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Performance evaluation of dry-pressed concrete curbs with variable cement grades by using Taguchi method

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KEYWORDS

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Abstract Producing concrete curb with improved properties is crucial nowadays. The two important factors of lifetime and mechanical properties can impact curb construct. Specifically, porosity is a parameter influencing durability of curb construct while compressive strength and flexural strength are the elements affecting mechanical properties of curb construct. This study conducted an experimental study to statistically investigate the prominence of porosity, and compressive and flexural strength on dry-pressed concrete curbs (DPC). To this end, 27 mix designs of (DPC) were prepared based on three cement strength grades of 32.5, 42.5 and 52.5 MPa. Water-to-cement ratio (w/c) (0.2, 0.25 and 0.3) and cement content (300, 350 and 450 kg/m^3) were considered as the main parameters of the experiments. The statistical properties of the factors were assessed using Taguchi method.

The results of Taguchi method revealed that specimen construct with 0.2 of w/c, 400 (kg/m^3) cement content, and strength grade of 52.5 MPa had the maximum compressive strength of DPC. It was also found that cement strength grade affects its mechanical properties.

1. Introduction

One of the essential materials used for building is concrete that begins as a fluid mixture and cures into solid. To produce concrete curbs, using different methods such as normal (vibrating), dry-pressed, and wet-pressed is common nowadays [1–3]. Due to having an extended lifetime (caused by their higher porosity) and being rapidly produced, pressed curbs have attracted a lot of attention [4–6]. Since DPCs' lifetime can be highly influenced by porosity, it is considered as a more critical parameter than compressive strength in determining freeze-thaw resistance of concrete [7]. Additionally, porosity is a factor that has a substantial impact on mechanical properties of solid materials [8,9]. The space between material and the fraction of the volume of empty space of the total volume is defined as porosity that is a value between 0 and 1, or

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0–100% [10]. Porosity is dependent on several key factors such as type of material, material size, pore distribution, and composition [11]. Generally, decrease in porosity leads to an increase in the strength of the solid materials [10,12,13]. However, studies that empirically and quantitatively support relationship between strength and porosity are limited in the extant literature and their findings are not generalizable [14–17]. Another factor that has gained considerable attention is the pore structure of cement-based materials [18,19]. Indeed, one of the parameters that directly impacts the strength and durability of cement-based materials is porosity [20–22]. As such, cement-based material with lower porosity may have higher strength [10,23,24]. The relationship between compressive strength and porosity of cement mortar was examined in a previous experimental study [9]. To carry out the mentioned study, specimen was prepared in cubic shape by 2 cm dimension and porosity was determined by mercury intrusion. Along with porosity, another factor that affects mechanical properties of cement-based material is cement content [25–28]. Based on the findings of an earlier study, cement enhances aggregated cohesion in the fresh mix and by devoting mortar to the substrate, mechanical strength could be increased while water permeability would be decreased [29]. There are various methods of optimization which may be applied in various engineering and interdisciplinary subjects which notify the importance of obtaining optimal results [30–35]. In this regard, there are a number of methods that can optimize concrete mix design [36,37] among which Taguchi as a one of the most frequently used methods in various industrial fields and research areas is applied in this work. Evidences show that Taguchi method has been recently applied in concrete design studies [38–41]. One of the advantages of the Taguchi method over the conventional experimental design methods, in addition to keeping the experimental cost at the minimum level, is that it minimizes the variability around the target when bringing the performance value to the target value. Its other advantage is that the optimum working conditions determined from the laboratory work can also be reproduced in the real production environment [39,42] It is worth noting that several parameters that affect the properties of concrete are controlled in these studies.

Although previous researches have noted that increasing in porosity value results in decreased strength of cement based materials, there are not enough researches about influence of porosity, cement content and cement strength grade on DPC. In this study, 27 different mixes of DPC were thus produced aim to determine the compressive and flexural strength of DPC samples, and examine simultaneous effect of porosity, cement grade, and cement content on mechanical properties of the samples. Additionally, Taguchi experimental model was utilized in this study to investigate the effect of selected synthesis parameters on the strength and porosity of DPC.

2. Experimental plan

2.1. Composition of DPC and manufacturing of samples

To carry out the experimental study, an adequate series of dry-pressed concrete (DPC) samples were prepared using ordinary Portland cement type II in three strength grades of 32.5, 42.5, and 52.5 MPa in Sabzevar Factory, Iran. This study used 9.5 mm aggregated size for dry-pressed curbs which is in line with the national method for concrete mix design in Iran [43]. The fineness modulus (FM) was estimated as 4.57. Three cement content of 300, 350, and 400 kg/m^3 and three water-to-cement ratios (0.3, 0.25, and 0.20) were used for preparing DPC sample construct. The maximum value of free water content was estimated at about 120 kg/m^3 in order to obtain a slump value lower than 1 cm for DPC mixtures. To achieve standard dimensions of specimen, DPC samples were cut by cutting machine in $50 \times 10 \times 10$ cm and $10 \times 10 \times 10$ cm. After the cutting DPC samples into the desired dimensions, their surface were cleaned and smoothen.

2.2. Test procedures

2.2.1. Strength

For measuring compressive strength, British Standard 1881 was considered in this study [44]. For this purpose, all samples ($10 \times 10 \times 10$ cm) were cured in water for 28 days. Then each of the three specimen mixtures was tested. The three specimens ($50 \times 10 \times 10$ cm) of each mixture were then assessed for point bending flexural tests which was conducted based on the American Society of Testing and Materials (ASTM) C78 [45]. As pointed out earlier, all the tests were performed in triplicate and the average values were calculated.

2.2.2. Porosity

For four samples of the mixture, porosity was estimated and the mean value was then obtained. To determine porosity, saturated surface of dry and water-immersed samples was both weighed. Then, the samples were placed in an oven at a temperature of 105 °C to ensure their constant weight [46]. To calculate porosity, the following equation was used:

$$P = \frac{W_{SSD} - W_d}{W_{SSD} - W_w} \times 100\% \quad (1)$$

where P is porosity (%), W_{ssd} is the weight of saturated surface dry samples, W_d is the dry weight of the samples, and W_w is the water-immersed weight of samples. This is a common method that can successfully measure porosity of cement-based materials [12,47–49].

3. Performance evaluation of dry-pressed concrete curbs

Due to being a simple, proficient, and systematic approach, Taguchi's method of experimental design is suitable for optimizing the experimental designs to assess performance quality [50]. Taguchi uses standard orthogonal arrays to evaluate each independent factor or its interaction effect on the process characteristics. Then, to calculate deviation between the experimental value and the desired value, a loss function is defined. This loss function is further transferred to a signal-to noise (S/N) ratio, g [19]. There are three common S/N ratios available that depend on the types of characteristic; the lower-the better (LB), the higher-the better (HB), and the nominal-the better (NB). For each type of characteristic, the S/N ratios can be estimated as follows:

1. Lower is better, choose when objective was to minimize the response. The S/N can be calculated by Eq. (2) for smaller the better

$$S/N = -10 \times \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \quad (2)$$

2. Higher is better, choose when objective was to maximize the response. The S/N is calculated by Eq. (3) for larger the better

$$S/N = -10 \times \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{Y_i^2}\right) \quad (3)$$

3. Nominal is better, choose when objective was to target the response and it is required to base the S/N on standard deviations only. The S/N is calculated by Eq. (4) for smaller the better.

$$S/N = -10 \times \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} (Y_i - Y_0)^2\right) \quad (4)$$

where in Eqs. (2)–(4), Y_i is the value of characteristic and n is the number of observations.

This study used two control factors, namely (1) water-to-cement ratio (w/c) and (2) cement content (C) (kg/m^3), as well as three control levels for each control factor as illustrated in Table 1.

4. Results and discussion

4.1. Strength investigation

To determine compressive strength and porosity, three specimens with the dimensions of 10 × 10 × 10 cm from each mixture were tested. The average values of strength and porosity were used to assess the coefficients in the mentioned equations. In order to analyze flexural strength, pieces of the samples with the dimensions of 50 × 10 × 10 cm were tested and the data were obtained. Fig. 1 depicts w/c-porosity-strength diagrams for the three grades of cement (32.5, 42.5, and 52.5). As shown in Fig. 1, by increasing w/c, compressive strength decreases while porosity increases. Overall investigation of the Fig. 1 indicates that the specimen prepared by 400 (kg/m^3) cement content has higher compressive strength and lower porosity compared to the specimen prepared by 300 and 350 (kg/m^3) cement content. The maximum compressive strength and minimum porosity were recorded as 0.2 of w/c and 400 (kg/m^3) cement content. The compressive strength at this point by three cement grades of 32.5, 42.5 and 52.5 MPa is 30, 35 and 39 MPa respectively. In other words, porosity is 6%, 5% and 4%. Thus, by increase in strength grade of cement and cement content, compression of DPC increases. Moreover, porosity decreases by increase in strength grade of cement and cement content.

Table 1 Factors and values tested.

Factor	Level 1	Level 2	Level 3
Water-cement ratio (w/c)	0.20	0.25	0.30
Cement content (C (kg/m^3))	300	350	400

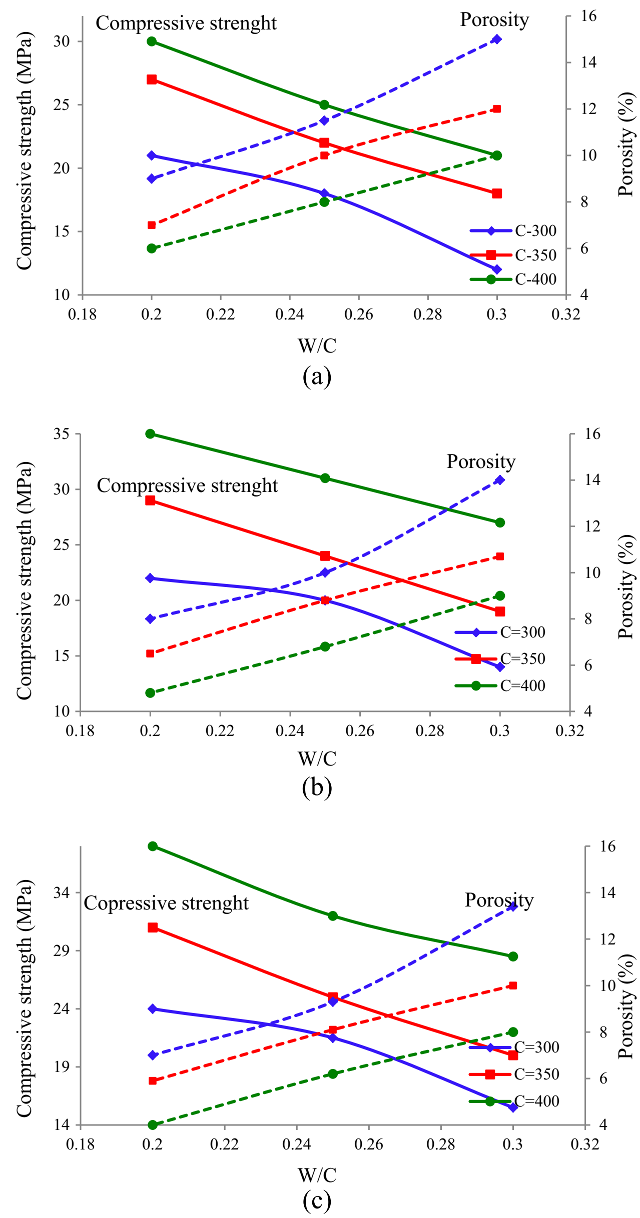

Figure 1 Relationships among w/c, compressive strength and porosity (32.5 (a), 42.5 (b) and 52.5 (c) MPa grade cements).

Fig. 2 illustrates the relationship among w/c, flexural strength, and porosity for three cement grades 32.5 (a), 42.5 (b) and 52.5 (c) MPa. As depicted, by changing of w/c, the behavior of flexural strength could be similar to compressive strength. As the results indicate, by increase in cement content and cement grade, flexural strength increases. In addition, the samples prepared by 400 (kg/m^3) cement content and 0.2 of w/c have the maximum flexural strength. It is shown that DPC samples prepared by 42.5 MPa cement grade have individual behavior. Specifically, samples prepared by 300 (kg/m^3) cement content have more strength than samples prepared by 350 (kg/m^3) cement content which is different in 32.5 and 52.5 MPa grade cements. It is also revealed that porosity of 300 (kg/m^3) cement content with w/c of higher concentrations (0.25) is different from others. The gradient of porosity in this

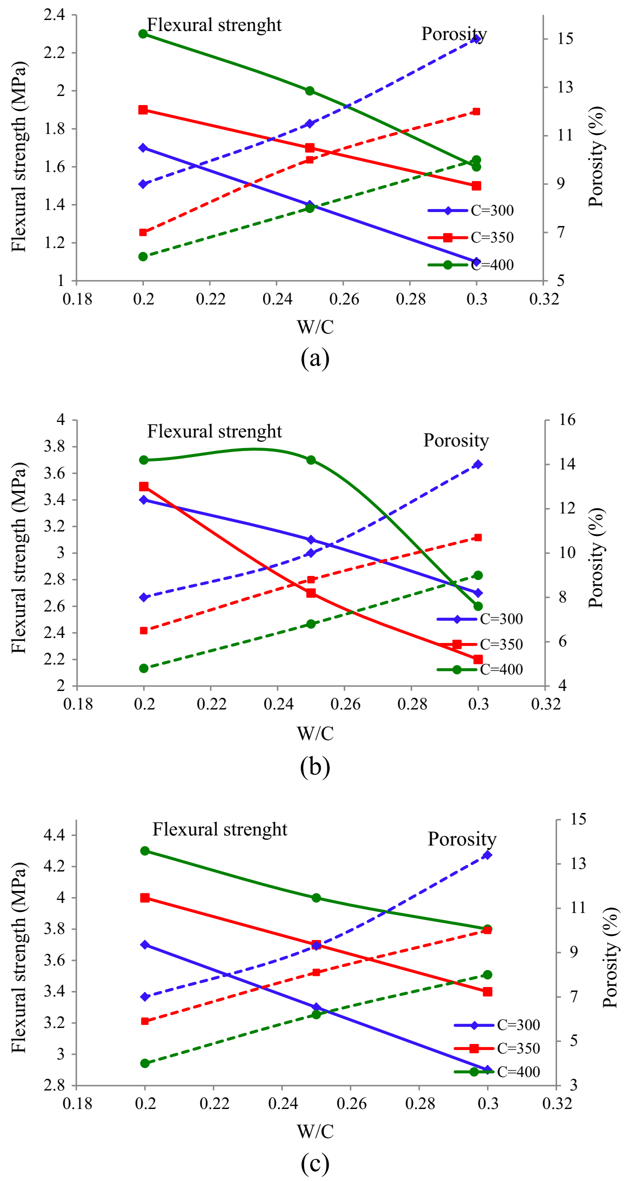

Figure 2 Relationships among w/c, flexural strength and porosity (32.5 (a), 42.5 (b) and 52.5 (c) MPa grade cements).

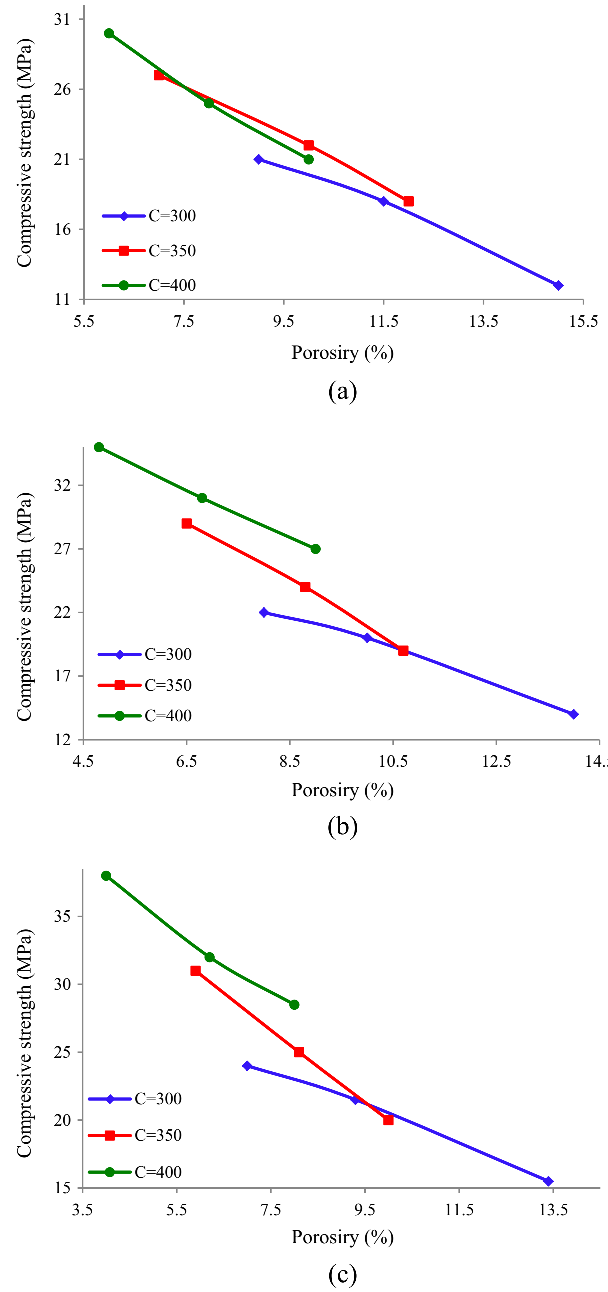

Figure 3 Relationships among compressive strength and porosity (32.5 (a), 42.5 (b) and 52.5 (c) MPa grade cements).

range is more than other cement content. This indicates that porosity is sensitive to change which can be considered as a limitation in this regard.

Fig. 3 illuminates the relationship between porosity and compressive strength for three cement strength grades. As seen, compressive strength in all three cement strength grades decreased with increasing porosity. In addition, with a constant porosity percent, increased cement content was associated with increase in compressive strength. In this similar situation, increased cement strength grade resulted in enhanced difference between compressive strength in various cement contents; that is, for the cement grade of 32.5 MPa and the porosity of 9.5%, the compressive strength values were 19, 21, and 22 MPa for 300, 350, and 400 (kg/m^3) cement contents, respectively. However, for cement grade of 42.5 MPa these values were 20, 22 and 28 MPa, and for cement grade of 52.5 MPa varied from 22 to 29 MPa. It is also obvious that, in the same value of cement content by increase in cement grade from 32.5 to 52.5 MPa, the porosity value decreased, i.e. for the cement content of 300 (kg/m^3) and 32.5 MPa grade cement, porosity value varied from 5.9% to 15.2%. On the other hand, this range for 42.5 and 52.5 MPa grade cements was 4.6–14.2% and 3.9–13.5% respectively. In each cement grade, increased cement content amount led to the increased rate of compressive strength changes. For example, for 52.5 MPa grade cement, the curve slope of 400 (kg/m^3) cement content is more than 300 and 350 (kg/m^3). It can be concluded that increased cement content involved higher effects of porosity on compressive strength improvement. Finally, the most appropriate choice in order to achieve maximum strength and minimum porosity in DPC, was cement grade of 52.5 MPa and cement content of 400 (kg/m^3).

Fig. 4 illustrates the relationship between flexural strength and porosity of DPC in various cement content and cement strength grades. The flexural strength of DPC in cement grades of 32.5, 42.5 and 52.5 MPa is changed respectively from 1.1, 2.2, and 2.9 to 2.3, 3.7, and 4.3 MPa. As seen, increased porosity was associated with decreased flexural strength. Considering a constant cement grade, increased cement content corresponded to decreased porosity and enhanced flexural strength. Nevertheless, this treatment is not valid for cement grade of 42.5 MPa (see Fig. 4b) where DPC samples included 300 (kg/m^3) of cement content involved more strength values comparing to 350 (kg/m^3). This irregularity could be due to laboratory faults. For the flexural strength, similar to the compressive strength, increased influence of porosity would be observed by increase in the cement content.

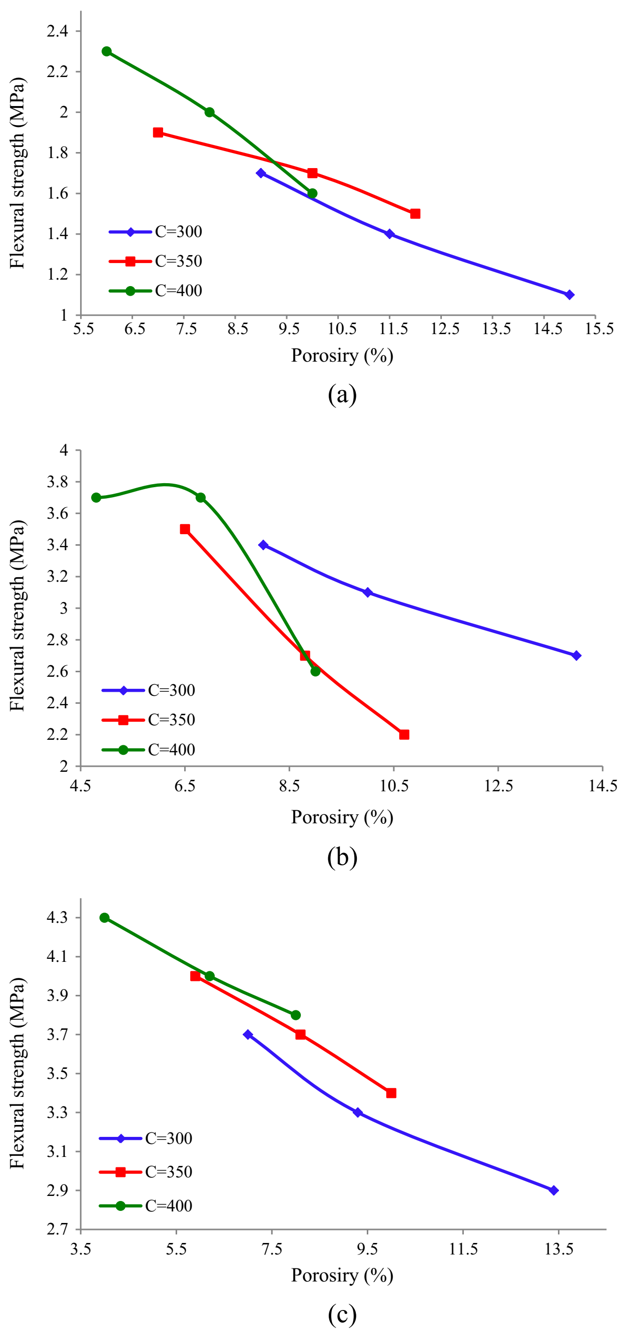

Figure 4 Relationships among flexural strength and porosity (32.5 (a), 42.5 (b) and 52.5 (c) MPa grade cements).

4.2. Taguchi analysis

To achieve maximum compressive and flexure strengths of concrete, two factors of water-to-cement ratio and cement content were controlled in this study. The mean objective/response function was obtained from the experimental data. Response variation using selected S/N ratio is examined by Taguchi method. Generally, the S/N ratio refers to the ratio of the mean (signal) to the standard deviation (noise). In this study, the best possible levels of mix proportions are investigated for the maximization of compressive strength, flexural strength and for the minimization of porosity, values by using the Taguchi method. The performance statistics for "the larger the better" situations are evaluated for maximization properties of DPC and "the smaller the better" situations are evaluated for minimization properties of DPC. Figs. 5–7 depict mean values in terms of S/N ratio for the control factors with main effect of the parameters on mean response. Fig. 5 demonstrates the factors (w/c and cement content) impacting porosity. As it can be seen in Fig. 5, increase in W/C parameter increases the porosity but increasing the cement content and cement grade value decreases porosity of DPC. As respects that in DPC samples lower porosity can improve its feature and increaseits durability. As the results show, the specimen produced by 0.2 of w/c, 400 (kg/m^3) and 52.5 MPa of cement strength grade is the best mixture that the amount of S/N is about 14. Overall, w/c is more effective on porosity than cement content.

Figs. 6 and 7 illustrate analysis of the two factors on compressive and flexural strength. When w/c is increased in the concrete mix, the normal 28 days compressive and flexural strength of DPC is decreased (see Figs. 6 and 7). However, increase in cement content and cement strength grade increased the normal 28 days compressive and flexural strength. In the other hand, from amounts of S/N shown in Figs. 6 and 7, inferred w/c and cement content have more influence on the compressive strength. According to the results, the best mixture for compressive strength parameter is the one prepared by 0.2 of w/c and 400 (kg/m^3) cement content and used 52.5 MPa cement strength grade. In particular, compressive strength is highly influenced by cement content. Likewise, Fig. 5 depicts that DPC with 52.5 MPa of cement strength grade, 400 (kg/m^3) cement content, and 0.2 of w/c has the maximum flexural strength. Notably, w/c impacts flexural strength more than cement content on DPC. S/N values illuminate that the flexural strength of DPC produced with cement grade of 32.5 MPa is lower than two cement grades (see Fig. 7); therefore, using this cement grade is not proper for flexural specimen.

DPC has the best performance in high porosity and strength simultaneously. Based on the results obtained from Taguchi DPC analysis, the best mix design that can enhance porosity is in specimen with 32.5 MPa cement strength grade,

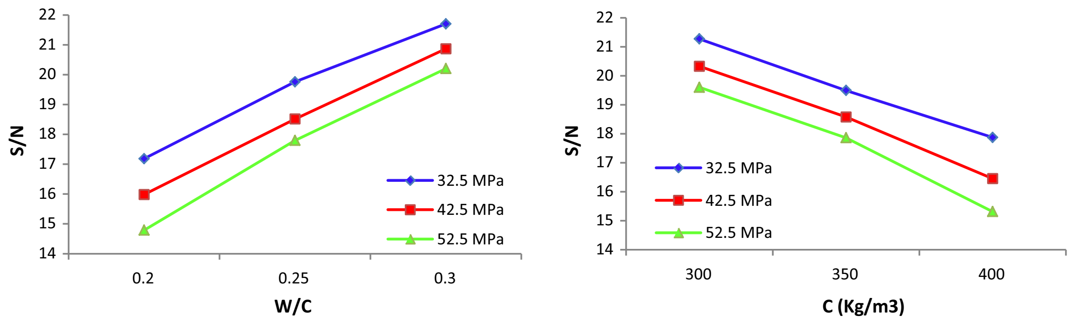

Figure 5 Effects of parameters on mean S/N ratio (porosity).

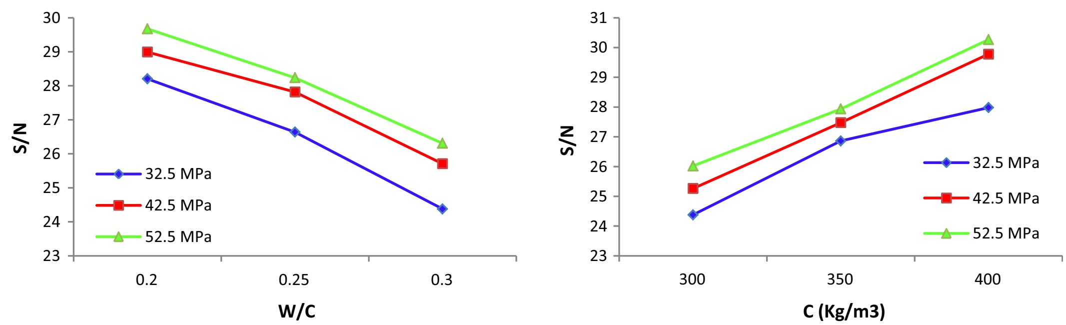

Figure 6 Effects of parameters on mean S/N ratio (compressive strength).

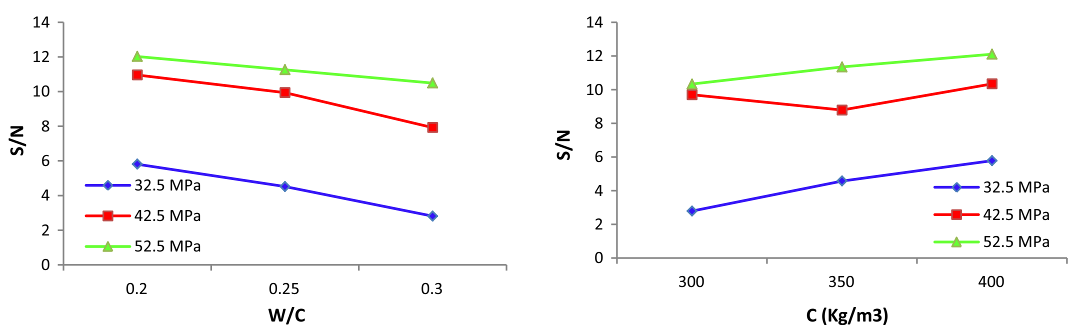

Figure 7 Effects of parameters on mean S/N ratio (flexural strength).

0.3 of w/c, and 300 (kg/m^3) cement content. In other words, a mix design with 52.5 MPa cement strength grade, 0.2 w/c, and 400 (kg/m^3) cement content is considered provides the most suitable strength. Hence, DPC properties are very crucial in obtaining optimum mix design. Subsequently, to construct appropriate DPC specimen, it is paramount to consider all factors and parameters that impact DPC.

5. Conclusions

The effects of experimental parameters on porosity, compressive and flexural strength of Dry-Pressed Concrete (DPC) were examined in this study. The conclusions drawn based on the statistical and experimental studies are as follows:

- Based on the experimental results, by increase in cement strength grade cement content strength of DPC increases. Additionally, porosity decreases by increasing the strength grade of cement and cement content.
- The appropriate value of porosity is recorded for the specimen produced by 0.3 of w/c, 300 (kg/m^3), and 32.5 MPa of cement strength grade. Also, w/c has found to be the important parameter that highly impacts porosity.
- In congruence with the S/N ratio results, the specimen prepared by 0.2 of w/c, 400 (kg/m^3) cement content, and 52.5 MPa cement strength grade provides the optimum compressive and flexural strength value. Cement content factor is found to be the most influential control factor in compressive strength. Besides, the impact of w/c on flexural strength is more than cement content on DPC specimen.

- Utilizing the powerful tool of Taguchi model allows for investigating the effect of different parameters on DPC. Study findings suggest that identifying the most important parameter for a specific type of concrete is a necessary step in designing DPC.

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