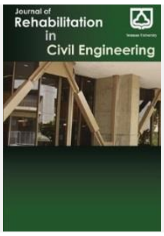

Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

Effects of Polycarboxylate-Lignosulfonate Superplasticizer on the Engineering Properties and Cementitious Paste Thickness of Pervious Concrete

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ARTICLE INFO

Article history:
Received: 31 March 2023
Revised: 03 July 2023
Accepted: 14 September 2023

Keywords:
Pervious concrete;
Polycarboxylate-lignosulfonate superplasticizer;
Cementitious Paste Thickness;
Mechanical properties;
Porosity and permeability.

ABSTRACT

This study investigates the effects of polycarboxylate-lignosulfonate superplasticizer (PLS), water, and cement content on mechanical, physical and cementitious paste thickness of pervious concrete (PC) for its further application in urban areas. For this reason, 17 PC mixtures containing different portions of PLS (0.10% to 1.00% of the cement content), water-to-cement ratio (0.30 to 0.40), and cement content (315 to 350 kg/m3) with a constant range aggregate size (4.75 to 9.5 mm) were designed, tested, and analyzed by Design of Expert (DoE). The results showed that increasing the proportion of PLS, water, and cement increased the compressive strength of PC at ages of 7, 11, and 28 days. However, the permeability and porosity would decrease due to formation of a pasty mixture. The effect of water content on changing the compressive strength was more significant than other variables, especially in the range of 0.3 to 0.35. Apart from this, increasing the portion of variables resulted in increasing the average cementitious paste thickness and the number of line segments, which both resulted in an increment of compressive strength. The PC mixture with 1.00% of PLS, W/C ratio of 0.40, and cement content of 350 kg/m3 had the maximum compressive strength of 18.35 MPa with reasonable porosity and permeability. This system is suitable as pavements in urban areas with light-traffic load, green spaces, and sidewalks to mitigate the anthropization impacts.

E-ISSN: 2345-4423

How to cite this article:
Teymouri, E., Noraziemah Mohd Pauzi, N., Kwong Soon, W., Forouzan, M., & Salari, M. (2024). Effects of Polycarboxylate-Lignosulfonate Superplasticizer on the Engineering Properties and Cementitious Paste Thickness of Pervious Concrete. Journal of Rehabilitation in Civil Engineering, 12(3), 61-84. https://doi.org/10.22075/jrce.2023.30291.1832

1. Introduction

Anthropization is the act of transforming natural environments and open spaces to meet specific functions by human activities, especially during urbanization process. Although identifying a space's accurate level of anthropization unattainable, the consequences of such activities are prominent and provide a general estimation on the matter. The impact of urbanization for instance could cause flooding, rapid urban runoffs, prevent underground water recharging, and intensification of greenhouse and heat island effects [1,2]. In a natural soil, only 10% of total rainwater should flow as runoff while the residual proportion of water should dissipate through evapotranspries and infiltration process [3]. However, impervious surfaces in urban areas are responsible for more than 50% of the whole area; thus, hindering the effectiveness of infiltration process. For instance, Fig. 1 shows the distribution of green spaces, which have a high percentage of permeable surfaces, in 22 different regions of Tehran. This data establishes that a vast part of Tehran is covered by concrete, asphalt, and other impermeable pavements [4]. Besides, the permeable surfaces distribution throughout the different regions of Tehran is also imbalanced, which complicate matters further. Pervious Concrete (PC) provides significant benefits in mitigating the detrimental impacts of anthropization in urban areas by avoid flooding and recharging underground waters. Hence, it is crucial to study the performance of PC as a viable and effective solution as a permeable pavement.

PC is an eco-friendly type of concrete, which consists of either little or no fine-grain aggregate, and has manifold interconnected pores which allows water and air through it. This system has the ability to decrease stormwaters volume, and capture the pollutants of stormwater and wastewater within its pores [5,6]. This system is applicable in light-traffic areas, tennis court, pedestrian paths and walkways, parking areas, residential streets, greenhouses, and alleys [5,7–11]. In addition, sound adsorption and road noises reduction are other merits of this system, which allows escaping of air between the pavement and tire; hence, generating a lower frequency of road noise [12].

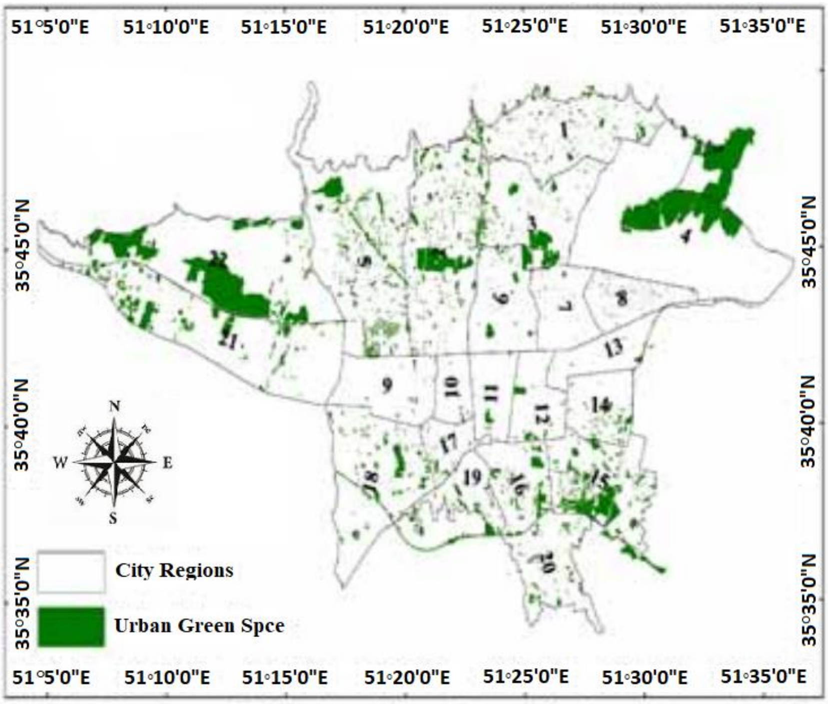
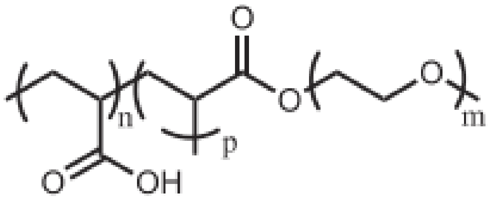


Fig. 1. Distribution of green spaces in 22 regions of Tehran (modified from [4]).

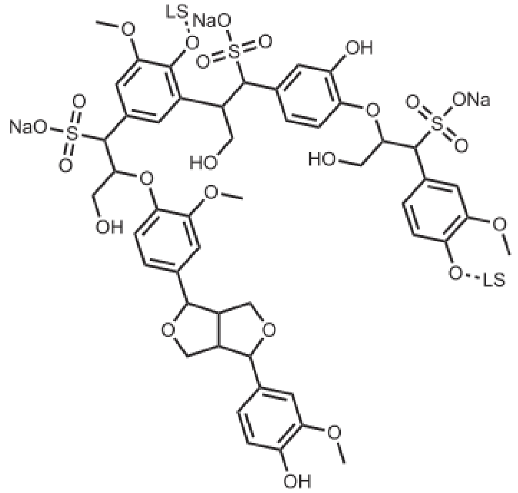
Nevertheless, PC still inherits several negative points, such as lower compressive strength and abrasion resistance in comparison to ordinary concrete, clogging issues, and poor durability [13–18]. The mechanical and physical properties of PC could be enhanced by using superplasticizers and changing its mixture design. Therefore, it is essential to determine an optimum PC mixture for its further application in urban areas.

Portland cement, water, coarse aggregate, and little or no fine-grain are the basic composition of PC's framework, and in some cases, it includes supplementary cementitious materials and/or chemical admixtures as well. PC's mixture results in high permeability, ranges from 5.78×10-3 to 2.69×10-2 m/s [19], high porosity value, between 11 and 35 % [20], and low compressive strength, ranges between 3.5 and 28 MPa [21–23]. Meanwhile, the flexural strength ranges between 2 and 4 MPa, and tensile strength from 1.0 to 3.4 MPa [2,24,25]. Nevertheless, Scholz, M. and Grabowiecki, P. (2007) claimed that it is possible to develop PC with higher strength, however, it requires the composition of aggregates with uniform grading and smaller particle size as well as the incorporation of silica fume and superplasticizer into the PC mixture [26]. High compressive strength and high void content and/or permeability are two main features of PC which are inversely proportional to each other. The effect of water and cement ratio is also important on the strength and porosity of PC [27]. Sonebi and Bassuoni (2013) showed that the aggregate, water, and cement content, and their interactions are the main factors in the performance of PC [28]. Moreover, a single-sized aggregate with a constant w/c ratio of 0.35 was recommended as a suitable PC mixture by [29]. Apart from these, there are various types of additives such as lubricants and superplasticizers (SPs) that can improve concrete strength [30–32]. Adding superplasticizers to PC can also boost its compressive strength, while marginally affecting its physical properties [33–35]. The primary role of SPs is to maintain the workability of the PC while sustaining the diminution of water content; hence, this resulted in a significant reduction of void formation in the PC matrix and led to the enhancement of the PC's strength and durability [36].

Fig. 2 (a) shows the structural representation of Polycarboxylate Superplasticizers (PCE) which are fossil fuel derived. Over a decade, PCE has been extensively utilized in concrete mixtures to enhance the strength of concrete and provide better workability through the diminution of water content. PCEs scatter the cement particles' surface by adsorption wherein the cement particles along with electrostatic excretion provide a steric force effect, which resulted in rheology paste boosting [37]. Notwithstanding, due to the increasing demand for renewable and natural products, it is necessary to transition from current non-renewable SPs (i.e. PCE) to more sustainable SP alternatives. In this context, Lignosulfonate (LS) shows encouraging potential for the synthesis of bio-based SP, as it is a renewable byproduct of wood pulp production. Fig. 2(b) indicates the structural representation of LS. LS is a natural polymer that exhibits mechanisms of electrostatic repulsion effect, steric hindrance, and water adsorption from surfaces that were applied in 1930s in favor to its abundancy and cost-effective features [13,37–43]. Although LS has high economical market value, its low water reduction properties had limited its application in high-performance concrete designs. The chemical structure of LS contains hydrophilic (sulfonic, hydroxyl, and methoxyl) and hydrophobic, alkylbenzene [40]. Breilly et al. (2021) found that utilization of LS as concrete admixture had resulted in higher dispersing ability and lower air entrainment, which leads to higher compressive and flexural strength in comparison to the control specimens [36]. Nevertheless, they also highlighted that to effectively replace the common petroleum-based SPs with renewable alternatives such as LS, extensive research on the application of LS in concrete is necessary since the chemical structures of SPs could significantly affect concrete properties, especially in the aspect of fluidity, adsorption, and mechanical strength.



(a)



(b)

Fig. 2. Structural representation of (a) Polycarboxylate and (b) Lignosulfonate [36].

In essence, the w/c ratio as well as PCE, LS, and cement content have a significant impact on the PC performances. Therefore, this study aims to investigate the interactions of various proportions of a new type of superplasticizer through a combination of polycarboxylate and lignosulfonate (0.10%, 0.55%, and 1.00% of the cement weight), water-to-cement ratio (W/C of 0.30, 0.35, and 0.40), and cement content (CC of 315, 332.50, and 350 kg/m3) on the strength and physical properties of PC. Slump, fresh density, compressive strength at ages of 7, 11, and 28 days, cementitious paste thickness, porosity, and permeability of PC were investigated. Besides, the most appropriate mixture design of PC for further application in urban areas was identified. Moreover, in order to understand the behavior of mixed constituents under various circumstances, this study applied Design of Experiment (DoE) software to analyze the data.

2. Material and Methods

2.1. Materials

Table 1 shows the chemical properties of the Portland Cement Type II, which is used in this study and is in accordance with the requirements of ASTM C150 (2012) [44]. By following the requirement specified in ASTM C33 (2003) [45], the crushed coarse aggregates were used in sizes of 4.75-9.5 mm. The grading distribution of coarse aggregates is indicated in Fig. 3 which is close to the lower limit of the standard. In addition, Table 2, represents the properties of coarse aggregate, which is calculated based on the AASHTO T85 (2004) [46]. Meanwhile, tap water was used in this study for the mixing and curing process.

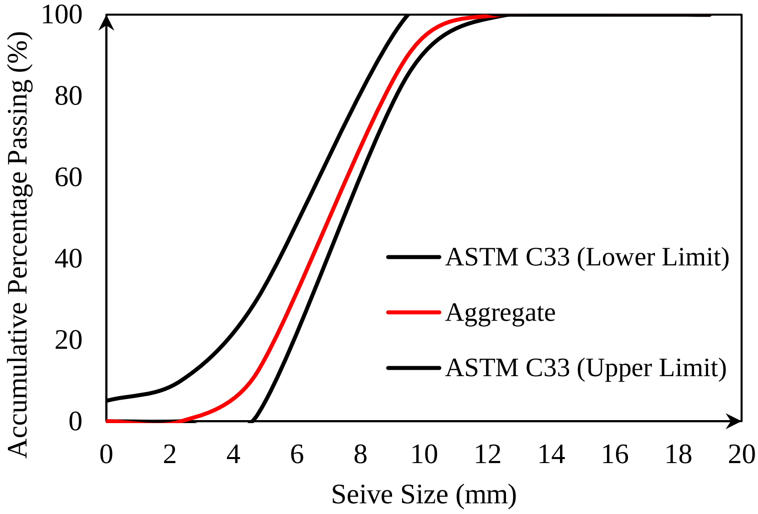


Fig. 3. Particle size distribution of coarse aggregate.

Table 1. Chemical analysis of Portland Cement, Type II.

Component	Value	ASTM C150 requirement (2012) [44]	Uncertainty
SiO_2	21.0±0.5	>20	0.14
Al_2O_3	4.6±0.15	<6	0.02
Fe_2O_3	3.9±0.15	<6	0.02
CaO	62.5±0.5	-	0.01
MgO	2.9±0.2	<5	0.02
SO_3	2.0±0.2	<3	0.02
Na_2O	0.5±0.05	-	-
K_2O	0.45±0.05	-	-
I.O.I.	1.4±0.3	<3	0.03
I.R.	0.3±0.1	<0.75	0.02
C_3S	54±4	-	-
C_2S	23±4	-	-
C_3A	5.6±0.5	<8	-
C_4AF	12±1	-	-

Table 2. Specific gravity of coarse aggregate (AASHTO 2004) [46].

Properties	Value
Bulk Specific Gravity (Gsb)	1559 kg/m^3
Bulk SSD Specific Gravity (Gsb SSD)	1574 kg/m^3
Apparent Specific Gravity (Gsa)	1582 kg/m^3
Absorption (% Abs.)	0.947%

2.2. Polycarboxylate-Lignosulfonate Superplasticizer (PLS)

The PLS applied in this study was HYPER FLOW 20 with a light brown color, as shown in Fig. 4, and chemical properties is provided in Table 3.

Fig. 4. The color and type of the Polycarboxylate-Lignosulfonate Superplasticizer used in the study.

Table 3. Chemical properties of PLS (Sharq Cement Product Co.).

Properties	Quantity / Quality
Color	Light Brown
Carboxylate	40.00%
Lignosulfonate	40.00%
Sodium nitrate	0.50%
Water	19.30%
Formalin	0.10%
Defamer	0.10%
Mixing Ratio	0.10%-1.00% by weight

2.3. Mixture Design of PC

Table 4 shows the material proportions of PC containing different portions of PLS, cement content, and w/c ratio. The material proportions were designed by Design of Experiments (DoE), which is in accordance with ACI 211 3/R (2006) [47]. DoE was applied to the experiments to research reduce the number of tests and providing the analysis of variance (ANOVA) for the results to differentiate the effects of each variable [48,49]. different percentage of PLS from 0.1% to 1% by weight of cement, portion of w/c ratio from 0.30 to 0.40 weight of cement, and cement content between 315 kg/m3 and 350 kg/m3 were the variable ranges of the study. The upper and lower ranges of variables were input to DoE using the central composite design (CCD) method. The CCD method is an augmented factorial design with widespread applications in product optimization. By employing a CCD experiment design, it becomes possible to estimate a full quadratic model for each response. In Arabi et al.'s study (2011), CCD methods were used to analyze the impact of adding constituent material parameters on the fresh and hardened state properties of self-compacting concrete [50]. The developed numerical models were found to be valid across a wide range of mixture proportioning. These derived models were deemed useful in reducing test procedures and the number of trials required for the mix proportioning of self-compacting concrete [50].

Table 4. Mixture design proportions.

Mix Nominations	PLS Percentage	w/c ratio	Cement Content (kg/m^3)	Water Content (kg/m^3)	PLS content (kg/m^3)
A-W/C0.30-CC315	A=0.10	0.30	315.0	94.5	0.32
A-W/C0.30-CC350		0.30	350.0	105.0	0.35
A-W/C0.35-CC332.5		0.35	332.5	116.4	0.33
A-W/C0.40-CC315		0.40	315.0	126.0	0.32
A-W/C0.40-CC350		0.40	350.0	140.0	0.35
B-W/C0.30-CC332.5	B=0.55	0.30	332.5	99.8	1.83
B-W/C0.35-CC315		0.35	315.0	110.3	1.73
B-W/C0.35-CC332.5		0.35	332.5	116.4	1.82
B-W/C0.35-CC350		0.35	350.0	122.5	1.93
B-W/C0.40-CC332.5		0.40	332.5	133.0	1.83
C-W/C0.30-CC315	C=1.00	0.30	315.0	94.5	3.15
C-W/C0.30-CC350		0.30	350.0	105.0	3.50
C-W/C0.35-CC332.5		0.35	332.5	116.4	3.33
C-W/C0.40-CC315		0.40	315.0	126.0	3.15
C-W/C0.40-CC350		0.40	350.0	140.0	3.50

Note: The weight of coarse aggregate is 1600 kg/m^3 for all treatments

2.4. Experimental Program

All the materials were weighed by digital scale prior to mixing. Dry mixing of cement and coarse aggregates were carried out in Hobart mixer for 1 minutes, followed by wet mixing for 2 minutes. The PLS were dissolved in water and then added to the mixtures. Next, the fresh PC were tested for slump and fresh density before being casted in a cubic mold whereby the internal surfaces of the molds were covered with oil. All PC specimens were de-molded after 24 hours and placed in a water tank for curing process. The PC specimens were cured for 7, 11, and 28 days to determine the effect of aging on the compressive strength. All designated PC specimens were tested for fresh and hardened PC properties. Slump and fresh density of PC were determined based on the ASTM C143 (2012) and ASTM C1688 (2008), respectively [51,52]. The compressive strength was tested on cube specimens of 150 mm in length with a constant rate of loading based on [53]. Moreover, to investigate the effects of variables on the PC's compressive strength at the age of 28 days, the cementitious paste thickness (CPT) tests were carried out. CPT, which is the average distance between the aggregates in PC that are covered by the cement paste, was performed completely manually by Torres et al. (2015) [54]. Nevertheless, a more precise and accurate method was used by Yu et al. (2019) [55], and this method was applied in this research. At first, in this semi-manual method, the PC samples were cut in cross sections and smoothed to clear the residual stone debris. Then, the cross-sections were wetted and a high-resolution photo was taken. The intention of wetting the surface before capturing the photo is to have a better distinguishing between cement and aggregate phase (Fig. 5 (a)). These images were transferred to AutoCAD afterwards. Using the command line in AutoCAD, and type the "l" and "di" orders enabled us to draw and measure the length of each line segment from the edge of an individual aggregate to the outermost edge of another aggregate, which is the CPT (Fig. 5 (b)). Finally, after measuring the number of line segments and their length, the results were transferred to the Excel file for drawing the required charts. The measurement method is shown in Fig. 5.

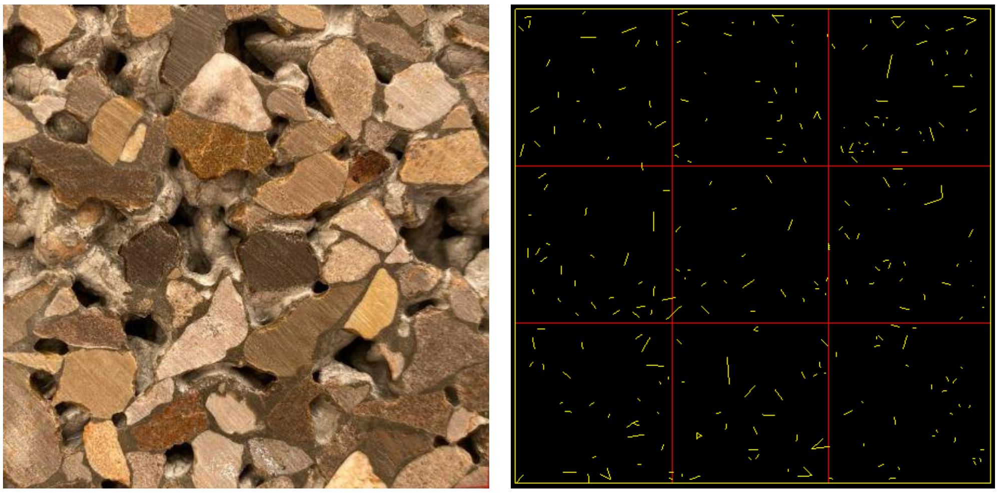
Furthermore, the porosity of PC was assessed using water displacement method, which is based on Archimedes' principle of buoyancy. The 100 mm cube PC specimens were ovendried for 24 hours at 105 °C. The immersed weights of PC specimens were measured and its porosity were calculated using equation 1. Also, the permeability of PC measured via a falling-head device, where 100 mm cube PC samples could fit in. The edges of each PC sample were sealed to ensure the water only flow vertically through the specimens. The permeability coefficient of PCs was determined per second, and calculated using equation 2. All the tests were conducted based on the necessary standards and each data point represents the average value of three specimens to minimize the possibility of measurement errors.

$$A_t = \left(1 - \left(\frac{W_2 - W_1}{\rho_w V}\right)\right) 100\% \quad (1)$$

where, A_t is the porosity (%), V is the volume (cm^3), ρw is the water density (g/cm^3), W_1 and W_2 are the specimen's weight in water and dry weight (g).

$$K = \frac{al}{At} \text{Ln}\left(\frac{h_1}{h_2}\right) \quad (2)$$

where, K is the coefficient of permeability (mm/s), a is the area of the cross section of device (mm^2), L is the length of PC sample, A is the cross-section of the concrete sample (mm^2), h_1 and h_2 are the initial and final height of water column (mm), and t is time (sec) that water requires to reach from h1 to h_2.



(a) (b)

Fig. 5. (a) the cross-section of PC transferred to AutoCAD and (b) Drawing the line segments and measuring the cementitious paste thickness in AutoCAD software.

3. Results and Discussion

3.1. Workability and fresh density

Fig. 6 illustrates the effect of different portions of variables on the slump of PC, which is sorted based on the PLS proportion. As shown in Fig. 6, the increase in the PLS dosage and water content would increases the slump value of the specimens. The maximum slump value observed in the sample of C-W/C0.40-CC315 (210 mm) with the maximum PLS and water and minimum cement content. Conversely, the minimum slump value of 130 observed in the samples with maximum cement and minimum PLS and water content. It was also concluded that water content has more considerable effect on the slump compared to PLS and cement portions. These results are in line with the findings of Pandey et al. (2021) [33].

Furthermore, slight changes observed in the fresh density of PC samples in which those with a higher portion of PLS, water and cement tend to have a higher fresh density. PC's fresh density changes between 2.01 gr/cm3 (A-W/C0.30-CC315) and 2.14 gr/cm3 (A-W/C-0.40-CC350), and the effects of water and cement proportion was more significant than PLS content.

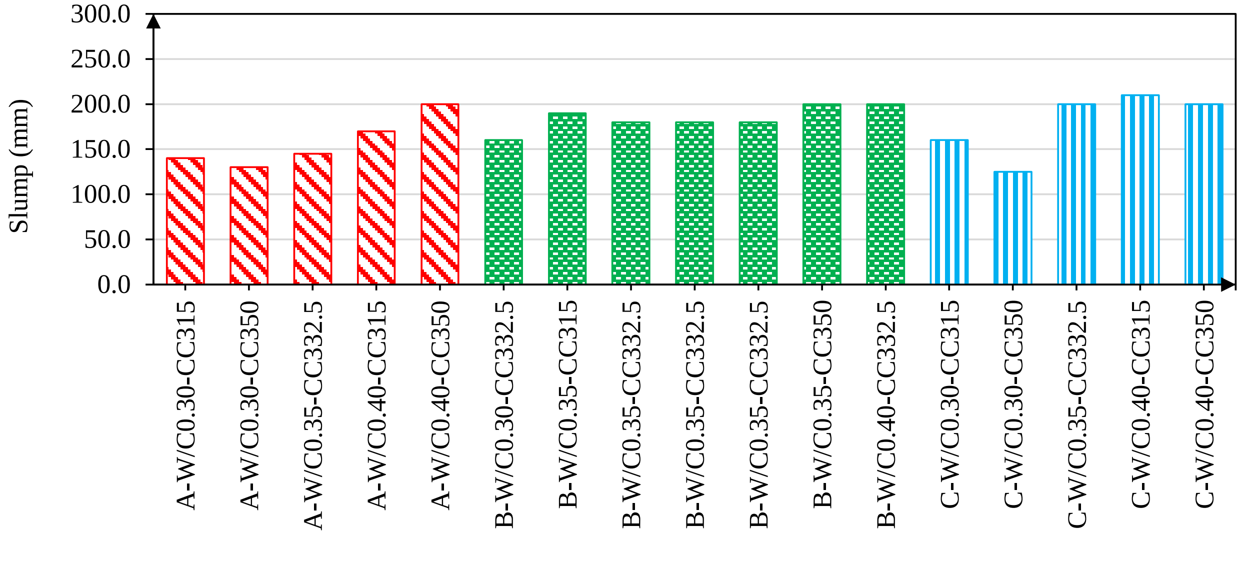


Fig. 6. Effects of water, cement and PLS content on the slump of PC.

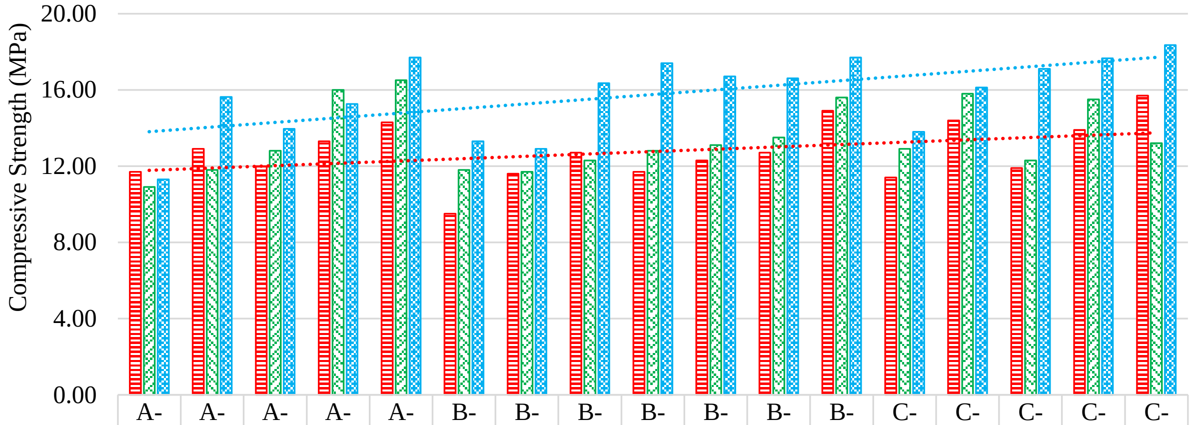
3.2. Compressive strength

Fig. 7 shows the compressive strength of PC samples at ages of 7, 11, and 28 days. As displayed in Fig. 7, the sample of A-W/C0.30-CC315 with minimum w/c ratio, cement, and PLS portion had the lowest compressive strength of 11.30 MPa while the highest compressive strength observed in the samples of C-W/C0.40-CC350 with maximum w/c ratio, cement, and PLS content. Increasing the portion of variables resulted in a high free volume of cement paste that is able to encapsulate the aggregates and caused an increment in the PC compressive strength, as depicts in Fig. 8. The slope of w/c ratio graph is steeper than cement and PLS graphs, which approves the higher impact of w/c ratio on the PC compressive strength. This observation is parallel with the findings of Sonebi and Bassuoni (2013) [28]. Comparing the samples of A-W/C0.30-CC350 and C-W/C0.30-CC350, with higher and lower portion of PLS and constant water and cement content, confirmed the positive role of PLS in increasing the PC compressive strength. However, the effect of water content on the compressive strength was more considerable than other variables.

Apart from this, an increment in the PC compressive strength observed as the age of samples grew from 7 to 28 days; nevertheless, in some cases (i.e. C-W/C0.40-CC350) the value of compressive strength at age of 7 days was higher compared to age of 11 days, which might be due to the mixing and curing conditions, and existence of pores in PC structure. The maximum and minimum PC compressive strength at age of 28 days were 11.3 MPa (A-W/C0.30-CC315) and 18.35 MPa (C-W/C0.40-CC350), respectively. In addition, it was identified that samples with w/c ratio of higher than 0.35 has resulted in higher compressive strength, which is in accordance with the findings of Kováˇ and Siˇcáková's (2018) [56].

Table 5 presents the ANOVA results for PC compressive strength, and different proportions of water, cement and PLS in the PC mixture resulted in $F(1,3) = 19.50$, $P = <0.0001$, $R2 = 0.818$. A linear model, equation 3, was suggested for the compressive strength of PC at age of 28 days.

$$Compressive\ Strength\ (age\ of\ 28 days) = +15.75 + 1.65A + 0.92B + 1.35C \quad (3)$$



	A-W/C 0.30-CC315	A-W/C 0.30-CC350	A-W/C 0.35-CC332.5	A-W/C 0.40-CC315	A-W/C 0.40-CC350	B-W/C 0.30-CC332.5	B-W/C 0.35-CC315	B-W/C 0.35-CC332.5	B-W/C 0.35-CC332.5	B-W/C 0.35-CC332.5	B-W/C 0.35-CC350	B-W/C 0.40-CC332.5	C-W/C 0.30-CC315	C-W/C 0.30-CC350	C-W/C 0.35-CC332.5	C-W/C 0.40-CC315	C-W/C 0.40-CC350
Age of 7 days	11.7	12.9	12	13.3	14.3	9.5	11.6	12.7	11.7	12.3	12.7	14.9	11.4	14.4	11.9	13.9	15.7
Age of 11 days	10.9	11.8	12.8	16	16.5	11.8	11.7	12.3	12.8	13.1	13.5	15.6	12.9	15.8	12.3	15.5	13.2
Age of 28 days	11.3	15.63	13.95	15.26	17.7	13.3	12.9	16.35	17.4	16.7	16.6	17.7	13.8	16.13	17.1	17.65	18.35

Mix Nominations

Fig. 7. Effects of water, cement, and PLS content on the PC compressive strength in different ages.

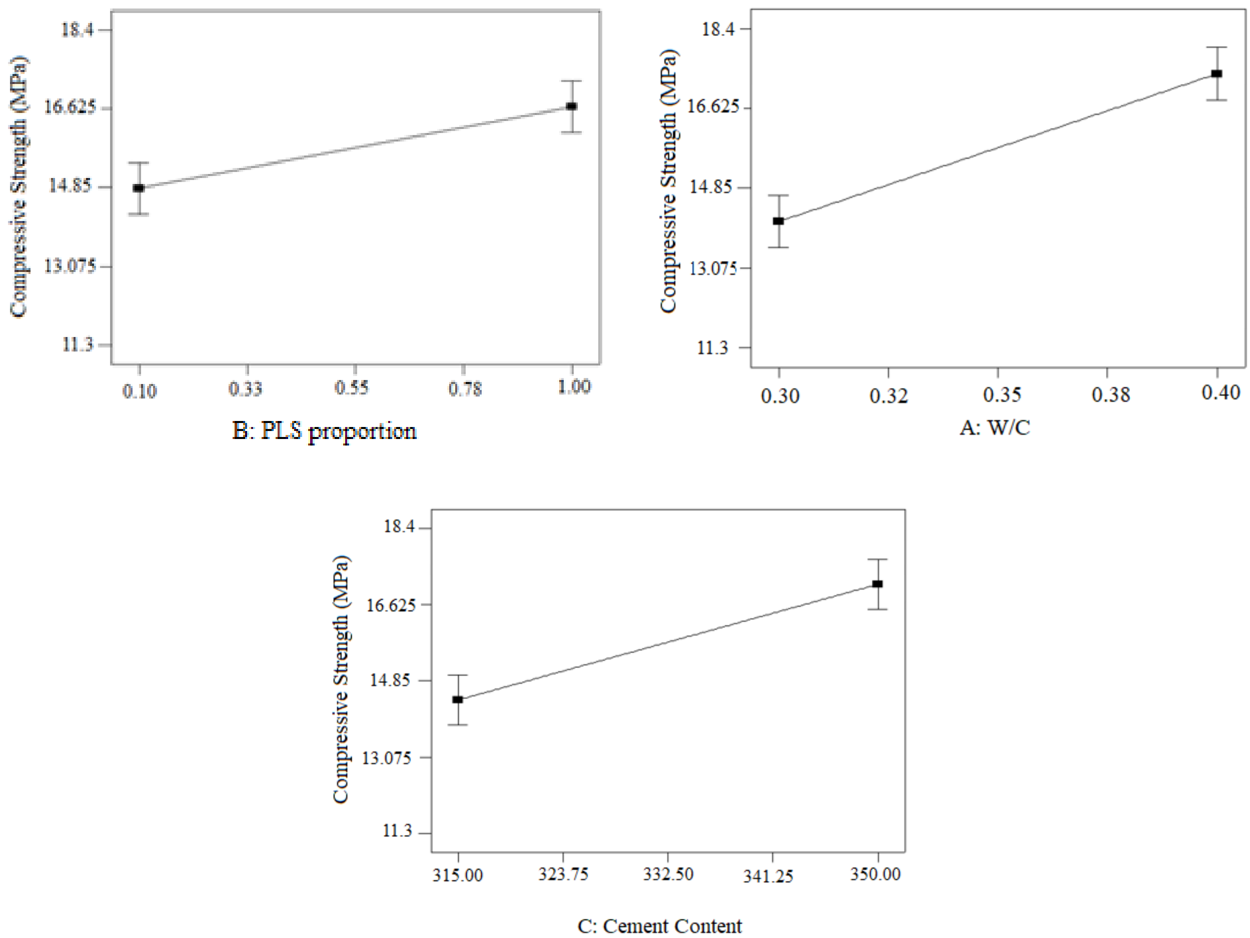


Fig. 8. Effect of variables on compressive strength of pervious concrete.

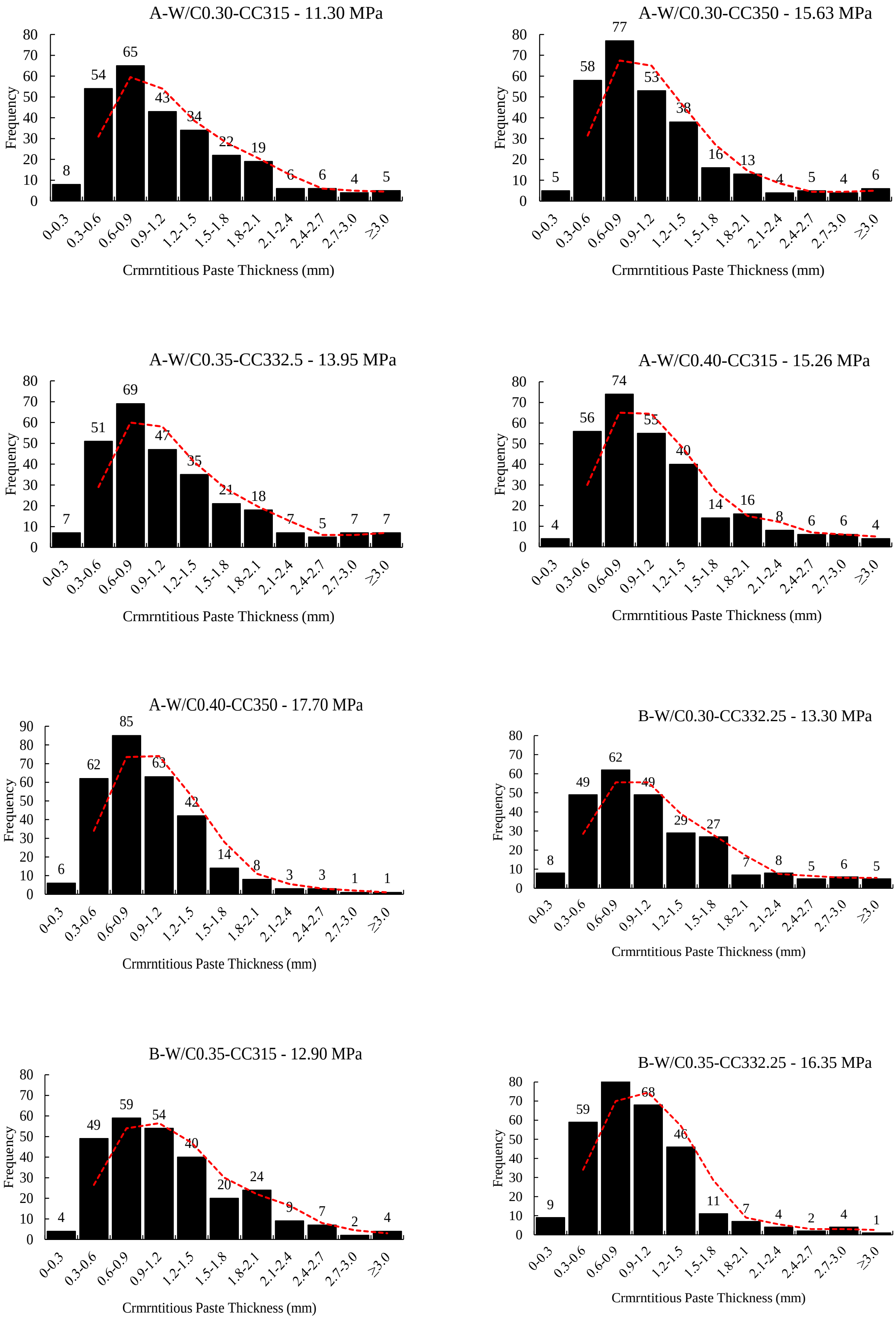
Table 5. ANOVA analysis of variance for compressive strength at age of 28 days of pervious concrete.

Source	Sum of Square	DF	Mean Square	F Value	Prob>F
Model	53.90	3	17.97	19.50	<0.0001*
A: w/c ratio	27.23	1	27.23	29.55	0.0001
B: PLS proportion	8.45	1	8.45	9.17	0.0097
C: Cement Content	18.23	1	18.23	17.78	0.0007
Residual	11.98	13	0.92		
Lack of Fit	11.41	11	1.04	3.63	0.2358**
Pure Error	0.57	2	0.29		
Cor Total	65.87	16			

* Significant ** Not Significant Std. Dev.=0.96 C.V.%=6.09 R^2=0.818 Adj R^2=0.776

3.3. Effects of average cementitious paste thickness on the 28 days-compressive strength

The average CPT, number of line segments, and number of pores considerably affect the compressive strength of PC in which increasing the number and size of small pores (0-1.5 mm2) markedly reduce the PC's compressive strength. It is claimed that increasing the CPT up to 1.15 mm is responsible for increasing the compressive strength of PC while for a CPT of 1.5 mm and more, the compressive strength of PC does not change markedly and stays quite stable [55]. Also, adding fine-grained materials such as adsorbents to the PC mixture or replacing the regular coarse aggregate of PC with other materials might result in different outcomes of compressive strength as the shape, size, and water adsorption of the materials are important in the CPT [57,58]. Fig. 9 displays the CPT distribution of PC samples. It is reported that increasing the length of line segments up to 1.15 mm contributes to n increment in the PC's compressive strength while the CPTs of 1.5mm and more do not make a significant change in the PC's compressive strength [55]. As can be seen in Fig. 10, the distribution of PC samples with a compressive strength of higher than 15.0 MPa is between 0.30 and 1.50 mm while this range changes to 0.03 to 1.8 or 0.30 to 2.1 for samples with the compressive strength of less than 15.0 MPa. For this reason, the increment in the water, cement, and PLS moved the peak value of the frequency to the left, and also increased the number of line segments. The average total number of line segments for the samples with the compressive strength of less than 15.0 MPa was 270 while this value changed to more 285 for the PC samples with the compressive strength of more than 15.0 MPa. The sample of C-W/C0.40-CC350 with the highest compressive strength of 18.35 MPa had the maximum number of line segments (312) among all samples. Therefore, increasing the water, cement, and PLS content increases the compressive strength at the age of 28 days due to increasing the average CPT, increase the number of line segments, and move the peak value of frequency to the left.


A-W/C0.30-CC315 - 11.30 MPa
Frequency
Crmrntitious Paste Thickness (mm)
0-0.3
0.3-0.6
0.6-0.9
0.9-1.2
1.2-1.5
1.5-1.8
1.8-2.1
2.1-2.4
2.4-2.7
2.7-3.0
≥3.0
8 54 65 43 34 22 19 6 6 4 5
A-W/C0.30-CC350 - 15.63 MPa
5 58 77 53 38 16 13 4 5 4 6
A-W/C0.35-CC332.5 - 13.95 MPa
7 51 69 47 35 21 18 7 5 7 7
A-W/C0.40-CC315 - 15.26 MPa
4 56 74 55 40 14 16 8 6 6 4
A-W/C0.40-CC350 - 17.70 MPa
6 62 85 63 42 14 8 3 3 1 1
B-W/C0.30-CC332.25 - 13.30 MPa
8 49 62 49 29 27 7 8 5 6 5
B-W/C0.35-CC315 - 12.90 MPa
4 49 59 54 40 20 24 9 7 2 4
B-W/C0.35-CC332.25 - 16.35 MPa
9 59 68 46 11 7 4 2 4 1

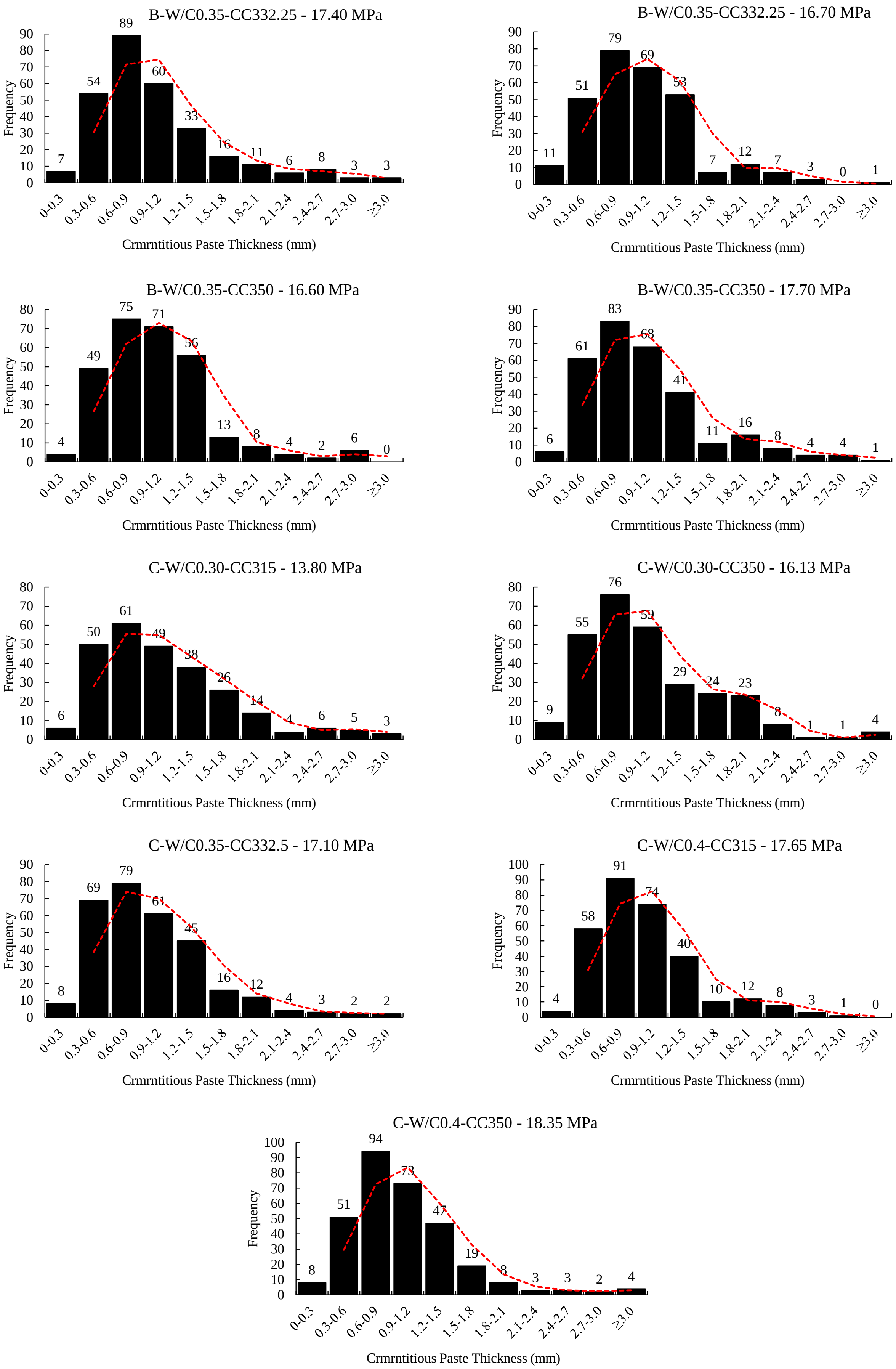


Fig. 9. CPT distribution of PC samples.

3.4. Permeability of PC

Fig. 10 shows the effects of different variables on the PC permeability. As can be seen in Fig. 10, the permeability of samples declines as PLS, w/c ratio, and cement content rise, whereby the effect of w/c ratio is more effective. The steeper slope of the w/c graph in Fig. 11 confirms that changing the w/c ratio of the PC mix could considerably affect its permeability while the effect of PLS and cement content are less effective. Samples of C-W/C0.30-CC315 and B-W/C0.35-CC350 had the highest (1.427 mm/s) and lowest (1.144 mm/s) permeability value, respectively.

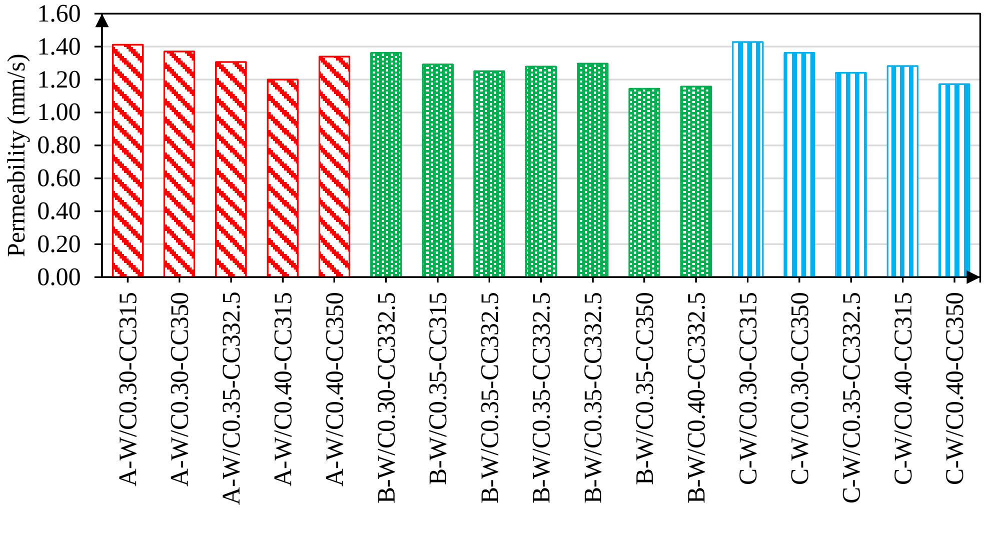


Fig. 10. Effects of water, cement, and PLS content on the PC permeability.

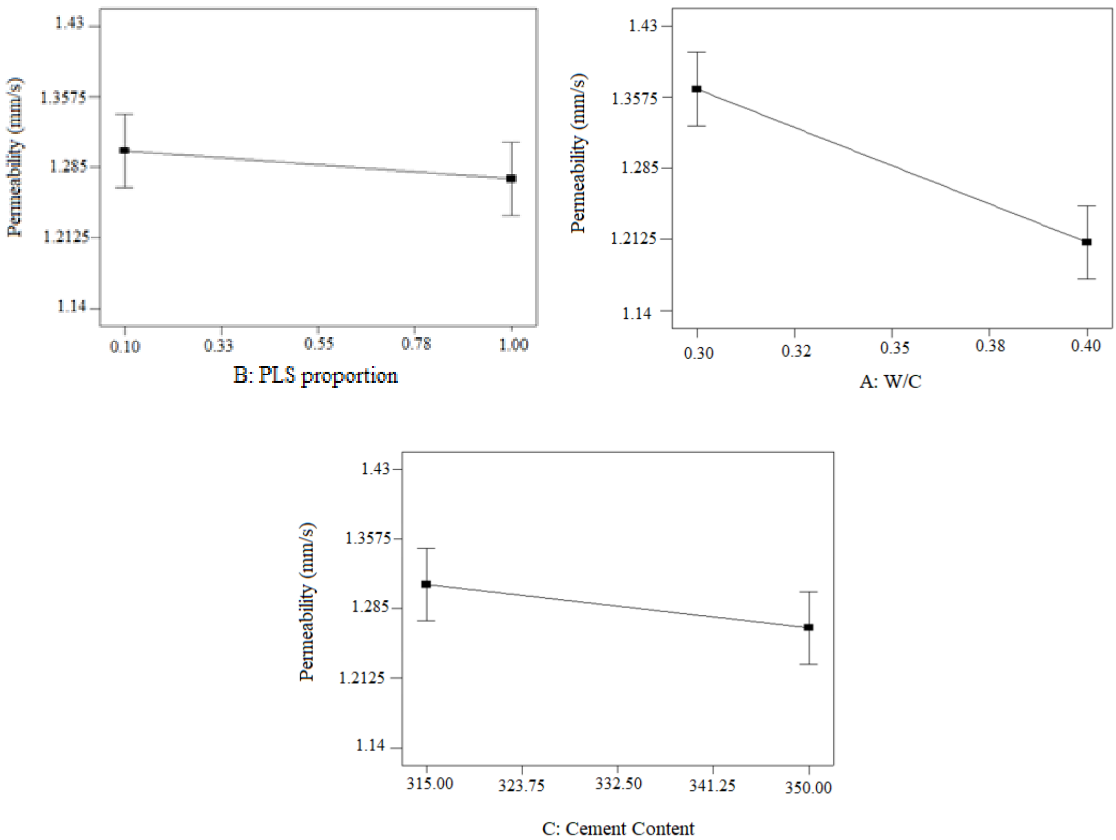


Fig. 11. Effects of different variables on permeability of pervious concrete.

Fig. 12 shows the bottom of PC samples and cohesion of the mixtures with different w/c ratio and PLS portions, and their effect on the PC permeability. By increasing the PLS proportion and w/c ratio, the mixture paste becomes diluted and filled the pores of PC and covered more areas of the aggregate surface. This event results in permeability reduction of PC. Based on visual observation, PC samples with 0.30 w/c ratio and 0.1% PLS dosage looks normal and contains opened pores. On the other hand, samples with 0.35 w/c ratio and 0.55% PLS dosage showed partial pores filling while samples with 0.40 w/c ratio and 1% PLS dosage displayed the bottom of the samples are flat with several holes that allow water to pass through. The results demonstrate that although the bottom of samples with maximum w/c ratio and PLS proportion have minor pores, their permeability is still acceptable due to incorporation of single-sized coarse aggregate.

(a)

(b)

(c)

Fig. 12. Bottom of PC samples (a) w/c ratio = 0.30 and PLS dosage of 0.01% (b) w/c ratio = 0.35 and PLS dosage of 0.55%, and (c) w/c ratio = 0.40 and PLS dosage of 1.00%.

Table 6 illustrates the results of ANOVA for PC permeability, F(1,3) = 5.95, P = <0.0088, R2 = 0.578. The effects of water, cement, and PLS content on the permeability is lower compared to the compressive strength. Also, a linear model, equation 4, was suggested for the permeability of PC.

$$Permeability = +1.29 - 0.078A - 0.014B - 0.022C \quad (4)$$

Table 6. ANOVA analysis of variance for permeability of pervious concrete.

Source	Sum of Square	DF	Mean Square	F Value	Prob>F
Model	0.068	3	0.023	5.95	0.0088*
A: w/c ratio	0.061	1	0.061	15.98	0.0015
B: PLS Proportion	2.074E-003	1	2.074E-003	0.54	0.4747
C: Cement Content	5.062E-003	1	5.062E-003	1.32	0.2708
Residual	0.050	13	4.424E-003		
Lack of Fit	0.049	11	5.373E-004	8.23	0.1132**
Pure Error	1.075E-003	2			
Cor Total	0.12	16			

* Significant ** Not Significant Std. Dev.=0.062 C.V.%=4.80 R^2=0.578 Adj R^2=0.4813

3.5 Porosity of PC

Fig. 13 shows the porosity of PC containing different portion of water, cement, and PLS, which is sorted based on the PLS increasing. The porosity value of samples containing the minimum portions of water and PLS content were higher comparing to those with the maximum portions of water and PLS. higher water and PLS content or lower cement content results in forming a pasty mixture that could not only cover the aggregate surfaces but also lessening the number and size of the pores, so decreasing the void content. It is also reported that the usage of superplasticizer could increase the porosity of PC as it reduces the water consumption in the PC mixture; so, increasing the PLS proportion also increased the porosity [59]. The w/c ratio considerably affect the porosity of PC compared to PLS and cement content in which samples with w/c ratio of 0.30 had the minimum void content of 24% and more while samples with w/c ratio of 0.40 had the maximum porosity of 22% and less. Samples of B-W/C0.35-CC332.5 and C-W/C0.30-CC315 had the minimum and maximum porosity value of 18.26, and 29.9%, respectively. It was also concluded that although the porosity and permeability follow a same trend, sometimes their changes are substantially different because the position of pores is an important factor in permeability and some pores might be dead-end while all pores have a direct impact on void ratio. Fig. 14 depicts an SM image of a pore in PC which is effective in both permeability and porosity.

Table 7 indicates the results of ANOVA for PC porosity, F(1,9) = 7.39, P = <0.0076, R2 = 0.904. The effects of water, cement, and PLS content on the porosity is higher compared their effect on the compressive strength and permeability. Also, a quadratic model, equation 5, was suggested for the permeability of PC.

$$Porosity = +18.31 - 3.40A - 0.39B - 0.62C - 0.68AB + 1.23AC - 0.68\,BC + 2.84\,A2 + 2.96\,B2 - 0.28C2 \quad (5)$$

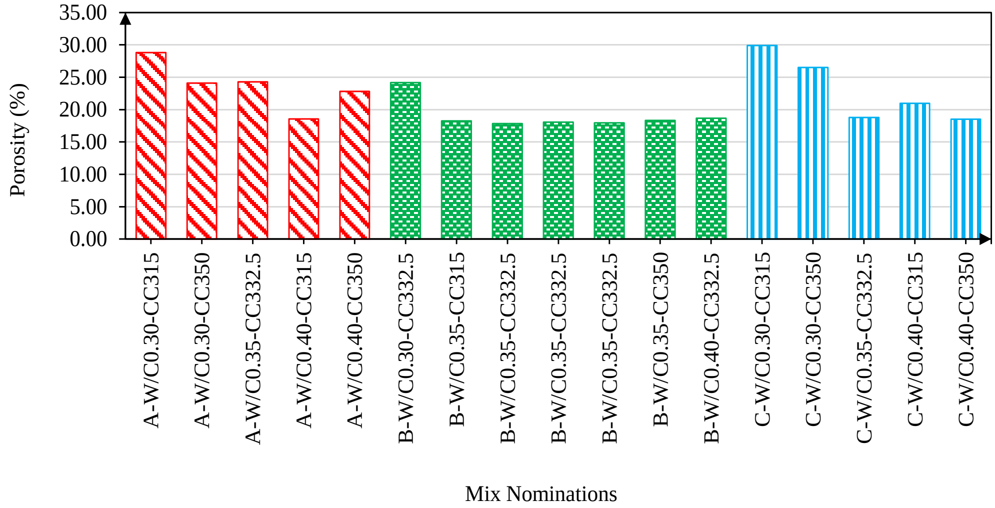


Fig. 13. Porosity changes sorted by PLS proportion increasing

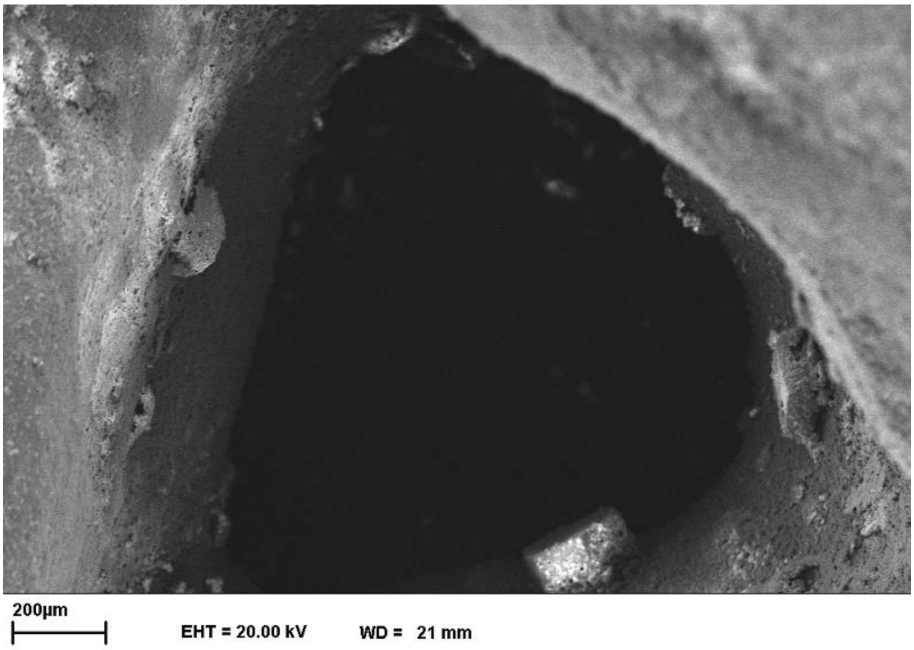


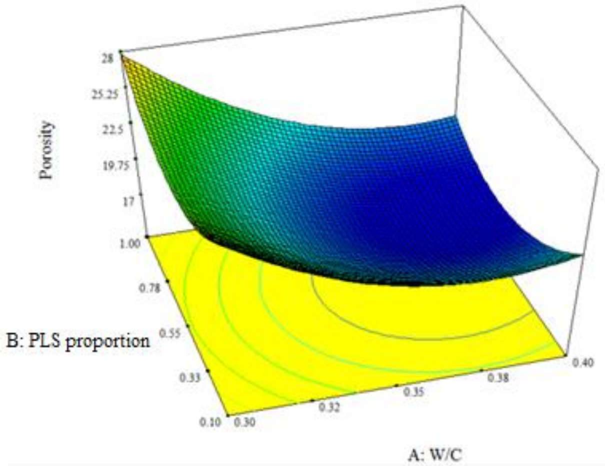
Fig. 14. SEM image of an effective pore in PC structure.

Table 7. ANOVA analysis of variance for porosity.

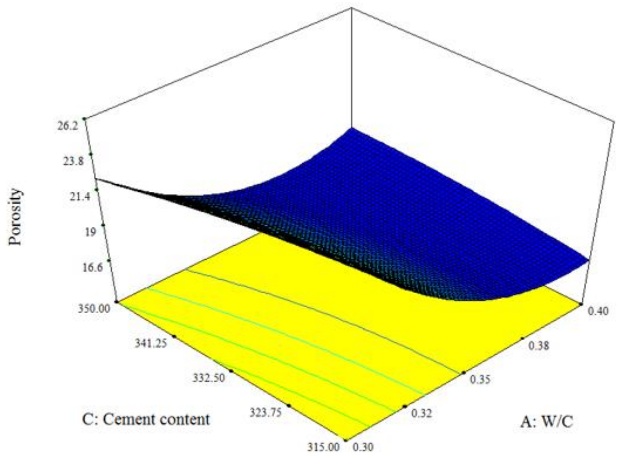
Source	Sum of Square	DF	Mean Square	F Value	Prob>F
Model	239.09	9	26.57	7.39	0.0076*
A: w/c ratio	115.46	1	115.46	32.11	0.0008
B: PLS Proportion	1.54	1	1.54	0.43	0.5342
C: Cement Content	3.84	1	3.84	1.07	0.3356
AB	3.66	1	3.66	1.02	0.3467
AC	12.18	1	12.18	3.39	0.1083
BC	3.71	1	3.71	1.03	0.3434
A^2	21.67	1	21.67	6.03	0.0438
B^2	23.54	1	23.54	6.54	0.0376
C^2	0.20	1	0.20	0.057	0.8185
Residual	25.17	7	3.60		
Lack of Fit	25.15	5	5.03		
Pure Error	0.029	2	0.015		
Cor Total	264.27	16			

* Significant Std. Dev.=1.90 C.V.%=8.80 R^2=0.904 Adj R^2=0.7823

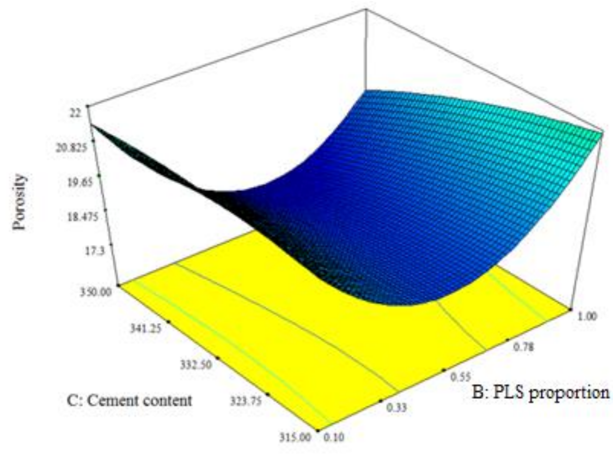
The 3D plots of response surface for the porosity in which cement, PLS, and water content were considered constant at center point, are shown in Fig. 15 (a-c). The PC porosity increases as the proportion of PLS and w/c ratio decrease to 1% and 0.30, respectively, and by comparing with w/c ratio, the cement content has not shown a significant change to the PC porosity.



(a)



(b)



(c)

Fig. 15. Response surface 3D plot for porosity with (a) CC is constant at center point, (b) PLS proportion is constant at center point, and (c) w/c ratio is constant at center point.

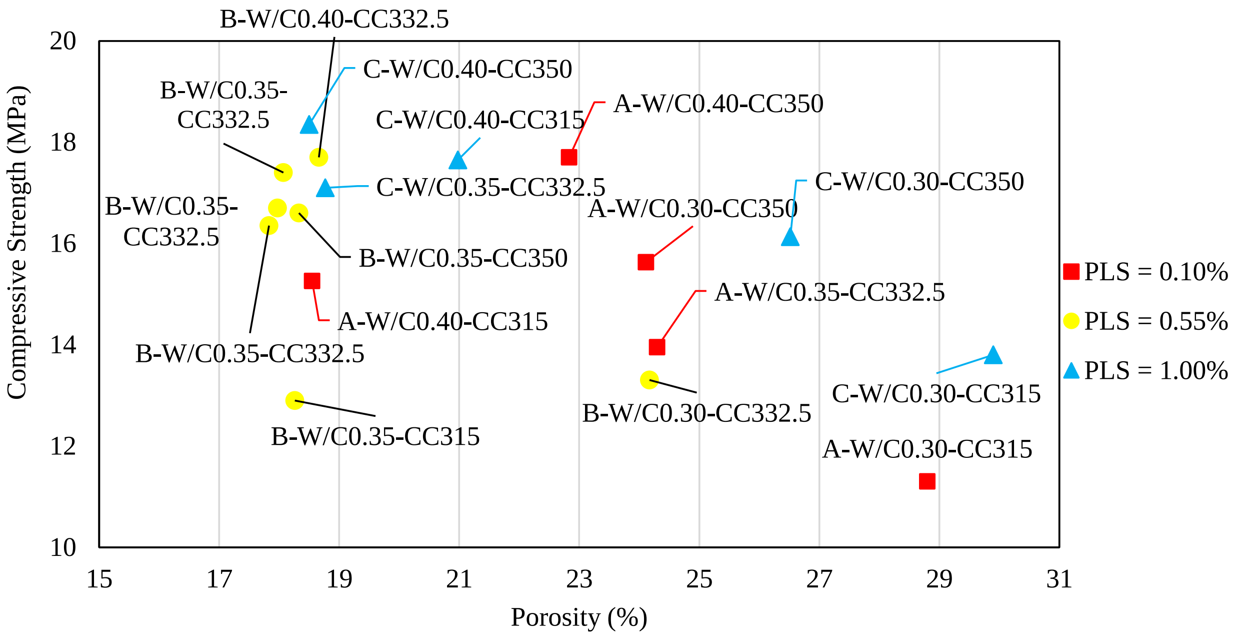


Fig. 16. The relationship between the porosity and the compressive strength of PC.

3.6. Relationship between the porosity and compressive strength of PC

Fig. 16 depicts the relationship between the porosity and the compressive strength of PC samples divided by the portion of PLS. In general, as the porosity decreases the compressive strength increases [58] and this trend is observed in the PC samples in this study with different portions of PLS. Different samples with the PLS portion of 1.00% experienced and increment in the compressive strength as their porosity declined. This statement is also observed in the samples with the PLS portion of 0.55% and 0.01%; however, in some cases, for instance A-W/C0.40-CC315, this trend did not happen. This sample has the least value of porosity among all samples with PLS potion of 0.55% and its compressive strength was anticipated to be the maximum while due to the laboratory and compacting conditions, its compressive strength might be affected. In short, the common rule of the relationship between the porosity and compressive strength still stands correct in the present study.

4. Conclusion

The effect of anthropization could be mitigated through enhancement of PC's ability, specifically in the aspect of mechanical and physical properties. The present study revealed the effects water, cement, and polycarboxylate-lignosulfonate superplasticizer on the PC performances. the drawn conclusions are as follows:

- The slump of PC increased as the water and PLS content increased and cement decreased. Also, no significant changes observed in the fresh density of different mixes of PC; however, increasing the water, cement, and PLS content, increased the fresh density.
- The PC compressive strength increased as the curing aged increased from 7 to 28 days; nevertheless, in some cases the compressive strength of PC samples at age of 11 days were lower than their compressive strength at age of 7 days due to a porous structure of PC. Moreover, the increment in the portion of water, cement, and PLS resulted in increasing the compressive strength in

which the maximum value occurred in the sample with the highest portion of water, cement, and PLS.

- Increasing the water, cement, and PLS content increased the number of line segments in the paste and decreased their length form 2.1 mm to 1.5 mm in the cement paste. Also, the average cementitious paste thickness increased as the portion of water, cement, and PLS rose, and resulted in increasing the compressive strength.
- the porosity and permeability of the PC samples decreased as the portion of water, cement, and PLS increased due to the formation of a pasty mix which resulted in decreasing the number and size of the PC pores. However, all PC samples had the reasonable porosity and permeability value.
- Application of PC systems in urban areas, sidewalks, green spaces, and parking lots not only decrease the anthropization impacts and manage the stormwaters but also provide the cities with positively environmental aspects.

Author Statement

Ehsan Teymouri: Conceptualization, Methodology, Validation, Conducting Experiments, Investigation, Writing- Original draft, Writing- Review and Editing, Visualization. **Nurul Noraziemah Mohd Pauzi:** Conceptualization, Validation, Visualization, Methodology, Supervision, Project Administration, Writing- Review and Editing. **Kwong Soon Wong:** Conceptualization, Validation, Visualization, Methodology, Supervision, Writing- Review and Editing, Project administration. **Mehdi Forozan:** Conceptualization, Methodology, Conducting Experiments, Investigation, Writing- Review and Editing, Formal analysis. **Marjan Salari:** Conceptualization, Methodology, Conducting Experiments, Investigation, Writing- Review and Editing, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to acknowledge the support and facilities provided by Sharq Cement Product Company, Mashhad, Iran.

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