] and BS standard (EN 12390-8:2009) [21] under a 5 bar pressure for 300 minutes. The results obtained using the two sets of methods are in good agreement which shows the efficiency of the present method. The test results show that samples with higher compressive strength (lower water/cement ratio and longer curing period) are less permeable. The effect of concrete strength on penetration depth, penetration flow velocity, permeability coefficient and penetration volume and their correlations are discussed for this purpose. It is observed that the correlations between compressive strength and permeability parameters can be approximated with high accuracy using a regression approach.

2. Experiments Procedure

2.1. Sample Properties

Cubic concrete samples (15cm×15cm×15xm) used in this investigation are categorized into five compressive strength groups of 10 (C10), 20 (C20), 30 (C30), 40 (C40) and 50 (C50) *MPa* after 28 curing days. Slump values range from 30 to 50 mm. Table 1 shows concrete mixes of the five compressive strength groups. Concrete samples were demoulded after 24 hours they have been made and were put in water for curing.

Table 1. Mix designs of the samples.

Samples	*Water* kg/m^3	*Portland cement type II* kg/m^3	*Water to Cement*	*Fine aggregate* kg/m^3	*Coarse aggregate* kg/m^3
C10	185	205.6	0.9	1055	960
C20	185	264.3	0.7	921	960
C30	185	324.6	0.57	836	960
C40	185	377.6	0.49	751	960
C50	185	462.5	0.4	601.14	960

60 samples were tested in accordance with BS EN 12390-8:2009 and cylindrical chamber method and 60 samples were tested using the compressive testing machine.

2.2. Compressive Strength Tests

The compressive strength results of samples with different curing periods are listed in Table 2. The compressive testing machine is shown in Fig. 1.

Fig. 1. Compressive testing machine.

Table 2. Compressive strength of the samples after 3, 7, 28, 49, 75 and 90 curing days (*MPa*)

SAMPLE	3 DAYS	7 DAYS	28 DAYS	49 DAYS	75 DAY	90 DAYS
C10	4.78	5.79	7.4	11.41	12.15	13.6
C20	8.34	13.58	20.62	22	23	27.34
C30	13.8	18.6	30.81	34.32	35.11	39.08
C40	20.45	23	41.03	41.66	41.94	42.95
C50	25.13	28.7	44.76	53.88	61.51	61.98

Fig. 2 shows the relation between compressive strength and curing period. It is observed that compressive strength increases when curing period increases. It is also concluded that higher water/cement ratio results in samples with lower compressive strength.

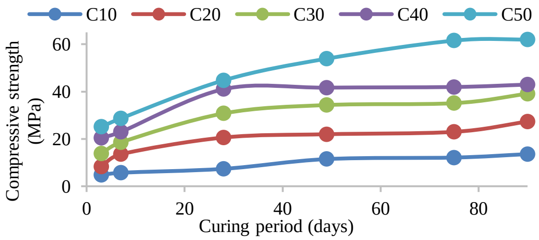
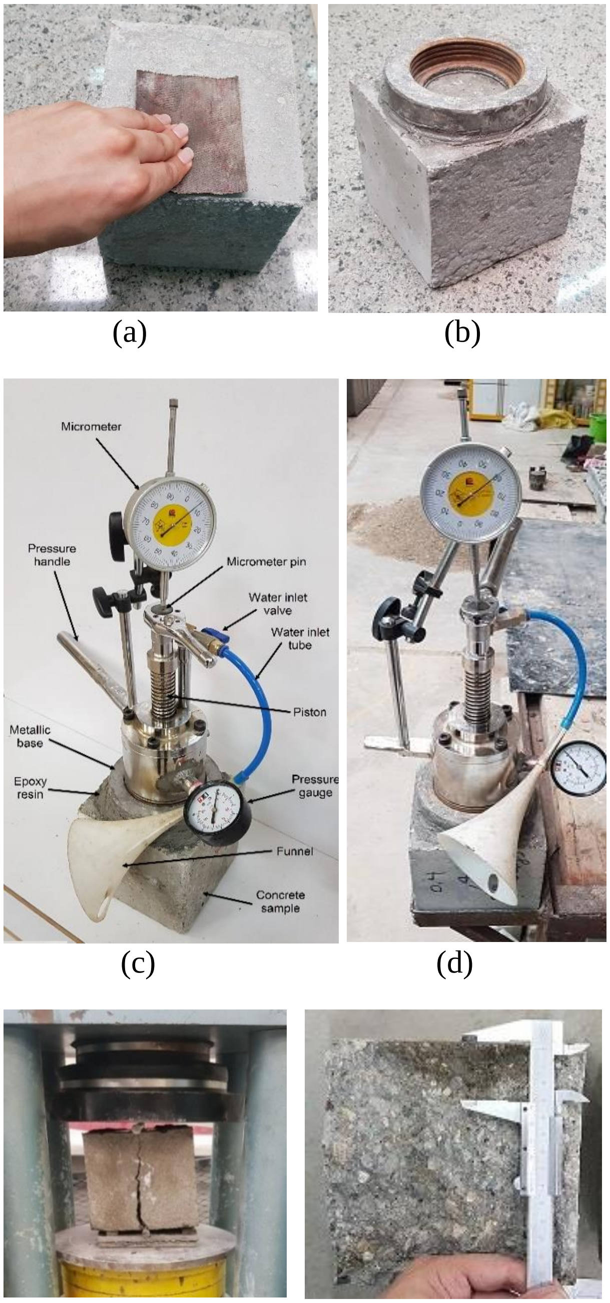


Fig. 2. Compressive strength of samples after 3, 7, 28, 49, 75 and 90 curing days.

2.3. Permeability Tests

Cylindrical chamber method was devised and developed by Naderi in 2011 and registered under the patent no.67726 [11]. In this method the setup of which is shown in Fig. 3, a metallic base is attached to the surface of the material the permeability of which is to be measured, using epoxy resin. Concrete surface should be cleaned before bonding the metallic base to provide a good adhesiveness between the surfaces. Depending on the epoxy resin curing time, several hours are needed to ensure that an adequate adhesiveness exists between the concrete surface and the metallic base. Then the whole setup is attached to the metallic base. An O-ring is placed between the setup and the metallic base, which seals the whole system. A water inlet tube also exists at the top of the pressure chamber. When the Pressure chamber is filled with water, the pressure inlet is closed using the pressure inlet valve and the pressure handle is turned which causes a piston to move downward and the pressure increases. The extra water and air exit the system through a de-airing hole provided in the setup. This process continues until the desired water pressure is displayed on the pressure gauge. As the water penetrates the concrete voids, water pressure decreases. So it is necessary to keep the water pressure at the desired constant value by turning the pressure handle. The setup is also provided with a micrometer. The micrometer pin is attached to the top of the piston surface. So the downward movement value of the piston is shown using the micrometer and the water penetration into concrete can be read at any time. The volume of water penetrated into concrete voids can be measured by multiplying the recorded micrometer readings by the pressure surface (surface of the piston) at any time. The

Advantages of the cylindrical chamber method are listed in Table 3.



(a) (b) (c) (d) (e) (f)

Fig. 3. Cylindrical chamber test setup and the test procedure; (a) Cleaning the sample surface (b) Metallic base attached to the sample (c) Cylindrical chamber setup (d) Permeability test (e) Sample split in half (f) Measuring penetration depth.

Table 3. The advantages of the cylindrical chamber method.

Advantage	
The simplicity of doing the permeability test	Being cost-effective
The ability of being used for other materials like mortars and bricks	The ability to repeat the test, portability of the setup
The ability to do in-situ tests	Doing the test in a semi-destructive manner
The test can be done without having any prior knowledge and skill	The sample size doesn't influence the test procedure
Permeability is evaluated quantitatively	The ability to do the test in places where sampling is impossible

In this investigation concrete samples were tested using cylindrical chamber method under a pressure equal to 5 bar for 5 hours and the micrometer values were read based on the schedule listed in Table 4. The time interval of the readings increases as the test continues. This is because the velocity of water penetration into concrete voids decreases by the passing of time.

Table. 4. Reading schedule of the micrometer.

Time interval	**Reading time interval (minute)**
0-10	1
10-20	2
20-80	5
80-300	10

Based on the compressive strength and porosity of the samples two cases can happen:

1- Sample with low compressive strength and high porosity: All of the water in the pressure chamber penetrates the sample. So the test duration is shorter than 5 hours.

2- Sample with high compressive strength and low porosity: The test continues for 5 hours (some water remains in the pressure chamber at the end of the test.)

The test duration measured using cylindrical chamber method for the samples are listed in Table 5. (The failure of the C10 samples after

3 and 7 curing days was observed in the first two minutes of the test due to the applied pressure and no data were recorded).

Table 5. The test duration of the samples (minutes).

Sample	*3 days*	*7 days*	*28 days*	*49 days*	*75 days*	*90 days*
C10	-	-	45	120	110	140
C20	14	35	130	300	300	300
C30	30	90	300	300	300	300
C40	160	300	300	300	300	300
C50	180	300	300	300	300	300

In accordance with BS EN 12390-8:2009 the test should be started when the specimen is at least 28 days old under a water pressure of 50 bar for 72 hours, but the concrete samples were tested for 5 hours in this investigation to make a comparison between the cylindrical chamber method and BS EN 12390-8:2009 results. After the test ends, samples are split in half and the maximum penetration depth is measured. It is impossible to measure the volume of water penetration using BS EN 12390-8:2009 procedure. BS setup should be equipped with extra equipments for this purpose. This is an advantage of the cylindrical chamber method. The BS testing machine is shown in Fig. 4.

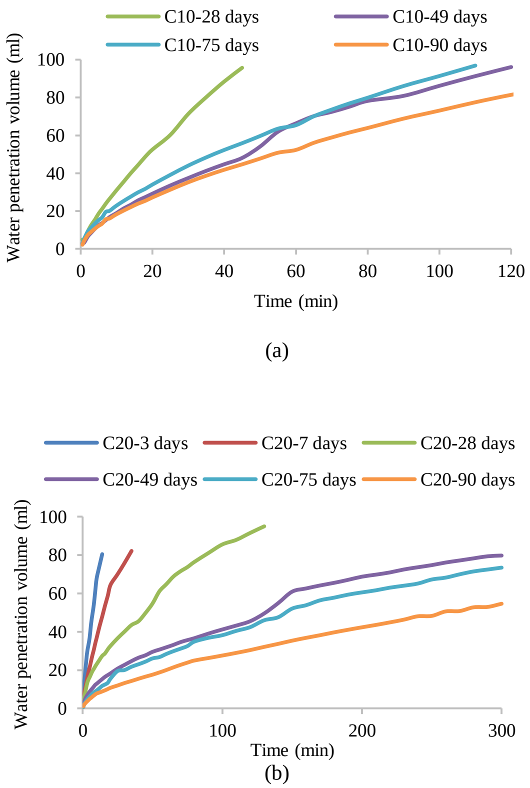
Fig. 4. BS permeability testing machine.

3. Results and Discussion

Water penetration volume, water flow rate, water flow velocity, depth of penetration, and the effects of compressive strength and curing period on water permeability of C10, C20, C30, C40 and C50 samples are discussed in this section. The correlation between permeability parameters and compressive strength are also investigated using a regression approach.

3.1. Water Penetration Volume, Penetration Flow Rate, Penetration Flow Velocity and Penetration Depth of the Samples

The water penetration volume of concrete samples after different curing periods are shown in Fig. 5.



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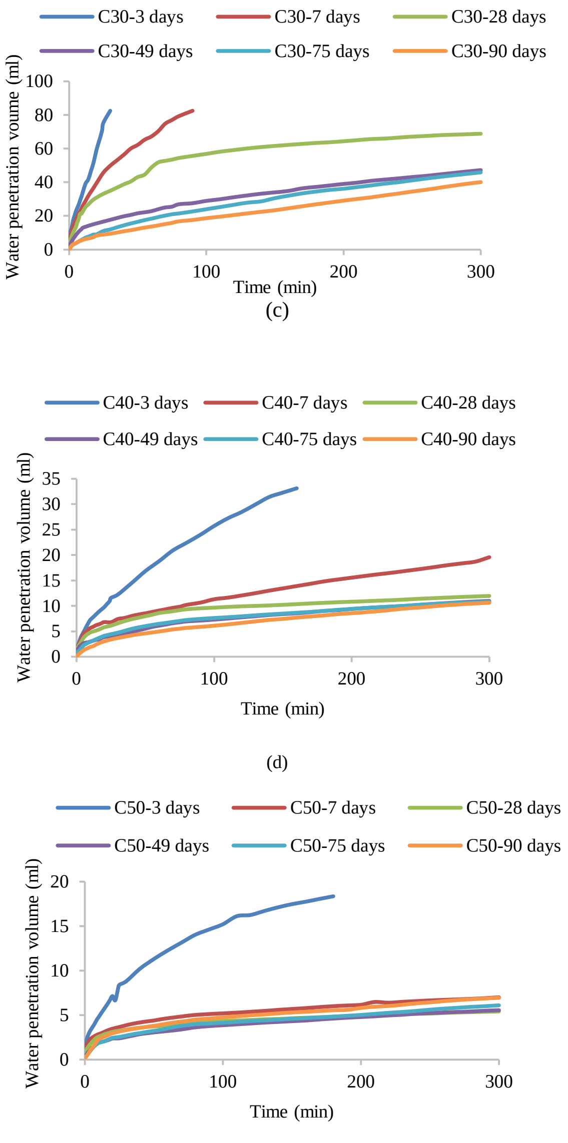


(c)

(d)

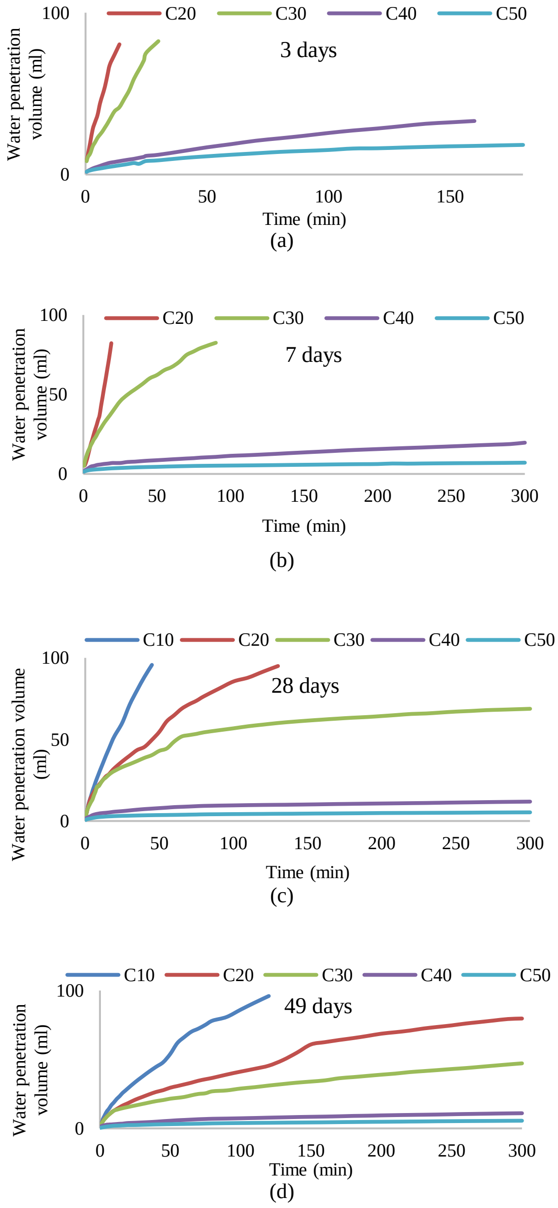
(e)

Fig. 5. The water penetration volume of the samples with different strength grades and curing periods; (a) C10 (b) C20 (c) C30 (d) C40 (e) C50 samples.

Based on Fig. 5, it is obvious that water penetration volume decreases when curing period increases. This is due to the hydration process. The capillary pores are filled with hydration products as hydration process progresses. So capillary pores porosity and their connectivity decrease, results in a less permeable concrete. It is seen that concrete samples after 3 days of curing have the highest water penetration volume while concrete samples after 90 days of curing have the lowest water penetration volume. As curing period increases, water penetration volume-time diagrams of a specific strength grade become closer. This is due to the change of hydration rate with time. Hydration occurs at a faster rate in the early stages after concrete placement and slows down as curing period increases until the hydration stops. This trend is clearly observed in penetration volume-time diagrams of samples with higher strength grades (C30, C40 and C50). Penetration volume-time diagrams of C40 and C50 samples after 49 days, 75 days and 90 curing days are approximately coincident. It is also evident that the slope of the diagrams decreases as permeability test duration increases, which shows the rate of water penetrating the samples becomes slower as permeability test continues. Water penetration rate stabilizes at a constant value with increasing the test duration. Samples with higher strength grades stabilizes at their final water penetration rate faster than samples with lower compressive strength.

The gap between penetration volume-time diagrams of the samples after 3 and 7 curing days increases significantly with increasing compressive strength. The compressive strength of the samples with lower water to cement ratio increases with a faster rate, which leads to larger obvious gaps between the penetration volume-time diagrams of the samples at early ages.

The effect of concrete strength grade on permeability after a specific curing time can be seen in Fig. 6. It is seen that after a specific curing period C50 samples have the lowest water penetration volume, while C10 samples have the highest one. It means that samples with higher strength grades are less porous. It is also seen that as curing period increases, penetration volume-time diagrams of concrete with higher strength grades become closer. This trend can be seen for C40 and C50 samples. As the test continues, the slope of the penetration volume-time diagram decreases and finally stabilizes at a constant value, which shows that concrete voids are filled with more water with increasing the test duration. The rate of water penetration decreases as the test continues.



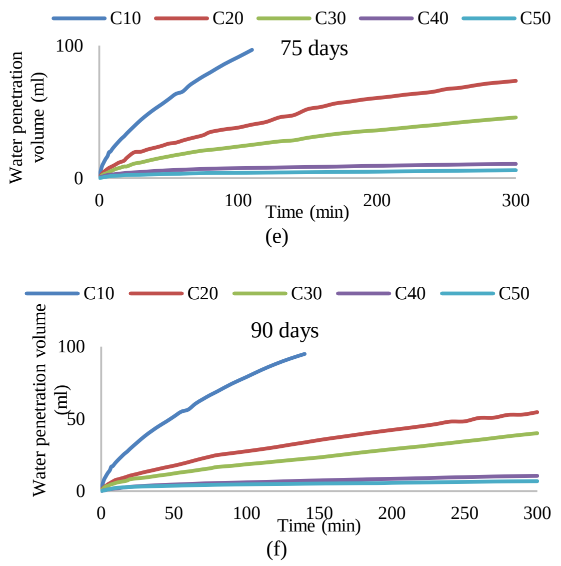


Fig. 6. The water penetration volume of the samples with different strength grades after a specific curing period; (a) 3 days (b) 7 days (c) 28 days (d) 49 days (e) 75 days (f) 90 days.

The total water penetration volume of all concrete samples obtained using cylindrical chamber method is shown in Fig. 7. Based on the bar graph, the C50 samples have the lowest total water penetration volume while the C10 samples have the maximum ones. It is seen that the total water penetration volume and effective porosity decrease as curing time increases. In some cases like C20 samples, it is seen that the total water penetration volume of the samples after 28 curing days is lower than the total water penetration volume after 49 curing days. This is due the test duration which is 130 minutes for C20 sample after 28 curing days and 300 minutes for the sample after 49 curing days.

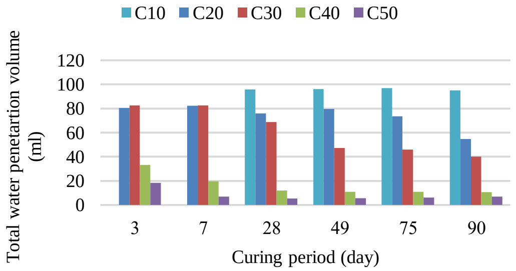
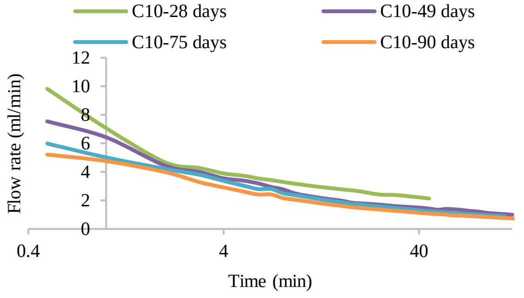
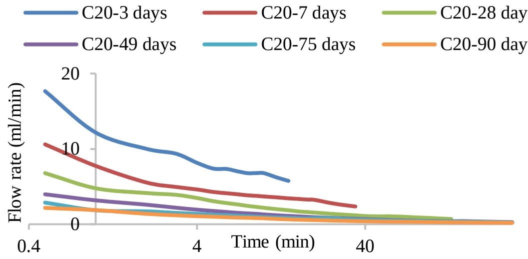


Fig. 7. The total water penetration volume of the samples after different curing periods.

Penetration flow rate of the samples after different curing periods is also shown in Fig. 8. A base-10 logarithmic scale is used for the time axis to make a more accurate comparison. The same conclusions drawn for water penetration volume are drawn. It is evident that penetration flow rate decreases with increasing curing period. The slope of the flow rate diagram also decreases as the test continues and finally stabilizes at a constant value. This constant value decreases as compressive strength increases. The final constant value tends to zero with increasing the test duration and curing period.



(a)



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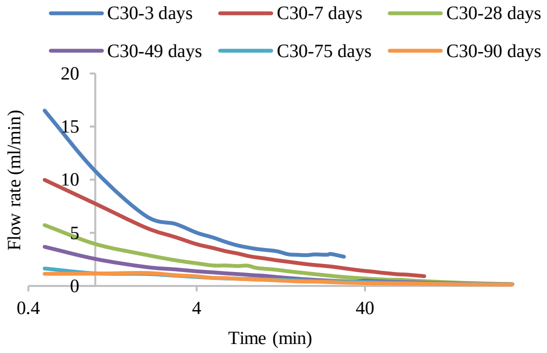

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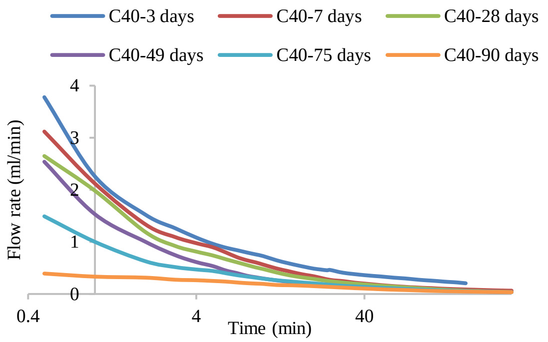

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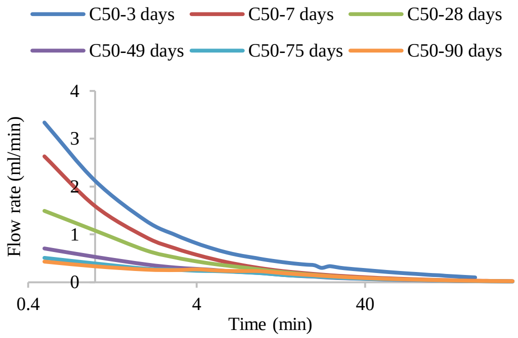
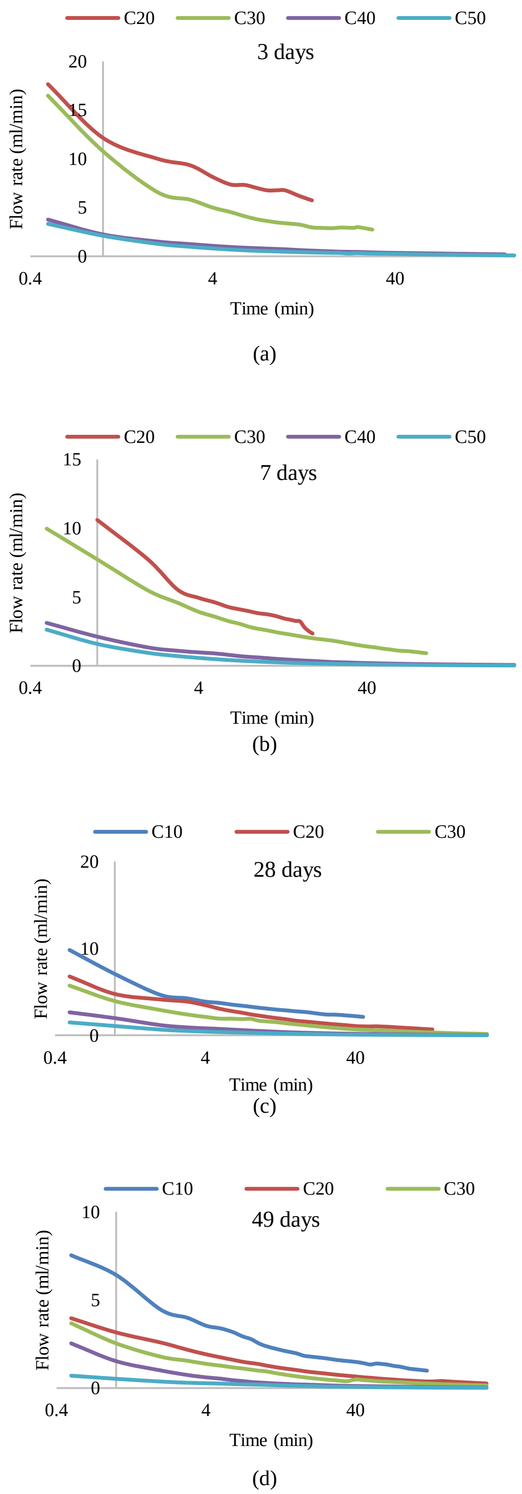


(e)

Fig. 8. The penetration flow rate of the samples with different strength grades after different curing periods; (a) C10 (b) C20 (c) C30 (d) C40 (e) C50 samples.

The flow rate of the samples with different strength grades after a specific curing time is shown in Fig. 9. The flow rate of the samples with higher compressive strength grade is lower than that of the samples with lower compressive strength. The C10 samples have the highest penetration flow rates and the C50 samples have the lowest ones. The diagram of penetration flow rate-time of the C20 and C30 samples are approximately coincident. The same trend is seen for the C40 and C50 samples. It can be concluded that samples with lower effective porosity has lower penetration flow rate.



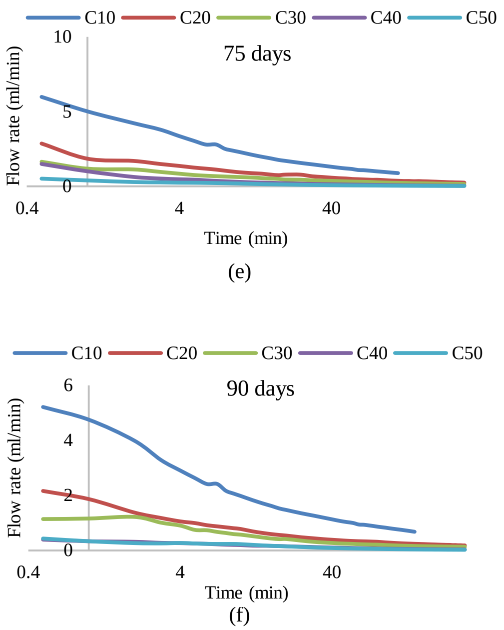


Fig. 9. The penetration flow rate of the samples with different strength grades after a specific curing period; (a) 3 days (b) 7 days (c) 28 days (d) 49 days (e) 75 days (f) 90 days.

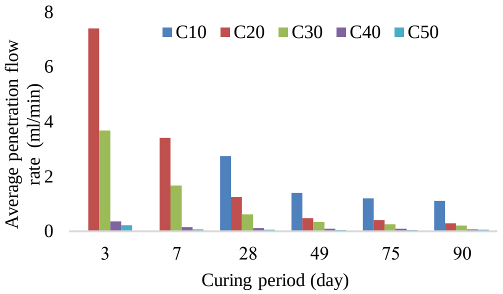


Fig. 10. The average penetration flow rate of the samples after different curing periods.

The average penetration flow rate of the samples was calculated by dividing the area under the penetration flow rate-time curve by test duration which is shown in Fig. 10. Based on the bar diagram, there is an inverse correlation between curing period and average penetration flow rate. An inverse correlation also exists between compressive strength and average penetration flow rate. It is seen that the penetration flow rate of the C40 and C50 samples is approximately equal to zero which shows the efficient durability of these samples to resist water penetration.

The C10 samples are the least durable ones in this investigation.

Penetration velocity is calculated by dividing the flow rate by the area over which the pressure is applied. So flow velocity-time diagrams of the samples are not discussed due to their similarity to flow rate-time diagrams. The same conclusions are drawn. As an example, the average flow velocity of the samples are shown in Fig. 11. It is seen that the average penetration flow velocity decreases as curing period and compressive strength increase.

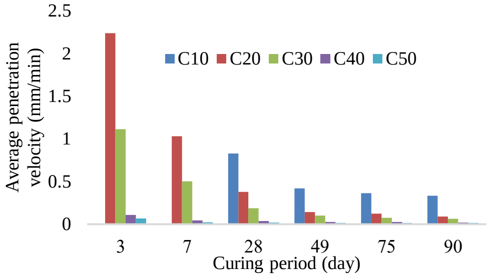


Fig. 11. The average penetration flow velocity of the samples after different curing periods.

3.2. Penetration Depth of the Samples Obtained Using Cylindrical Chamber Method and BS Standard

The penetration depth results obtained using cylindrical chamber method and BS standard are shown in Figs. 12 and 13. Water penetrated through the whole thickness of the C10 samples regarding the curing period. Water penetration depth is also equal to the thickness of the C20 samples after 3 and 7 curing days and C30 samples after 3 curing days. Other samples were durable enough and water couldn't penetrate through the whole thickness of the samples. In accordance with the cylindrical and BS permeability tests, penetration depth decreases with increasing curing period. It is also seen that concrete samples with higher compressive strength have lower penetration depth. So it is concluded that the C50 samples are the most durable samples and C10 are the least durable ones.

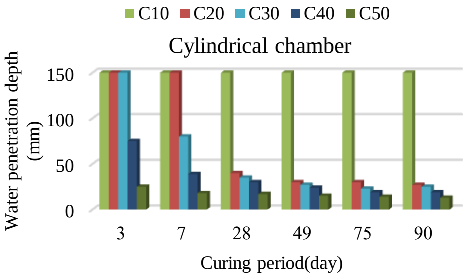


Fig. 12. The ater penetration depth of the samples obtained using cylindrical chamber method.

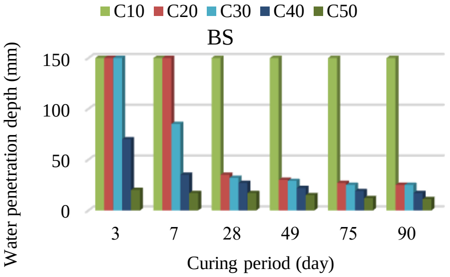
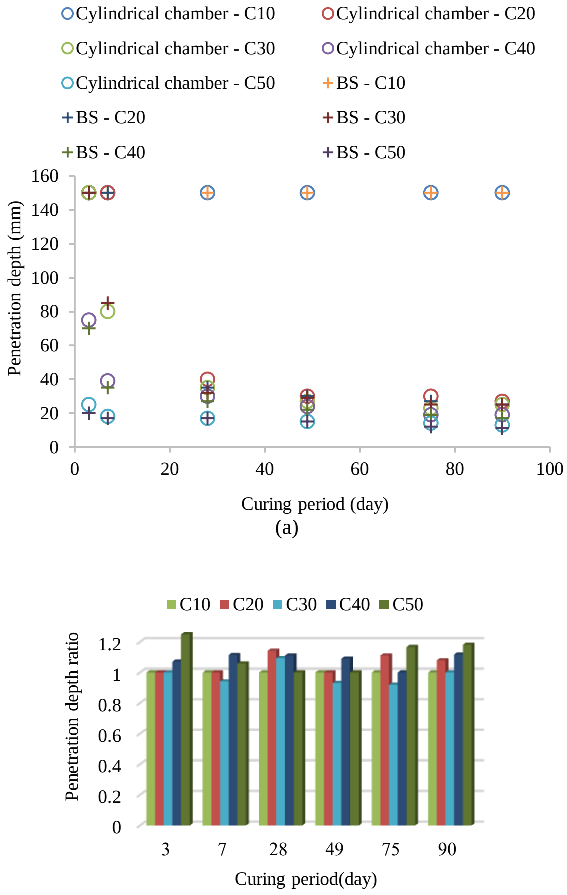


Fig. 13. The water penetration depth of the samples obtained using BS method.

Penetration depths of the samples after different curing periods obtained using cylindrical chamber and BS permeability tests are shown in Fig. 14a for comparison. It is seen that there is a good correlation between the two methods. To make a more accurate comparison between the obtained results, the ratio of the cylindrical chamber penetration depth to BS penetration depth was calculated and shown in Fig. 14b. Penetration depth ratio changes from 0.92 for C30 samples after 75 curing days and 1.25 for C50 samples after 3 curing days. There is a good accordance between the results obtained using the two methods.



(a)

(b)

Fig. 14. a) The penetration depth of the samples after different curing periods. b) The penetration depth ratio of the samples.

3.3. Permeability Coefficient Calculation

Based on Darcy's Law [22]:

$$u = \frac{d\chi}{dt} = Ki = k\frac{p}{\chi\mu} \rightarrow \chi . d\chi = \frac{kp}{\mu}dt \quad (1)$$

u is the flow velocity (m/s), χ is the penetration depth (m), t is the test duration (s), k is the permeability coefficient (m^2), i is the hydraulic gradient (unitless), p is the pressure (N/m^2) and μ is the dynamic viscosity of water ($N.s/m^2$). By integrating Eq. 1 with initial condition as $t=0$, $\chi = 0$

$$\frac{\chi^2}{2} = \frac{kp}{\mu}t \rightarrow k = \frac{\mu\chi^2}{2pt} \quad (2)$$

Eq. 2 is used to calculate water permeability coefficient. Table 6 shows the permeability coefficients obtained using cylindrical chamber method.

Table 6. The permeability coefficient obtained using cylindrical chamber method.

	Permeability coefficient (m^2) - Cylindrical chamber					
samples	3 days	7 days	28 days	49 days	75 days	90 days
C10	-	-	7.42E-15	2.78E-15	3.03E-15	2.38E-15
C20	2.38E-14	9.82E-15	1.83E-16	4.45E-17	4.45E-17	3.6E-17
C30	1.11E-14	1.05E-15	6.06E-17	3.6E-17	2.62E-17	3.09E-17
C40	5.21E-16	7.52E-17	4.45E-17	2.85E-17	1.78E-17	1.78E-17
C50	5.15E-17	1.6E-17	1.43E-17	1.11E-17	9.69E-18	8.36E-18

It is observed that permeability coefficient decreases as curing period and compressive strength increase.

3.4. Correlation between compressive strength and permeability parameters

The correlations between compressive strength and permeability parameters obtained using cylindrical chamber method (penetration depth, average penetration flow velocity, permeability coefficient and penetration volume) are approximated using different regression curves. The results obtained using different approximations are listed in table 7.

Table 7. The prediction of the correlation between permeability parameters and compressive strength using different regression curves.

Regression curve	*Compressive strength-penetration depth*	*Compressive strength-average flow velocity*	*Compressive strength-permeability coefficient*	*Compressive strength-penetration volume*
Linear	$-2.9441x+147.17$ $R^2=0.6681$	$-0.0193x+0.08649$ $R^2=0.3744$	$(-2e-16)x+(7e-15)$ $R^2=0.2775$	$-1.8821x+102.95$ $R^2=0.6935$
Second-order polynomial	$0.0935x^2+8.8666x+216.08$ $R^2=0.8617$	$0.0009x^2-0.0773x+1.6154$ $R^2=0.5741$	$(1e-17)x^2-(8e-16)x+(2e-14)$ $R^2=0.4968$	$0.0297x^2-3.8609x+128.57$ $R^2=0.7389$
Third-order polynomial	$-0.001x^3+0.1972x^2-11.73x+253.7$ $R^2=0.8673$	$-0.00004x^3+0.0046x^2-0.1875x+2.4946$ $R^2=0.6434$	$(-5e-19)x^3+(6e-17)x^2-(2e-15)x+(3e-14)$ $R^2=0.6042$	$0.0005x^3-0.0201x^2-2.3763x+116.73$ $R^2=0.7413$
Fourth-order polynomial	$-(2e-4)x^4+0.0315x^3-1.1966x^2+10.418x+134$ $R^2=0.9163$	$(9e-7)x^4-(2e-4)x^3+0.0104x^2-0.2895x+3.0577$ $R^2=0.6499$	$(1e-20)x^4-(2e-18)x^3+(1e-16)x^2-(4e-15)x+(3e-14)$ $R^2=0.6146$	$(-3E-6)x^4-(0.0009)x^3-0.0381x^2-2.0595x+114.98$ $R^2=0.7414$
Exponential	$177.26e^{-0.005x}$ $R^2=0.7966$	$1.275e^{-0.085x}$ $R^2=0.7740$	$(8e-15)e^{-0.137}$ $R^2=0.7184$	$171.72e^{-0.058}$ $R^2=0.7101$
Logarithmic	$-75.28\ln(x)+300.73$ $R^2=0.8049$	$-0.611\ln(x)+2.2698$ $R^2=0.5365$	$(-6e-15)\ln(x)+(2e-14)$ $R^2=0.4397$	$-50.61\ln(x)+211.15$ $R^2=0.7190$
Power	$1897.1x^{-1.204}$ $R^2=0.8458$	$188.59x^{-2.318}$ $R^2=0.8294$	$(-5e-11)x^{3.974}$ $R^2=0.8617$	$3557.7x^{-1.466}$ $R^2=0.6489$

As penetration flow velocity is the penetration flow rate per flow area, the strength-average penetration flow rate isn't discussed. Based on table 7, a higher coefficient of determination (R^2 in the table) is obtained using third-order and fourth-order polynomial regression curves in approximating the strength-penetration depth correlation, but the data trend isn't approximated accurately (A similar trend exists for the strength-penetration volume correlation). The power regression curve is the most accurate one to approximate the data trend. The power regression curve also approximates the strength-average penetration flow velocity and strength-permeability coefficient correlation with a higher coefficient of determination than other regression curves used in this investigation. In the case of strength-penetration volume correlation, a second-order regression curve satisfies both the accuracy and data trend. The approximated curves of strength-permeability parameters using the regression curves are shown in Figs. 15-18.

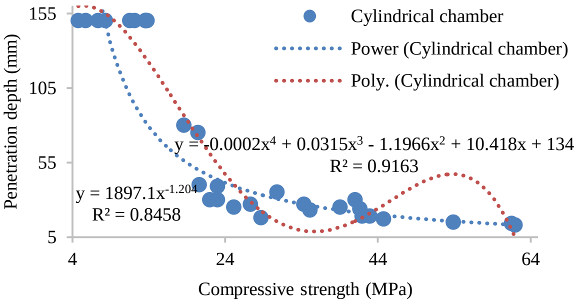


Fig. 15. The approximation of the compressive strength-penetration depth correlation with fourth-order polynomial and power regression curves.

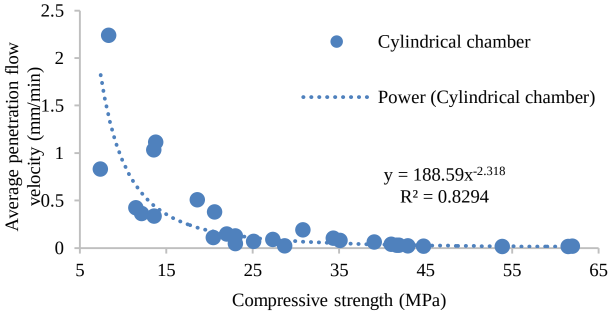


Fig. 16. The approximation of the compressive strength-average penetration flow velocity correlation with power regression curve.

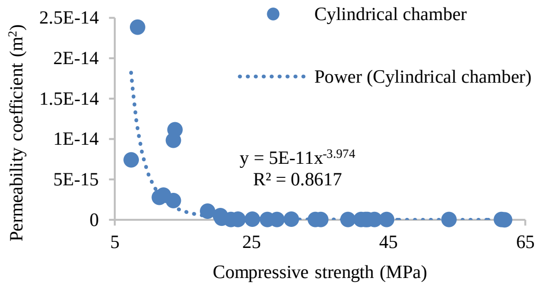


Fig. 17. The approximation of the compressive strength-permeability coefficient correlation with power regression curve.

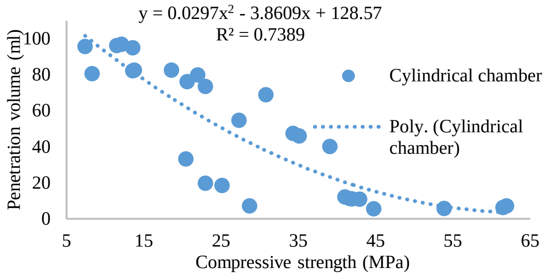


Fig. 18. The approximation of the compressive strength-Penetration volume correlation with second-order regression curve.

It is concluded that a high accurate approximation of compressive strength-permeability parameters correlation is achieved using power and second-order polynomial regression curves.

4. Conclusion

In this investigation samples with five different strength groups were tested using cylindrical chamber and BS methods. The following conclusions are drawn:

- As curing period increases, capillary pores porosity decreases due to hydration which results in a less permeable concrete. So based on the curing periods used in this investigation, for a specific mix design the samples after 3 and 90 curing days are the most and the least permeable ones respectively. The penetration depth, penetration volume, flow rate and flow velocity results obtained after different curing periods using cylindrical chamber method confirm this conclusion.
- For samples with a specific strength grade, penetration volume-time diagrams become closer with increasing curing period. This trend is clearer for samples with higher strength grades, which can be seen for samples after 75 and 90 curing days. The gaps between the diagrams at early ages of the samples are larger than the samples after longer curing periods (The same conclusion is drawn for flow rate-time and flow velocity-time diagrams).
- It is observed that after a specific curing period, penetration depth, penetration volume, flow rate and flow velocity results of the C50 samples are lower than the corresponding parameters of the other samples and the C10 samples are the most permeable ones. After a specific curing period, samples with higher compressive strength are less permeable
- The sample voids are filled with more water with increasing the test duration. So penetration flow velocity and flow rate decrease and finally stabilize at constant values. These constant values are higher for concretes with lower compressive strength.
- It is observed that water penetrated through the whole depth of the C10 samples regarding the curing period. These samples were not durable enough to resist water penetration.

The C50 samples were the most durable ones.

- Samples with different water/cement ratios after different curing periods were tested in this investigation. A lower water/cement ratio and a longer curing period result in concrete samples with a higher compressive strength and durability.
- The penetration depth of the samples measured using cylindrical chamber and BS method were very close which shows a good correlation between the two methods.
- The penetration depth is the only parameter obtained using BS method. The penetration depth is measured after splitting the sample which needs the sampling of the concrete for in-situ permeability tests. More quantitative parameters (flow rate, flow velocity and penetration volume) are obtained using cylindrical chamber method. These parameters can also be used to evaluate the concrete durability in a semi-destructive manner.
- The correlations between compressive strength and permeability parameters were investigated. It was observed that these correlations can be approximated using mathematical regression curves with high accuracy. Power and second-order polynomial approximations predicted the correlations more accurately considering the data trend.

The water permeability test presented in this study was based on a 5 bar pressure and mix designs without any admixtures. It is practical to do further investigations to evaluate the effect of different pressure values and admixtures on the water permeability of concrete samples. It was also observed that power and second-order polynomial regression curves predict the correlations between compressive strength and permeability parameters efficiently. The efficiency of these approximations should be investigated for concrete samples with different admixtures under different pressure values.

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