RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND VOID CONTENT OF PORTLAND CEMENT PERVIOUS CONCRETE- OKPS USING RESPONSE SURFACE METHODOLOGY

M.F.M. Jaafar, N. Ghazali, K. Muthusamy

Abstract

Nowadays, in Malaysia, there are flooding issues during heavy rain. The drainage system is not capable to smoothly manage the wastewater. This is caused by the increase in infrastructure and construction. It was recommended to use pervious concrete (PC) as an alternative for this issue. However, PC is not environmental-friendly due to the presence of non-renewable material in its production. The use of oil palm kernel shells in PC is considered the best alternative. A series of PC-OPKS mixes were designed up to 20% levels of replacement of OPKS to Portland cement PC. It was found that OPKS10 enhanced the strength but was lower than the control PC. The results also exhibited that PC-OPKS significantly and positively affect the void content. Based on RSM analysis, the inclusion of OPKS in PC has a strong relationship with strength and void content. Obviously, PC-OPKS features a lower compressive strength but greater void content when compared to PC alone.

Keywords Pervious concrete, oil palm kernel shell, compressive strength, void content.

M.F.M. Jaafar, N. Ghazali, K. Muthusamy

Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, Lebuhraya Tun Razak, 26300 Gambang, Pahang.

M.F.M. Jaafar (Corresponding Author)
e-mail: faizaljaafar@ump.edu.my

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Introduction

Portland cement pervious concrete (PC) consists of ordinary Portland cement, water, coarse aggregate, and little or no fines aggregate, in some cases admixtures. PC was classified as lightweight concrete due to its high porosity. Void content of PC ranged from 15% to 35% of its total volume. Porous structure and interconnectivity allow efficient water drainage through their matrix, and can provide sustainable drainage solutions. The primary benefit offered by PC is their ability to infiltrate large volumes of water through the material structure, thus reducing or eliminating problems associated with stormwater runoff (Powell and Morgenstern, 1985; Martin and Putman, 2016). The Environmental Protection Agency (EPA) recognised PC as one of the best management practices in reducing stormwater runoff. It is designed with an open-graded aggregate structure, resulting in a high interconnected air void content that allows water to penetrate through the pavement (Obla, 2010; Martin et al., 2014). PC is an alternative material for conventional pavements, particularly in low-volume traffic and parking applications.

Through the years of using PC as a beneficial sustaining medium for stormwater drainage, the idea of using environmental waste as a construction material to recover usable material from waste by-products become a global trend. Waste by-product has the potential as construction materials to cater sustainable issues relating to the construction industries. Utilisation of waste by-products is because of their properties and it can support the effectiveness of waste management in landfills. Demands for construction materials have risen to serve the rapidly growing global population. The exploited conventional material used in construction kept reducing due to this situation. AlShareedah and Nassiri (2020) reported that the potential to replace the ingredients in PC had become the main intention for researchers. One of the current global developments is based on recycling waste materials and waste by-products as an alternative ingredient in the concrete mixture (Ibrahim and Abdul Razak, 2016). However, the benefits and limitations of using various waste materials and by-products in PC concerning the mechanical properties have been explored and reported. Numerous studies have been conducted on the effect of using recycled aggregate from construction and demolition waste in PC mix (Sata et al., 2013; Zaetang et al., 2016; Liu et al., 2019). The result shows that incorporating recycled aggregate as aggregate replacement exhibited higher compressive strength than PC alone. Obviously, this study adds polymers in PC, which is not the standard practice for concrete, may partially refute the sustainability offerings of PC. Conversely, Zhang and Gao (2019) realised that the compressive strength of PC without the addition of polymer decreased with the replacement ratio of recycled aggregate.

Agricultural waste and biowaste materials have numerous applications in concrete. For instance, Liu et al. (2019) showed that this regenerative waste material could make PC with a compressive strength ranging from 9 MPa to 13 MPa and void content of 40% to 53% of volume. Mollusk shell waste was also used to replace 80% of coarse aggregates in PC, resulted in 274% higher compression when compared to control PC (Peceño et al., 2019). Another researcher, Kia et al. (2017), found that the compressive strength of PC can range from 1 MPa to 28 MPa at 28 days. These findings were also agreed upon by Debnath and Shankar (2020), who stated that the compressive strength of PC containing agricultural waste was found to be 3.4 MPa to 27.5 MPa. ACI 522 (2010) also reported that the void content of conventional PC could range from 15% to 35%, with typical compressive strengths of 2.8 MPa to 28 MPa. Therefore, the awareness of utilising agricultural waste, namely oil palm kernel shell (OPKS), is conducted in the PC mix. In addition, Malaysia is an ideal country to respond to sustainability in the construction industry, by being one of the largest oil palm producers. Khankhaje et al. (2017) found that the side effect of becoming the largest oil palm producer was the quantity of oil palm waste dumped was millions of tonnes annually. The construction industry promotes sustainability in production issues with the use of solid waste material as coarse aggregate. Until now, the strength and properties of PC-OPKS have little been explored and reported. These will be the main motivations to pursue the present study. It was concluded that OPKS are partially replaced as coarse aggregate, thus contributing to the enhancement of properties of PC-OPKS.

Methodology

Materials

The mixed proportion for this study was designed and modified based on previous research (AlShareedah and Nassiri, 2020). The alteration to this study was seen by the inclusion of OPKS. The cementitious used is ordinary Portland cement (OPC) Type I, complying with MS: Part I: 2007 provided by a local supplier. The crushed gravel was used as an aggregate and it was fixed to 10 mm passing. For OPKS, it passes through 5 mm and is predominantly retained on the 10 mm sieve. Before OPKS was used, the raw OPKS were undergoing the treatment process. The process was done by immersing the OPKS particles using sodium hydroxide (5% NaOH) solution for 4 hours. Next, the OPKS particles were washed to remove the NaOH solution using tap water. The OPKS particles were kept and dried at room temperature. Figure 1 shows the raw OPKS particles used in this study. The physical properties of OPKS were tested before being used. The specific gravity, density and water absorption of OPKS particles are 1.26, 1258.64 kg/m³ and 25.64%, respectively.

Figure 1: Oil palm kernel shell (OPKS) particles

Mix Designation and Testing Procedures

This study was conducted to investigate the effect of OPKS as an aggregate replacement to PC mix. Four (4) series of PC that contain different levels of percentage of OPKS were prepared. The control concrete mix (control PC) was prepared using conventional aggregate, while the PC-OPKS incorporating OPKS were prepared by replacing the OPKS amount with different percentage levels. The aggregates were replaced with OPKS at 0%, 10%, 15% and 20% from the total weight of aggregate used. All the PC samples were labelled as control PC, OPKS10, OPKS15 and OPKS20, respectively. Table 1 displays the mix designation for the control PC and a series of PC-OPKS used in this study. The water to cement factor used was constant at 0.37. After mixing the PC, the fresh concrete was poured and casted in a square steel mould size of 100 mm^3. The entire cast specimens were compacted by using a mechanical vibrated machine. The PC specimens were demoulded at 24 hours and cured in water for 7, 14 and 28 days before the tests were conducted. Two (2) tests, namely void content and compressive strength, were performed. The void content is a test to determine the total percentage of voids present by volume in cube specimens. The void content test is in accordance with ASTM C1754-12. For the compressive strength test, the recommendations of BS EN 196-3:2005 were followed.

Table 1: Mix proportion for control PC and a series of PC-OPKS used in this study

Mix Designation	Raw Materials (kg/m^3)			
	Cement	Coarse Aggregate	OPKS	Water
Control PC	301	1574.0	0	111
OPKS10	301	1416.6	157.4	111
OPKS15	301	1337.9	236.1	111
OPKS20	301	1259.2	314.8	111

Data Analysis

In this present study, all the data obtained were analysed statistically using Design Expert 6.0 software to establish the possible relationship between response and tested parameters (factors) adopted. For this purpose, the response surface method (RSM) model validated experimental data are obtained. By using historical data analysis, a three-dimensional (3D) graph can be produced and the equation is generated. The purpose of this analysis is to determine the significant relationship between factors with respect to responses. The factor identified in this study is compressive strength. On the other hand, the responses identified were curing days, percentage of OPKS replacement and void content. In addition, the regression equation generated from analysis of variance (ANOVA) analysis yields the relationship between response and factors. The ANOVA was established when the F-value (significance) was less than 0.05 and the model R-squared value was presented. Once the model was validated, the best model to fit the correlation was verified and discussed. To proceed with statistical analysis, the linear model was the best fit for all analyses throughout this study.

Results and Discussion

Relationship between OPKS Content and Curing Age towards Compressive Strength

Figure 2 charts the compressive strength of the control PC and a series of PC-OPKS. It is proven that the inclusion of OPKS shows a reduction in compressive strength as compared to the control PC. On day 7, the control PC recorded the highest compressive strength and followed by a series of PC-OPKS samples. There is also no strength enhancement on PC-OPKS samples at 14 days when compared to that control PC. The strength for OPKS10 was higher than those of PC-OPKS but lower than that of control PC. It is assumed that the lack of cement and slow nature of strength development of OPC were responsible for the premature failure of the samples. This could have been prevented by prolonging the curing time (Zaetang et al., 2013). However, PC-OPKS samples show no increase of 28 days compressive strength compared to that of control PC specimens. On day 28, the highest compressive strength is obtained by control PC, and followed by OPKS10, OPKS15 and OPKS20 samples with 10.28 MPa, 8.84 MPa, 5.98 MPa and 5.67 MPa, respectively. It is found that the compressive strength of the PC-OPKS decreases with an increase in the OPKS content. Among all the three mixed proportions of PC-OPKS, it is revealed that OPKS10 gives better results than those of PC-OPKS. PC contained 10% OPKS yielded the highest compressive strength of those tested contained OPKS.

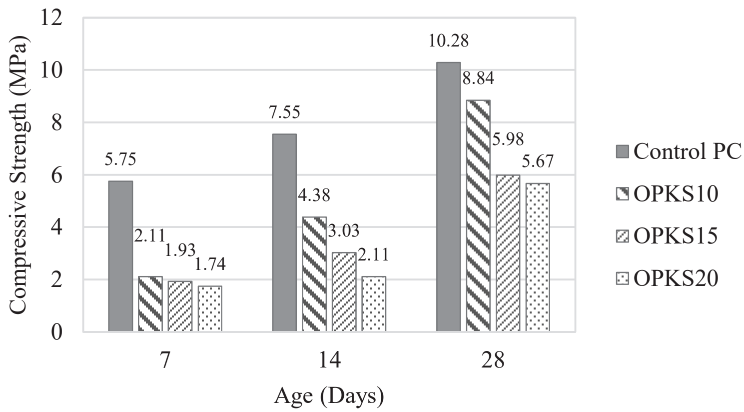


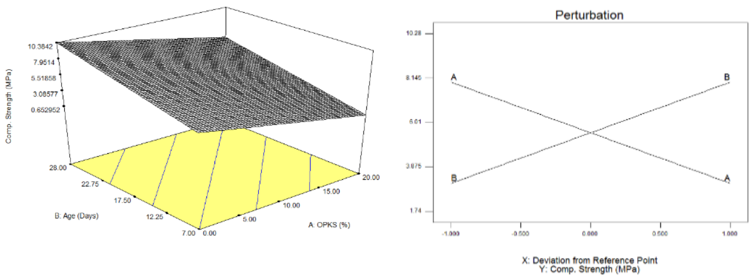
Figure 2: Compressive strength for control PC and a series of PC-OPKS

A similar trend previously reported by several researchers also found that the compressive strength of PC is remarkable in the ranges of 2.47 MPa, and the possibility of attaining 19 MPa depending on mix proportion and water to cement (w/c) ratio used. Azunna (2019), and Ahmed and Hoque (2020) used cement content of 548 kg/m^3 and 315 kg/m^3, and the compressive strength recorded was approximately below 10 MPa. In comparison, Ibrahim and Abdul Razak (2016), and Pratap et al. (2016) used a higher amount of cement compared to the present study, where it is found that the compressive strength of PC approximately achieved 10 MPa. Since PC contains no fine aggregate, strength depends primarily on the interaction between cement paste and coarse aggregate; thus, high porosity in pervious concrete reduces compressive. Therefore, the compressive strength of PC-OPKS obtained was in the ranges and comparable to the results obtained from those previous researches.

Figure 3 depicts the 3D surface of response plots to evaluate the relationship between OPKS content and curing age, with the compressive strength of control PC and PC-OPKS. As identified by RSM analysis in Figure 3(a), the compressive strength of control PC and a series of PC-OPKS decreased with an increased in OPKS content and curing duration. The plot clearly shows the concrete without OPKS (control PC) is recorded the highest in compressive strength. The trend of the relationship between the compressive strength of PC and a series of PC-OPKS plotting varies linearly with OPKS amount and age. The plot also reveals the PC inclusion of OPKS significantly affects the compressive strength. It shows that when the content of OPKS increased, the compressive strength of PC-OPKS decreased, while the increase of compressive strength matched well with the increase of age. Alternately, the use of 10% OPKS demonstrated superior performance in terms of compressive strength compared to that of OPKS15 and OPKS20. Concurrently, Figure 3(b) shows the perturbation graph for optimum values of the tested parameters. It is clearly a steepness for Line A (OPKS), and Line B (Age) indicates the sensitivity of the response factor (parameters). This means that OPKS amount and age (curing duration) have a significant effect and are factors contributing to compressive strength development. The regression models ANOVA are yielded when the levels percentage of OPKS and age significantly affected the compressive strength of control PC and PC-OPKS, as tabulated in Table 2. The significant value obtained from ANOVA is $p < 0.01$ and it indicates the model is highly significant. It also indicates that the relationship between compressive strength and those variables is strong, where R-squared is 0.9226. This means that 92.26% variation in compressive strength of PC is more dominant on the replacement of OPKS content in PC. The empirical relationship between compressive strength (response) and multiples factors (OPKS amount and Age) is expressed by the following equation and presented in Equation (1).

$$\textit{Compressive strength} = 3.897 - 0.243\,A + 0.232\,B \tag{1}$$

where A is OPKS amount (%) and B is age (days).



(a) (b)

Figure 3: Response surface plot (a) and perturbation plot (b) indicating the effects of the percentage of OPKS and curing age on compressive strength of PC and PC-OPKS

Table 2: Summary of AVONA in determining the interaction between the percentage of OPKS and curing age with respect to the compressive strength of PC and PC-OPKS

Models	Standard Deviation	R-Squared	Predicted R-Squared	Prob. > F	Remarks
Linear	0.67	0.9556	0.9226	< 0.0001	Suggested
Quadratic	0.72	0.9659	0.7649	0.5013	-
Cubic	0.63	0.9870	0.6039	0.3514	Aliased

Relationship between Curing Age and Void Content towards Compressive Strength

The void content for three series of modification PC contains OPKS obtained at 7, 14 and 28 days with reference to the control PC are charted in Figure 4. It is observed that the void content for all hardened PC-OPKS increased with the increase of level percentage OPKS as compared to hardened control PC. Similar trends were also recorded when the increment amount of OPKS and the void content in PC-OPKS slightly decreased with the prolonged age. Control PC has a lower void content compared to those of PC-OPKS mixes. As expected, OPKS20 specimens are shown in larger void spaces among the PC-OPKS. It can be noted that the void content in OPKS20 was 38.93%, 37.89% and 35.88% from the volume of specimen corresponding to curing age. The results also found that OPKS20 with a high percentage of the interconnected void allows water to drain through its interconnected void in the concrete. The void formation in OPKS10 specimens at 7, 14 and 28 days was about 36.89%, 35.88% and 35.96%, respectively, from its volume. On day-28, the void content of PC-OPKS inclusion 10%, 20% and 30% OPKS was increased by 7.95%, 8.20% and 8.64% from its volume compared to PC alone. This can be attributed to the angular shape of OPKS particles, causing a separation between the OPKS particles and cement paste. It can be noted that OPKS10 has a high interconnected pore structure, and is well bonding between cement paste to the aggregate and OPKS particles. A similar trend was also previously reported by Torres et al. (2015) and El-Hassan et al. (2019). As reported in ACI 522R-7 (2010), the void ratio is strongly dependent on aggregate gradation, cementitious materials content, water to cement (w/c) ratio and compaction effort. It can be remarked that PC-OPKS specimens enhanced porosity and increased the void space of the concrete. As the replacement levels percentage of OPKS in PC increased, the unfavourable effects became more pronounced, which caused the effective void content to increase.

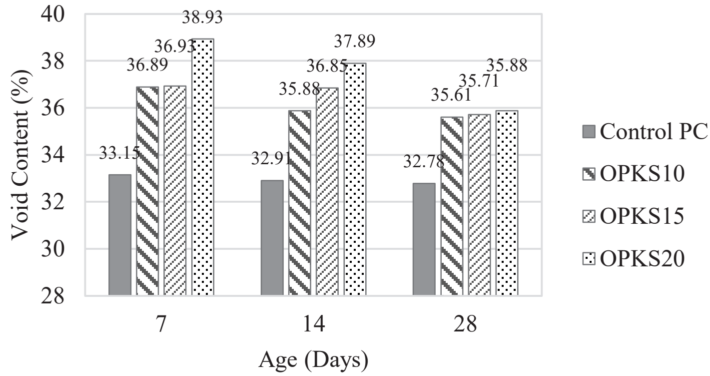
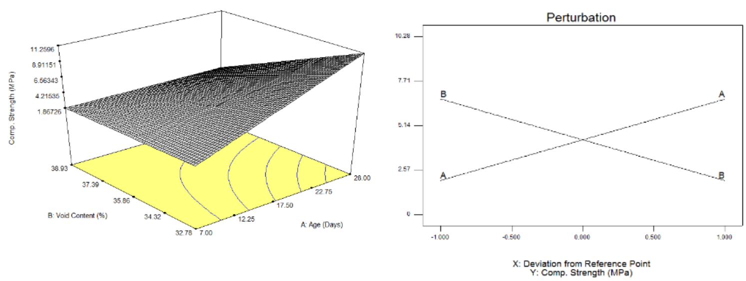


Figure 4: Void content for control PC and a series of PC-OPKS

In order to validate the previous discussion, Figure 5 depicts the 3D surface of response plots for evaluating the relationship between age and void content corresponding to the compressive strength of control PC and a series of PC-OPKS. As identified by RSM analysis, the compressive strength of control PC and a series of PC-OPKS increased with an increase in curing duration (age) and void content. Figure 5(a) plot clearly shows that the highest strength (control PC) is recorded the lowest in terms of void content. The trend of the relationship between the compressive strength of PC and a series of PC-OPKS plotting varies linearly with age and void content. The plot also reveals the void content in PC-OPKS significantly affects the compressive strength. It shows that when the content of OPKS increased, the void content in PC-OPKS decreased, while the increase of compressive strength matched well with the increase of curing age. Alternately, the use of 10% OPKS demonstrated good performance in compressive strength and void content compared to that of OPKS15 and OPKS20. Higher compressive strength and a lower percentage of void content can be expected due to the lack of void spaces. The model has also been checked, by examining how the void content and curing age affect the compressive strength, as demonstrated in Figure 5(b). The steep slope for Line A and Line B for age and void content, respectively, indicates the sensitivity of the response factors. This means that both parameters have a more dominant contribution and are closely related to the compressive strength. From the ANOVA analysis, a linear regression analysis, as tabulated in Table 2, indicates that the R-squared was found to be 0.6955. This means that approximately 69.55% of the variability in curing duration (age) void content can be contributed to that compressive strength. The empirical relationship between response and multiples factors is expressed by the following Equation (2).

$$Compressive\ strength = -15.947 + 2.725\,A - 0.456\,B - 0.070\,AB \quad (2)$$

where A is age (days), and B is void content (%).



(a) (b)

Figure 5: Response surface plot (a) and perturbation plot (b) indicating effects of curing age and void content on compressive strength of PC and PC-OPKS

Table 3: Summary of AVONA in determining the interaction between curing age and void content with respect to the compressive strength of PC and PC-OPKS

Models	Standard Deviation	R-Squared	Predicted R-Squared	Prob. > F	Remarks
Linear	1.77	0.7509	0.6955	0.0019	Suggested
Quadratic	1.48	0.8846	0.7900	0.4315	-
Cubic	1.32	0.9536	0.8297	0.3765	Aliased

Conclusion

From this finding, the conclusions are as follows:

1. Based on 28 days compressive strength, it was demonstrated that the replacement amount of up to 20% aggregate by OPKS, mass for mass, did not positively affect the strength development of PC-OPKS compared to that of control PC. Amongst the PC-OPKS specimens, it was shown that the use of 10% OPKS marked superior compressive strength.
2. It is revealed that there was a reduction in void content for PC-OPKS compared to control PC. It is demonstrated that the inclusion of different OPKS content would increase the void content in PC-OPKS.
3. It was discovered that the use of 10% OPKS in PC is sufficient compared to those of OPKS15 and OPKS20. Also, it can be concluded that the inclusion of 10% OPKS in PC significantly had the potential to be used in PC-OPKS production.

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Author(s) Biodata

Mohd Faizal Bin Md Jaafar
faizaljaafar@ump.edu.my
26 July 1978

Mohd Faizal Md Jaafar graduated with his Diploma and Bachelor's degree in Civil Engineering from Universiti Teknologi Mara (UiTM). Subsequently, he received a Master's degree in Civil Engineering (by research), specialising in polymer concrete from the same university. In 2019, he received a Ph.D. in Civil Engineering, specialising in ultra-high performance concrete and nano metaclay from UiTM. He has been serving Universiti Malaysia Pahang (UMP) since 2006 as a lecturer at the Faculty of Civil Engineering Technology. His research interest includes concrete technology and advanced materials. He is also a registered professional technologist from the Malaysia Board of Technologists (MBOT) and a member of the Concrete Society of Malaysia (CSM).

Norhaiza Binti Ghazali
nhaiza@ump.edu.my
8 December 1984

Professional Technologist (Ts.) Norhaiza Ghazali graduated from Universiti Malaysia Pahang (UMP) with a Bachelor of Civil Engineering and Master's degree holder from Universiti Sains Malaysia (USM) in structural engineering. She had worked with UMP since 2007 as a tutor and became a lecturer in 2010. Currently, she is completing her Ph.D. studies in the field of concrete materials. She is actively involved with environmental-friendly concrete research. She is also a member of the Board of Engineer Malaysia (BEM) and Malaysia Board of Technologists (MBOT).

Khairunisa Binti Muthusamy
khairunisa@ump.edu.my
15 December 1978

Khairunisa Muthusamy is an associate professor who has been involved in teaching and research activities for almost 15 years in the Faculty of Civil Engineering Technology, Universiti Malaysia Pahang (UMP). She received her Ph.D. in Civil Engineering from Universiti Teknologi Malaysia (UTM) in 2009. Since then, she has been actively involved in environmental-friendly concrete research. She has published almost 70 journal papers and conference proceedings related to concrete research. Her keen interest in exploring the potential of local waste materials, especially from the palm oil industry for concrete use has resulted in the development of lightweight-green concrete. She is a registered professional technologist with the Malaysia Board of Technologists (MBOT). She is also a member of the Board of Engineer Malaysia (BEM) and Concrete Society of Malaysia (CSM).