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A model to develop the porosity of concrete as important mechanical property

Rayed Alyousef [1], Hisham Alabduljabbar [1], Abdeliazim Mustafa Mohamed [1],
Abdulaziz Alaskar [2], Kittisak Jermsittiparsert*[3,4] and Lanh Si Ho [5]

[1] *Department of Civil Engineering, College of Engineering, Prince Sattam bin Abdulaziz University, Al-kharj 11942, Saudi Arabia*
[2] *Department of Civil Engineering, College of Engineering, King Saud University, Riyadh 11362, Saudi Arabia*
[3] *Department for Management of Science and Technology Development, Ton Duc Thang University, Ho Chi Minh City, Vietnam*
[4] *Faculty of Social Sciences and Humanities, Ton Duc Thang University, Ho Chi Minh City, Vietnam*
[5] *Institute of Research and Development, Duy Tan University, Da Nang 550000, Vietnam*

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Abstract. This numerical study demonstrates the porosity conditions and the intensity of the interactions with the aggressive agents. It is established that the density as well as the elastic modulus are correlated to ultrasonic velocity The following investigation assessed the effects of cement grade and porosity on tensile strength, flexural and compressive of Ultra High Performance Concrete (UHPC) as a numerical model in PLAXIS 2d Software. Initially, the existing strength-porosity equations were investigated. Furthermore, comparisons of the proposed equations with the existing models suggested the high accuracy of the proposed equations in predicting, cement grade concrete strength. The outcome obtained showed a ductile failure when un-corroded reinforced concrete demonstrates several bending-induced cracks transfer to the steel reinforcement. Moreover, the outcome also showed a brittle failure when wider but fewer transverse cracks occurred under bending loads. Sustained loading as well as initial pre-cracked condition during the corrosion development have shown to have significant impact on the corrosion behavior of concrete properties. Moreover, greater porosity was generally associated with lower compressive, flexural, and tensile strength. Higher cement grade, on the other hand, resulted in lower reduction in concrete strength. This finding highlighted the critical role of cement strength grade in determining the mechanical properties of concrete.

Keywords: strength-porosity relationship; cement grade; mechanical properties of concrete; PLAXIS 2d; UHPC

1. Introduction

A predominant global issue is the corrosion of steel reinforcement which is embedded in Ultra High Performance Concrete. This severely impacts various reinforced concrete (RC) structures. Corrosion is recognized for being precarious ever since the early stages of refinery along with mining for metals. Although, corrosion in RC structures has gauged research interest only sometime between the 1960s and 1970s, shortly after an extensive usage of de-icing salts for highways in the United States along with a massive growth in the construction sector. Ever since, studies have been set in motion globally, in order to address the issues of corrosion (Shariati *et al*. 2020g). To predict concrete structure's service life and behavior life of concrete structures with the corroding steel bars, theoretical models were created and also calibrated with experimental findings. Concrete is produced from solid substances whose strength decreases with increasing porosity (Shariati *et al*. 2020d). Concrete is known to have low tensile strength, hence why it is common to have cracks in reinforced concrete elements. It is typically common for cracking to occur in the reinforced concrete structures at a service load (i.e., during normal usage of structures) which are usually unavoidable. Amongst all studies published after 2019, only one study, which was conducted by Toghroli *et al*. (2020) actually considered preloaded test models as cracks existed before the testing accelerated corrosion. However, the test program for this research never applied a sustained loading condition. Surface cracks, sustained service loads on structures, or rather a mixture of both these conditions may impact the corrosion rate, the repair effectiveness and the corroded RC members' residual moment strength. In developing countries, where there is ongoing large-scale urbanization occurring, insulation in buildings is key to lessen the energy consumption. Research by Davoodnabi *et al*. (2019) suggested how factors like durability, low cost and reinforcement have resulted in researchers developing numerous kinds of lightweight concrete to reduce the consumption of energy. Withal, the usage of these materials is quite limited in terms of using them as thermal insulators, due to their reasonably high density (210–1530 kg m^3) as compared with other porous organic materials like expanded polystyrene and polyurethane board. Lightweight concrete's thermal insulation performance is able to be improved through an increase in the porosity from these materials (Shariat *et al*. 2018). Research by Hoff (1972) proposed a single strength-porosity relationship as a simple tool for the design of cellular concretes. Some other studies have also considered cement paste as the main cause of porosity and evaluated

*Corresponding author, Ph.D.,
E-mail: engineering1130@yahoo.com

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the strength of porous concrete accordingly (Du *et al*. 2014, Ramezanianpour and Hooton 2014). A number of studies have also sought to introduce empirical and theoretical equations to interpret porosity's effects on the strength of different types of Ultra High Performance Concrete (Matusinović *et al*. 2003, Papayianni and Stefanidou 2006, Patil and Bhattacharjee 2008, Abousnina *et al*. 2016, Justo-Reinoso *et al*. 2018). A two-phase study assessed the effects of viscosity modifiers on porosity, water penetration, and the compressive strength of self-compacting concrete and found higher porosity (up to three times) in samples whose preparation involved air entrainment (Łaźniewska-Piekarczyk 2013). Another research examined the relationships among porosity as well as the compressive strength of two sets of mortars prepared with cement, water, and rocks either alone or in combination with silica fume, super plasticizers, and limestone. Griffith's theory (Griffith 1921) was applied to predict the mortar's compressive strength and the results were compared with experimental data. In a recent research, Griffith's theory was used to illustrate the relations between porosity and compressive, flexural, and tensile strength. A sample series was prepared with 42.5 cement grade at a sand/cement ratio of 3 and different cement/water ratios (i.e., 0.7, 0.4, 0.3, and 0.6). The strength of the samples was measured on the seventh and 21th days and the relations between porosity and compressive, flexural, as well as tensile strength have been determined using four linear and non-linear relations. Ultimately, the non-linear model was found to predict concrete strength with a lower level of error (Chen *et al*. 2013). Thus, for this work, high-porosity foamed concrete (HPFC) had been readied through adding performed foam for a Portland-cement slurry, along with the HPCF slurry's stability, at the point of the hardening process had been examined by Shariati *et al*. (2020f). The curing method, compressive strength, air-void structure and the thermal-insulation properties had also been determined. The findings gathered from this research might offer an insight to the low-cost preparation as well as the application of foamed concrete that have much more improved thermal-insulation features than the alternative lightweight concretes (Xu *et al*. 2004, Sedghi *et al*. 2018, Shariati *et al*. 2020e). Porous concrete's compressive strength was investigated in a prior numerical study. This examination may be applied as an index to characterize mechanical capacities of the porous Ultra High Performance Concrete from this study. However, the pore structure for a porous material may be characterized through numerous parameters such as but not limited to pore surface toughness, pore size, pore volume fraction (porosity) as well as pore connectivity. Out of these, the porosity is understood as the main parameter of porous material microstructure which was investigated by Shariati *et al*. (2019f).

2. Methodology

2.1 Numerical method preparation in PLAXIS 2d

To cast and prepare the test models, all numerical models were ensured of being inclusive of a coarse aggregate to fine aggregate ratio of 4.9, a water to cement ratio (w/c) of 0.23 and a cement content of 689 Kg/m^3 (ASTM Type I Portland cement). In four batches, 10, 962 × 86 × 312 mm (45 × 6 × 92 inch) test models were casted. To identify the compressive strength of each batch, several cylindrical shaped were casted using the same concrete. These cylinders were 204 mm (8 inches) in length and 102 mm (4 inches) in length. Fig. 1 represents the reinforcement configuration of the test models.

2.2 Compessive strength

In this research, to prepare porous concrete, the composition utilized was inclusive of ordinary Portland cement, water, and coarse aggregates. Nevertheless, to achieve a varying strength, admixtures such as but not limited to Ultra High Performance Concrete or Portland II, quarry sand as well as superplasticizer were added to some of the mixes. As a result, two separate groups of test models were prepared. Table 1 shows the relative proportions for each group. Water, cement, and coarse aggregate were used to produce the first group of samples. The coarse aggregate consisted of dolomite, quartzite, and limestone whilst three gradings were selected as well (G1: 7.7–3.75 mm; G2: 9.5–4.7 mm; G3: 7.5–4.75 mm). The second group was preparing using additives which consisted of 7% of silica fume and 0.8% of superplasticizer by weight of some quarry sands as fine aggregates and cement (Trung *et al*. 2019a, Naghipour *et al*. 2020b, Razavian *et al*. 2020, Safa *et al*. 2020, Shariati *et al*. 2020b, c). Dolomite was utilized as a major coarse aggregate for preparing the second group. For obtaining samples with different porosity and strength, in second group of samples, the water to cement ratio was altered from 0.3 to 0.38 incrementally (Xie *et al*. 2019). The article discussed the mixing procedures and preparation steps.

2.3 Porosity of concrete

Research by Nosrati *et al*. (2018) specified that the largest number of pores that can be in porous concrete, happen to be developed by the leftover spaces amongst coarse aggregates while they can be determined between air void content and porosity. Their study explains the fraction of measurable voids transferred through fluids in which in their tests was named porosity. The total addition of measurable voids between aggregates as well as entrapped air or entrained in the cement paste was called air content. On the other hand, the definition of porosity of porous concrete can get discussed through a novel approach. In this

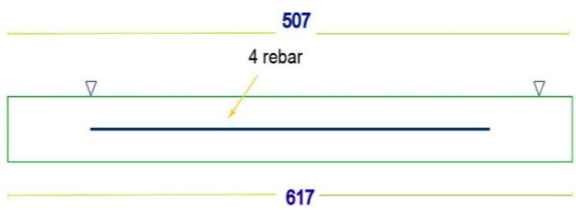


Fig. 1 Reinforcement ultra high performance concrete within test slabs (mm)

Table 1 21-Day mix proportioning and compressive strength of porous concrete

Cement model number	Mix properties	W/C Ratio	CA (kg)	FA (kg)	Percentage of sand	Compressive strength (MPa)
G1	Q-G2	0.36	631.7	969.7	0	11.9
G2	Q-G3	0.23	599.5	723.9	12.3	12.6
G3	Q-G4	0.36	477.2	837.4	0	98.3
G4	Q-G9	0.23	531.1	950.8	0.32	12.5
G5	D-G1	0.36	602.6	876.9	3.65	12.4
G6	D-G6	0.89	573.2	841.4	5.98	13.9
G7	L-G2	0.39	635.1	814.2	6.23	78.5
G8	L-G9	0.42	631.7	824.8	0.12	95.6
G9	L-G10	0.25	667.6	858.8	6.89	78.5
G10	L-G12	0.94	631.7	456.5	7.0	63.5
G11	L-G13	0.64	631.7	969.7	5.78	45.3

research and for the purpose of clarity of information, the measurable voids can be known as the effective porosity due to the fact that it links to permeability while their total porosity can be defined as the overall air content. The volume of total voids in concrete can alter the strength of Ultra High Performance Concrete (Shariati *et al*. 2019d, 2020f, Trung *et al*. 2019b, Cao *et al*. 2020). From macro-scale to nano-scale, the pores can be observed in the concrete's complex microstructure. This complex microstructure is very unique as it is difficult to figure out the overall porosity of porous concrete. As a comparison to the pores amongst cement paste, the voids between coarse aggregates happen to be bigger by just millimeters which are also interconnected. If UHPC is subjected to pressure, majority of interconnected voids amongst porous concrete can lead to leakage as well as dripping of mercury even though one of the most effective ways to observe the pore configuration within ordinary UHPC happens to be the approach of mercury intrusion porosimetry (MIP). Therefore, it can be deduced that the approach of MIP is not feasible for porous concrete (Shariati *et al*. 2019b, c, d, e, Suhatril *et al*. 2019, Trung *et al*. 2019a). In order to accurately observe and test porosity for porous concrete, it is more feasible to use vacuum sealing apparatus especially in laboratory experimental studies (Nguyen-Thoi *et al*. 2009, Toghroli *et al*. 2018a, Shariati *et al*. 2019a). Nevertheless, it is essential to note that preparing such precious and precise apparatus for concrete producers are challenging therefore straighter forward and effective approach is preferred. In a literature review completed by Hosseinpour *et al*. (2018), it can be found that they applied the Sajedi equation (Sajedi and Shariati 2019) to approximate what the overall porosity of foam concrete is, successfully. Likewise, Shariati *et al*. (2019b) has proposed an equation for the purpose of approximating the overall porosity of porous UHPC which happened to be discussed as an analogous to the Hoff equation. The difference is that the proposed equation consisted of a variable for the aggregate proportions for porous concrete. Porosity measurements were completed on all samples from each mix design while their mean values were used for analysis. The samples were then put in an oven with a specific temperature of 105°C (221°F) until they reach a constant weight, samples saturated surface dry and immersed weights, also were determined and used in porosity calculations. Porosity was then calculated using Eq. (1) and

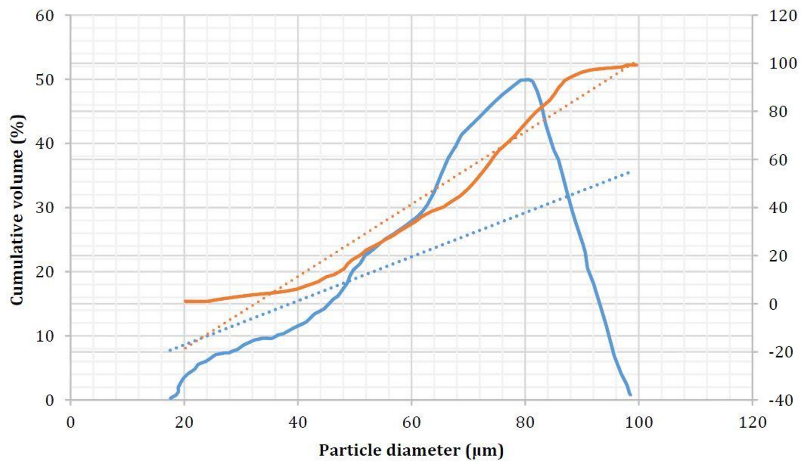


Fig. 2 Particle size distribution of the cement

(2) (Safa *et al*. 2019, Shariati *et al*. 2019d, 2020f, Cao *et al*. 2020a, b)

$$\max_{0\le x\le 1} xe^{-x^2} \tag{1}$$

$$\rho = \frac{100+\rho_c+0.36\rho_c}{\frac{120}{\rho}+\frac{\rho}{\sigma}+(9\frac{3}{4})} \tag{2}$$

Where ρ is the percentage of porosity, WSSD is weight of test model in the saturated surface dry (SSD) situation, Wd is the dry weight, and Ww is the immersed weight of the samples. Previous researches have confirmed the accuracy of the above-mentioned equation in porosity calculations (Mansouri *et al*. 2019, Milovancevic *et al*. 2019, Shariati *et al*. 2019c, Trung *et al*. 2019a). Table 1 shows the chemical compositions of the cement. Fig. 1 which corresponds to Table 1 on the other hand, demonstrates how the size distribution of particles that was determined by utilizing a Mastersizer 2000 (Malvern, England). To speed up the hardening reaction, a set-accelerator that was made from mainly aluminum sulfate was utilized.

This research highlights that silica fume had been applied in Group 2 for the means of increasing the porous UHPC's strength. As a result, the qc gravity had to be modified. In order to deduce qc, the relative gravity for silica fume and cement was extracted as 2.2 and 3.15 respectively. Thus, q_c = (2 + 0.26) / (2.95 – 0.079/23) for Group 2. Fig. 3 demonstrates the measured effective porosity as well as the approximated overall porosity for each mix. It was found that the relationship is almost linear. Fig. 3 also shows the best fitted regression line for the given data.

3. Results

As a result, that is from Fig. 4, the fitted exponential curve yields the equation: s = 231 exp (0.012p), alongside an R^2 value of 1.2, that is significantly lower than that of the value of 0.36 This could also be due to the fact that they examined the hardened cement paste's strength applied in the porous UHPC as well as the fineness modulus of the aggregates. Consequently, all these values had been applied to calibrate the constants of the equation. The study aims to theoretically calibrate the model of the situations during the time at which the hardened cement paste's strength is unavailable.

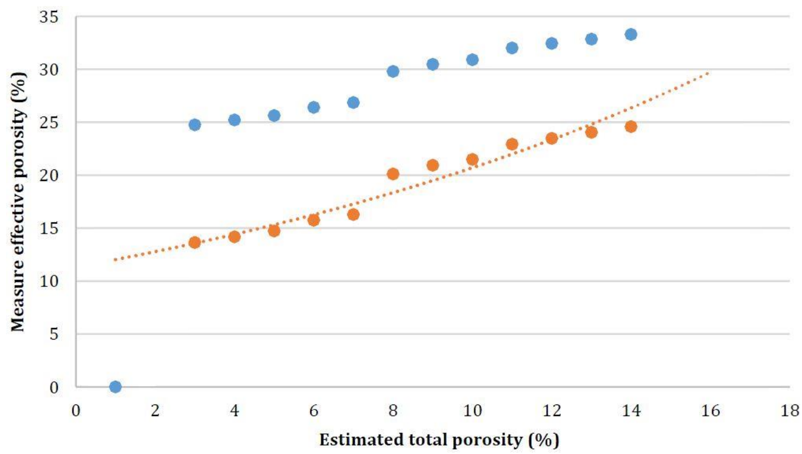


Fig. 3 The relationship between measured effective porosity and estimated total porosity

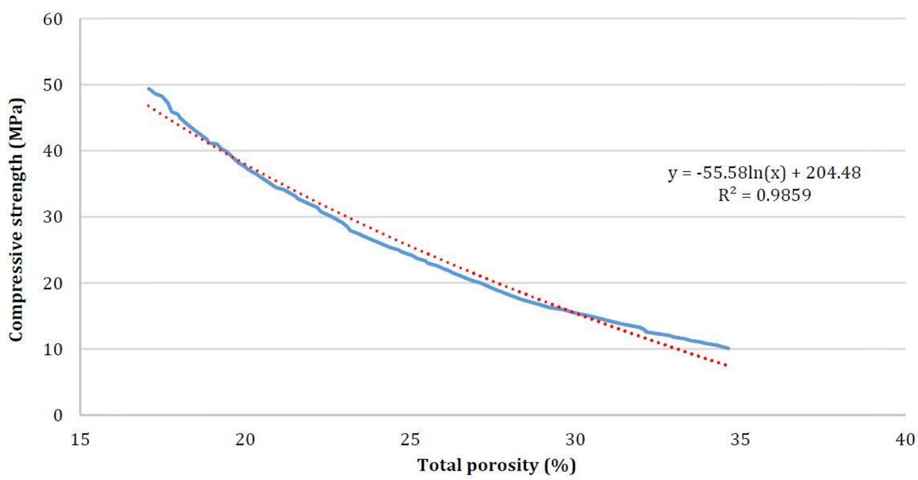


Fig. 4 Relationship between effective porosity and total porosity

Several equations were proposed with the intention of clarifying the relationship between the strength of cement-based materials as well as porosity. An equation for the calculation of the tensile strength of metal-ceramic bond existed

$$\sigma = \sigma_0(1-P)^b \tag{3}$$

Where σ_0 is the strength in zero porosity and thus, b is the empirical constant.

The following equation to describe the compressive strength of Al_2O_3 as well as ZrO_2 also exists

$$\sigma = \sigma_0 e\beta^{-kP} \tag{4}$$

The density of the HPFC's solid phase on was lessened through an increase in w/c. Meanwhile, its strength at 7 days, 28 days as well as 56 days was elevated seemingly as portrayed in Fig. 5. In actuality, 56-day compressive strengths at 0.91 Mpa as well as 0.25 Mpa was acquired with w/c values of 0.9 as well as 0.8, respectively. The number of capillary pores rose when the w/c values were increased. Indeed, for a similar porosity, an elevating fraction of capillary pores results in a lessening number of air-voids. Air voids happen to be relatively bigger as compared to that of capillary pores, and thus the strength rises when the void's density decreased. Additionally, for the same porosity, samples that consist of small air voids actually contain a bigger total surface area of voids compared to their counterparts, that contain bigger voids (Toghroli *et al*. 2018b, Wei *et al*. 2018, Zandi *et al*. 2018, Ziaei-Nia *et al*. 2018). The big air voids which are created in the HPFC, at high w/c values, contribute to foam coating and thus reduce pore connectivity as well as strength increase. The high w/c values contribute to lower plastic viscosity and thus result in a decrease in the density of large irregular pores as well as strength increase (Daie *et al*. 2011, Shariati *et al*. 2011a, Sinaei *et al*. 2011, 2012, Jalali *et al*. 2012, Toghroli *et al*. 2014, 2018a, Shah *et al*. 2015, Khanouki *et al*. 2016, Shah *et al*. 2016a, c, Shahabi *et al*. 2016a, b, Wei *et al*. 2018, Chen *et al*. 2019, Katebi *et al*. 2019, Li *et al*. 2019, Luo *et al*. 2019).

Most statisticians consider R^2 values equal or higher than 0.7 for reasonable models. Therefore, the derived empirical equations might favorably apply to demonstrate the relationship among the strength, porosity along with the cement grade of UHPC samples (Hamidian *et al*. 2011, Shah *et al*. 2015, Mansouri *et al*. 2017, Nasrollahi *et al*. 2018, Paknahad *et al*. 2018, Chahnasir *et al*. 2018, Shariati *et al*. 2018, Zandi *et al*. 2018, Ziaei-Nia *et al*. 2018, Naghipour *et al*. 2020a). Notably, the compressive, flexural and tensile strength of UHPC may get affected from various factors like the teating method used, W/C ratio, curing time, aggregate type and test model size. Additionally, aside from these factors, the strength of concrete can get affected by fineness of a Portland cement which is the key factor in determining cement strength characteristics (Arabnejad Khanouki *et al*. 2010, Mohammadhassani *et al*. 2013a, 2014a, Shariati *et al*. 2014b, 2017, Toghroli *et al*. 2017, Heydari and Shariati 2018, Ismail *et al*. 2018). In this regard, the proposed equations in this investigation are given as a function of concrete strength, porosity, as well as the cement grade used. However, further research may be necessary to validate the relationships derived on this research, as well as to find the effects of other factors like chemical composition of Portland cement (Tahmasbi *et al*. 2016, Khorami *et al*. 2017a, b, Khorramian *et al*. 2017, Armaghani *et al*. 2020, Naghipour *et al*. 2020a, b, Razavian *et al*. 2020, Safa *et al*. 2020, Shariati *et al*. 2020a, b, c, d, e, f, g, h, Toghroli *et al*. 2020).

To explain the impacts that the pore content has on surface energy and Young's modulus for different materials, many equations is derived (Shariati *et al*. 2011b, 2012b, 2014a, Sinaei *et al*. 2012, Mohammadhassani *et al*. 2013b, 2014b, Khorramian *et al*. 2015, Shah *et al*. 2016b). Throughout this current research, two different approaches were taken into consideration during the time at which it was necessary to choose the proper empirical equations for E and c to be incorporated in Eq. (5). First of all, (Mansouri *et al*. 2019) discovered the decrease in Young's modulus and described as E = E_0 exp, where E_0 is the elastic modulus of the material at zero porosity with t as a constant. In addition to that, Mansouri also distinguished the fracture

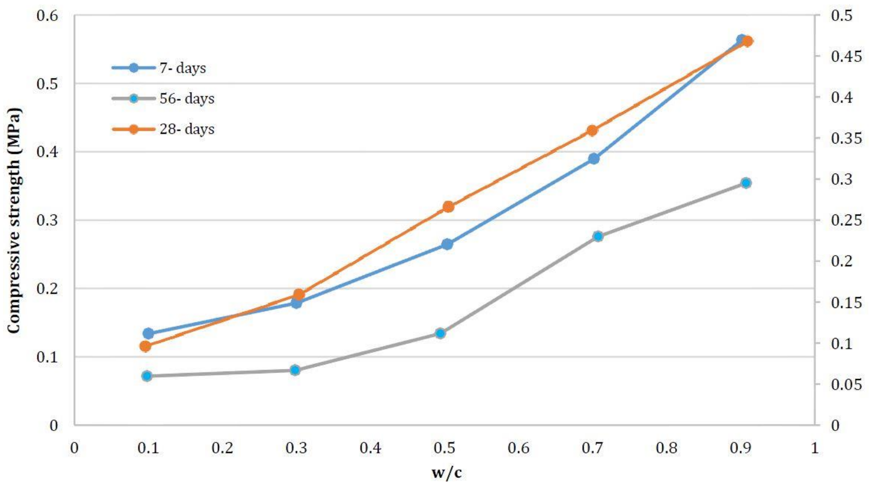


Fig. 5 Effect of w/c on the compressive strength

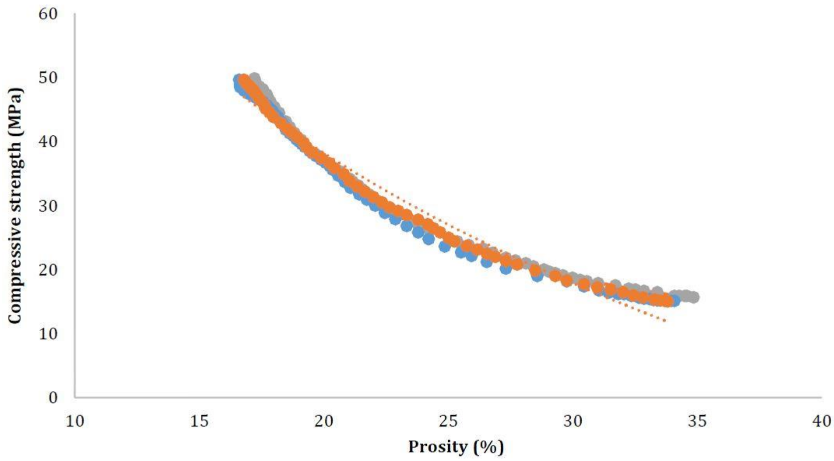


Fig. 6 The proposed model for compressive strength versus porosity

energy of pores as: c = c_0 exp, where c_0 is the fracture energy at zero porosity and q is a constant. In the case of porosity, the discovered differences of the fracture energy are exactly similar to the Young's modulus (Arabnejad Khanouki *et al*. 2011, Shariati *et al*. 2011c, Shah *et al*. 2016c). The relationship shown in Eq. (5) can be derived if the mentioned relationship from other researches is assumed for porous concrete.

$$\partial = \sqrt{\frac{2E_0 e - qp\gamma_0 e}{\beta a}} = \sqrt{0.44}\frac{2E\partial_0}{\partial a} = Ke^{-mp} \qquad (5)$$

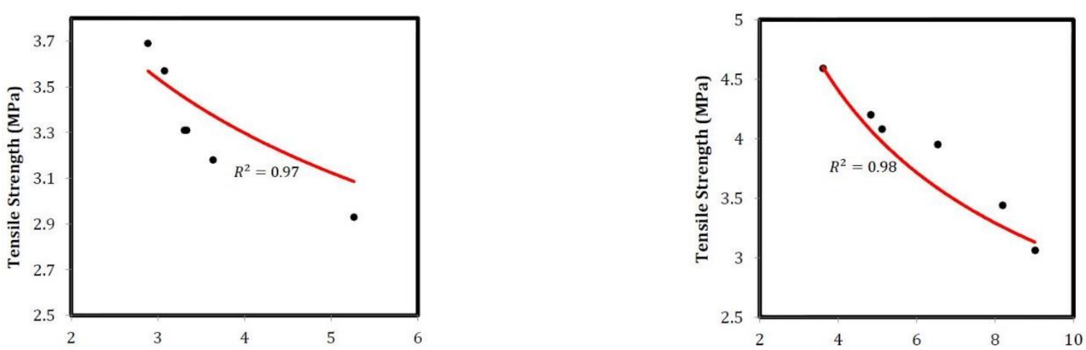
This equation is plotted in Fig. 7 alongside the experimental data. It is evident how the regression lines of Eq. (6) portrayed a reasonably good relationship among the predicted as well as observed tensile strength values. The coefficient of determination for the predicted tensile strength values was 0.97, 0.98, and 0.96 for 32.5, 42.5, and 52.5 cement grades, respectively. Therefore, as these values were all close to one, the model had sufficient validity for the prediction of tensile strength (Shariati *et al*. 2012a, 2013, 2015, 2016).

$$\sigma = (\sigma/c/8.5) \times P(-0.025P) \qquad (6)$$

4. Conclusions

In present researches, there were various experiments which were performed to find the porosity and compressive, flexural, and tensile strengths of UHPC samples. Their experimental findings had also been contrasted with the predicted values using previously developed and also presented empirical models. The following conclusions could be made based on the obtained findings:

(1) The experimental findings show how greater porosity was generally associated with lower compressive, flexural, and tensile strength. Higher cement grade, on the other hand, resulted in lower reduction in UHPC strength.
(2) Among existing equations, Schiller's model had more realistic coefficients and parameters and was hence the best fitting model to formulate the relationship amongst concrete porosity as well as strength.
(3) With a series of experimental data on porosity and tested compressive, flexural and tensile strength, three newly developed empirical models have been proposed. The presented equations can thus be applied whenever the effects of porosity and cement grade need to be simultaneously considered.



(a) 32.5 Mpa (b) 42.5 Mpa

Fig. 7 Comparison of the predicted and actual tensional strength values for 32.5 (a), 42.5 (b) MPa cements grade. (Note: 1 MPa = 145 psi)

(4) Comparison between experimental and model results showed that the proposed models provide better relationships among the strength as well as the porosity of porous UHPC, alongside a model regression statistic R^2 that reaches 0.99. This illustrates the high accuracy of the proposed equations.
(5) The porous concrete's effective porosity was calculated. Although, ever since the non-intrusive pores weaken concrete's strength, total porosity was able to be estimated and consequently contrasted with effective porosity. It was illustrated how the estimated total porosity has a good correlation with measured effective porosity. This particular type of method for estimation may be applied if the total porosity testing apparatus is unavailable.
(6) The existing equations which relate compressive strength as well as porosity for cement-based materials had been presented and thus, a potential and suitable equation for porous UHPC was praised through fitting to the experimental data. Evidently, it is proven how even excluding additional knowledge of paste strength, the exponential function derived by applying the experimental data leads to a reasonably low correlation coefficient.

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