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Original Article

Evaluation on the rheological and mechanical properties of concrete incorporating eggshell with tire powder



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ABSTRACT

The construction industry is the largest consumer of raw materials which are under the risk of exhaustion and depletion in the near future, which has prompted the usage of waste materials for the conservation of resource and as a solution for waste management. Two wastes that are widely produced but often inefficiently disposed are eggshell and waste tire. Hence, this paper aims to evaluate the rheological and mechanical properties of concrete incorporating eggshell and waste tire rubber using Response Surface Methodology (RSM). Concrete with eggshell as cement replacement and waste tire rubber as sand replacement was prepared with an interval of 5% up to 15% replacement of both materials. Rheological properties of concrete were accessed using slump cone test while mechanical properties were studied through compressive strength and flexural strength test. Result showed that eggshell replacement has a minor effect on concrete slump while tire rubber reduces workability considerably. Result also showed that concrete mechanical strength was optimum at 5% and 10% eggshell replacement, while tire rubber reduced mechanical strength with percentage of replacement. Non-destructive tests indicated that concrete has excellent quality but excessive tire replacement beyond 10% compromised structural integrity of concrete. Overall, RSM models were able to model the properties of concrete with high accuracy and minimal deviation.

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1. Introduction

The construction industry is currently the largest consumer of raw materials of all economic activity, consuming about 3000 megatons annually which is about 50% by weight [1]. The most prominent raw materials of the construction industry include sand, stone, cement, steel and more, most of which are non-renewable resource. The material demand of construction industry is expected to continue growing with development across the globe [2]. However, scarcity of fossil fuel and raw material have become a looming concern. Filho et al. [3] reported that the increased extraction of sand could result in the depletion of sand reserve, which cause damage to flora and fauna as well as exacerbate the negative impact of climate change. Cement, the most widely used material in construction, is a major contributor of greenhouse gas emission [4] and a major source of air pollution [5]. Due to high reliance on natural resource in its production, cement is also expected to face resource constrain in near future due to the shortage of limestone [6,7].

Environmental and sustainable factors have prompted the research of alternative concrete materials. Waste materials or industry by-products are often proposed due to their ease of availability and the prospect of increasing the reuse of otherwise-discarded waste. This doubles as a solution to increase of solid waste disposal and mediocre recycling rate of certain reusable wastes [8]. Eggshells are one of the widely produced wastes, with about 250,000 tons of eggshell being produced annually. Eggshell waste is commonly sent to the landfill [9], but such disposal method is unfavourable as eggshell can attract vermin [10]. However, reusing eggshell waste has become a topic of interest. Thus far, eggshell has shown potential of being reused in papermaking, chemical, agriculture [11] and even medical [12] industry. In the construction industry, eggshell as binder replacement is being explored in the production of concrete and mortar. The suitability of eggshell powder as binder is attributed to its high calcium content [13] and chemical content similar to limestone [14]. Ansari et al. [15] concluded that 10% and 15% eggshell replacement of cement produced M25 concrete with better strength than the control. Similarly, Tan et al. [16] obtained concrete beyond 50 MPa at 28 days using 10% and 15% eggshell replacement. Apart from the improvement of mechanical performance, eggshell replacement also enhanced the durability of concrete and reduced the rate of water absorption.

Another waste material that sees great potential as construction material is waste tire rubber. Tire rubber is a solid waste that grows with the advancement of automobile industry [17]. Currently, combustion of tire is the cheapest disposal option but suitability of the method is questionable as rubber particle contain toxic substances and heavy metal that is harmful to living beings and environment if not probably managed [18]. Combustion of tire also generates residual oil that causes pollution of soil and water [19]. In the construction industry, rubber is an attractive material to be incorporated into concrete to alleviate the brittleness of concrete [20] and improves the resistance of concrete in aggressive environments [21]. Rubberised concrete also possesses

other utility such as better crash performance as road side barrier [22], resistance to adverse weather deterioration [23], and lightweight [24]. However, the use of tire rubber crumb as sand replacement has often compromised the mechanical strength of concrete [25]. Silva et al. [20] prepared high strength concrete which achieved a compressive strength of 97.4 MPa at 28 days but a strength drop of more than 20% is observed when 7.5% of the fine aggregate is replaced by tire rubber. At 30% replacement, concrete losses over half of its compressive strength as compared to control. Azevedo et al. [26] also experimented with high strength concrete with 75 MPa but about a third of the strength is loss when fine aggregate is replaced by 5% waste tire rubber.

To recover the loss of strength in rubberised concrete, treatment of rubber particle is often suggested, especially by soaking the rubber in aqueous NaOH solution [27,28]. However, another method to recover strength loss is to incorporate another waste material that is beneficial to concrete properties. Guneyisi et al. [29] used 5%–20% silica as cement replacement to recover the strength loss of rubberised concrete and to allow higher percentage replacement of rubber. In another study [30] 20% fly ash to improve concrete strength while keeping rubber replacement at 5% to minimise strength loss. Apart from common pozzolan, other materials such as palm oil fuel ash POFA has been attempt and is able recover strength loss of 20% rubber concrete slightly [31]. Currently, no study has used RSM modelling on combined eggshell and tire rubber in concrete.

Recently, computational software analysis saw increasing applications in various fields and industries due to its efficiency and accuracy. It has been utilised to great effect from the studies of law [32], social science [33] to engineering problem solving such as in fluid mechanics [34,35], industrial mechanics [36], and the structures and materials of civil engineering [37,38]. One common application of computational analysis in the study of concrete material involved the usage of Design of Experiment (DoE) methods to model the properties of concrete with respect to replacement materials. In this aspect, artificial neural network (ANN) and response surface analysis (RSM) are commonly conducted to study the effect of multiple variables on concrete properties [39]. Rizalman & Lee [40] used both ANN and RSM to model the compressive strength of concrete and most of the date in the model was within the 10% error margin. Senthil Kumar & Baskar [41] used RSM to model the influence of electronic waste aggregate on the workability and mechanical strength of concrete. Similarly, the properties of rubberised concrete has also been analysed with RSM [42]. For RSM modelling of compressive strength, combination of rebound hammer and ultrasonic pulse velocity is helpful to produce a satisfactory model [43].

This study aims to use eggshell powder as partial cement replacement along with waste tire rubber as sand replacement and investigate the effect of these two replacements on the rheological and mechanical properties of concrete. Varying percentages of both wastes are incorporated into concrete with an interval of 5% up to 15% replacement of both materials. Rheological properties of concrete are accessed through the slump cone test. Rebound hammer and ultrasonic pulse velocity data of concrete is also

Table 1 – Concrete mix proportions.

Mix	Eggshell Powder (%)	Rubber Powder (%)	Coarse Agg	Fine Agg	Cement (kg/m ³)	Water	SP
1	0	0	1035	610	600	192	6.0
2	5	0		610	570		
3	10	0		610	540		
4	15	0		610	510		
5	0	5		580	600		
6	5	5		580	570		
7	10	5		580	540		
8	15	5		580	510		
9	0	10		549	600		
10	5	10		549	570		
11	10	10		549	540		
12	15	10		549	510		
13	0	15		519	600		
14	5	15		519	570		
15	10	15		519	540		
16	15	15		519	510		

collected. Then, compressive strength test and flexural strength test are conducted to access the mechanical properties of concrete. Finally, RSM is employed to conduct data modelling on the slump and 28-day compressive strength of concrete. The effect of these waste materials is discussed in detail. Then, the coefficient of determination (R^2), as well as the adjust R^2 are used to evaluate the fitting of the model. Lastly, the margin of error and deviation are checked by the root mean square error (RMSE).

2. Materials and properties

Concrete specimens of the study were prepared with 'Orang Kuat' Ordinary Portland Cement from YTL Cement Berhad. The cement grade is 52.5N which conforms to the specification MS EN 197-1: 2014. Locally acquired river sand was the fine aggregate in this study. The sand was sieved through the 4.75 mm sieve to remove larger particles and then followed with the 0.075 mm sieve to get rid of fine dust. Crushed stone coarse aggregate was run through the 10 mm sieve to maintain a maximum nominal size of 10 mm. Chicken eggshells were used for the study. The raw eggshells were cleaned by rinsing with clean water and then drying in an electric oven under the temperature of 102 ± 2 °C for 24 h. After drying, the eggshells were placed in room temperature to cool down before being grinded with a grinding machine. The resulting eggshell powder was sieved through the 150 μ m sieve to be incorporated as cement replacement.

Tire rubber powder passing the 180 μ m sieve (mesh 80) was used as sand replacement. To enhance the ability of rubber particle to stick and form bond with cement paste, tire rubber was pretreated by soaking them in saturated sodium hydroxide (NaOH) aqueous solution for 20 min under room temperature. The rubber was then rinsed with tap water and left to dry at ambient condition for one day.

3. Experimental work

3.1. Specimen preparation

Table 1 showed the mix design used in the study. Concrete of Grade 55 was designed with a water-cement ratio of 0.32 and target medium workability of 75 ± 25 mm slump. To enable the adoption of lower water-cement ratio, Pye Kwiset Plasticizing Accelerator was added as the water reducer. The dosage used was fixed at 1.0% by weight of cement for all mixes. Concrete specimens were casted using a rotating drum mixer.

3.2. Slump cone test

Slump cone test was conducted on fresh concrete to investigate the rheological properties of concrete specimens. The procedure was specified at BS EN 12350-2 [44] (2019). Slump cone was placed on the base plate and set on a smooth and level surface. The cone was filled with fresh concrete for one-third of its height. Then, the tamping rod was dropped into the cone to for 25 times. The process was repeated for three times until the cone was filled. Finally, the cone was vertically removed, and the length between the peak of the slump cone and fresh concrete was measured using a meter rule and taken as the slump value.

3.3. Rebound hammer test

Rebound hammer test is a non-destructive test which access the hardness of concrete surface and predict the quality of concrete. Test procedure was outlined the European code BS EN 12504–2:2001. Test was conducted on concrete cube of size $100 \times 100 \times 100$ mm³ at 7 days and 28 days after curing. The surface of the concrete was smoothed with sandpaper prior to the test. The rebound hammer was calibrated on the test

anvil. Then, it was held at right angles to the surface of the concrete. The plunger was pressed against concrete surface until the spring-loaded mass is released from its locked position. The rebound hammer index was read. Readings were taken multiple times across each surface and the average rebound number was computed.

3.4. Ultrasonic pulse velocity test

Ultrasonic pulse velocity (UPV) is another non-destructive test for determining the uniformity of concrete and detecting presence of crack. It can also be used to estimate the quality and strength of concrete. The test is based on the velocity of sound within solid mass. Concrete cubes of size $100 \times 100 \times 100 \text{ mm}^3$ was used for the test after 7 days and 28 days water curing. Before the test, concrete surface was smoothed with sandpaper and cleaned. The equipment is calibrated on the reference bar. Petroleum oil jelly was applied on test location to ensure proper contact. Direct transmission method was used, with the receiver and transducer being placed at opposing faces of concrete. Three readings were taken for every test location and four test locations were chosen for each concrete specimen by turning to other faces of concrete. The average pulse velocity was then calculated.

3.5. Compressive strength

Compressive strength of $100 \times 100 \times 100 \text{ mm}^3$ concrete was determined using a MATEST Autotac 2000 kN Automatic Compressive Machine (Treviolo, Italy). The procedure was conducted based on BS 1881: Part 116. The loading rate of the compression machine was set to 3.0 kN/s. Testing was conducted on concrete specimens at 7, 28, 56 and 90 days after curing to study the strength gain of concrete in more detail.

3.6. Flexural strength

Flexural strength of $100 \times 100 \times 500 \text{ mm}^3$ concrete beam was determined by a U-test machine following the procedure outlined on BS 1881: Part 112. The loading rate of the UTest machine was 0.5 kN/s. Flexural strength of concrete was studied at 7 days and 28 days after curing.

3.7. Data modelling

Data modelling was conducted through Response Surface Methodology (RSM) using the software Minitab 2018. The

Table 2 – General expressions of RSM model.

Effect	Term
Intercept/ Constant	B_0
First order	B_1x_1, B_2x_2
Second order	$B_{11}x_1^2, B_{22}x_2^2$
Interaction	$B_{12}x_1x_2$
General Expression	$y = B_0 + B_1x_1 + B_2x_2 + B_{11}x_1^2 + B_{22}x_2^2 + B_{12}x_1x_2$

Source: Chong et al. [39].

purpose of data modelling was to study the influence of eggshell powder and tire powder on the workability and compressive strength of concrete in greater detail. In addition, RSM was utilized to develop a prediction model for 28-day concrete compressive strength based on the result of non-destructive tests and proportion of material replacement. Unlike conventional mathematical expression which considers linear and quadratic terms of the variables, RSM also investigates the interaction effect of between variables for a more detailed modelling. In additional, it is capable to isolate the effect of each variable in great detail through the main effect plot, and to establish the spectrum of two variables in a contour plot. The general effects considered by RSM analysis was shown on Table 2. The performance of the models was evaluated through the determination coefficient (R^2), adjusted coefficient ($R^2 \text{ adj}$), which indicates the degree in which the series of variable is able to explain the variation in the dependant variables. The accuracy of the model was also determined through the Root Mean Square Error (RMSE) which measures the deviation between predicted value and the actual experimental value.

4. Result and discussion

4.1. Slump cone test

Figure 1 presents the workability of concrete through slump cone test. The control specimen has a slump of 75 mm, but workability decrease steadily as eggshell powder and tire rubber powder are used to replace cement and sand, respectively. It can be deduced from the figure that replacement of either eggshell powder or tire powder has a negative impact on workability of concrete. At 0% rubber replacement, the control concrete has a slump value of 75 mm but decreases to 60 mm when 15% eggshell powder replaces cement. At 5% rubber replacement, the slump of concrete is found to be 50 mm without eggshell but drops to 40 mm at 15% eggshell replacement. Likewise, replacement of sand with rubber powder further decreases the slump of concrete. Replacement of 5% sand with rubber causes the slump to drop from 75 mm to 50 mm, and the slump value drops further to 25 mm at 15% replacement. The slump range for medium workability

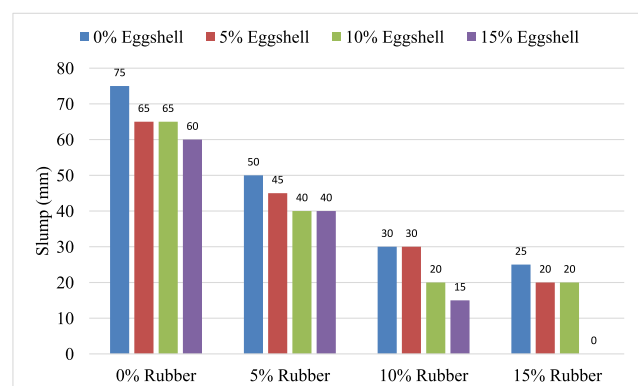


Fig. 1 – Slump cone result of concrete.

Table 3 – Rebound number of concrete.				
7-day Rebound Number	0% ES	5% ES	10% ES	15% ES
0% TR	25.80	27.90	29.50	23.70
5% TR	26.00	28.00	22.75	21.00
10% TR	21.83	22.00	21.20	21.60
15% TR	18.00	19.25	21.00	21.53
28-day Rebound Number	0% ES	5% ES	10% ES	15% ES
0% TR	30.42	30.17	27.67	27.67
5% TR	28.92	29.50	26.67	23.75
10% TR	20.33	26.67	24.50	19.50
15% TR	19.17	15.11	17.60	13.14

concrete is classified as 75 ± 25 mm and eggshell concrete usually falls between this range [45]. The slump of specimen with 5% tire rubber replacement and 0%–15% eggshell powder is around 40 mm–50 mm, which is viable for highway, pre-cast, and foundation applications. However, with the further replacement of sand with tire rubber, concrete specimen with 10% rubber replacement and more go into the range of low workability, which is not favourable for high strength concrete. Hence, the proportion of replacement material ought to be controlled and optimised.

The workability of concrete is lower when more eggshell powder was used to replace cement [46]. According to Jhatial et al. [47], eggshell powder causes a reduction in concrete workability as it absorbs the water otherwise used for hydration process. However, its rheological properties was not significantly affected as concrete with eggshell powder retained satisfactory homogeneity and bleeding or segregation did not occur [48]. Similarly, replacement of sand with tire rubber powder reduces workability of concrete, which is consistent with other research [49]. The reduction occurred

due to the rough surface and elastic behaviour of rubber particle and hence increased friction between rubber particle and other concrete constituents [50].

4.2. Rebound hammer test

The rebound number of concrete was presented on Table 3. At 7 days curing age, the control specimen without any replacement reached rebound number of 25.80. Concrete with 10% eggshell had the highest rebound number of 29.50, followed by concrete with 5% eggshell and 5% tire rubber with rebound number of 28.00. For concrete with no rubber replacement, 5% eggshell replacement increased the rebound number by 8.14%, from 25.80 to 27.90. Likewise, for concrete with 5% rubber replacement, additional 5% eggshell replacement increased the rebound number by 7.69%. The improvement can be attributed to the benefits provided by eggshell, which improves rate of hydration and causes concrete to develop strength faster. At 28 days, the specimens with the highest rebound number were the control specimen and 5% eggshell concrete. This was followed by 5% eggshell and 5% tire rubber concrete with a rebound number of 29.50.

While the rebound hammer could provide an indication of concrete hardness for specimens with 0% and 5% rubber replacement, the rebound number of specimens with 10% and 15% rubber replacement is more random and uneven. The 7-day rebound number of 15% rubber concrete shows an increasing trend with eggshell replacement, but the pattern disappears at 28-day, and the rebound numbers fluctuated. The shortcoming can be explained with the nature of rubber particle within the concrete specimen, which behave in a ductile manner under impact. In addition, it had been established that replacement of sand with tire rubber causes a decrease in rebound number based on percentage of replacement [51].

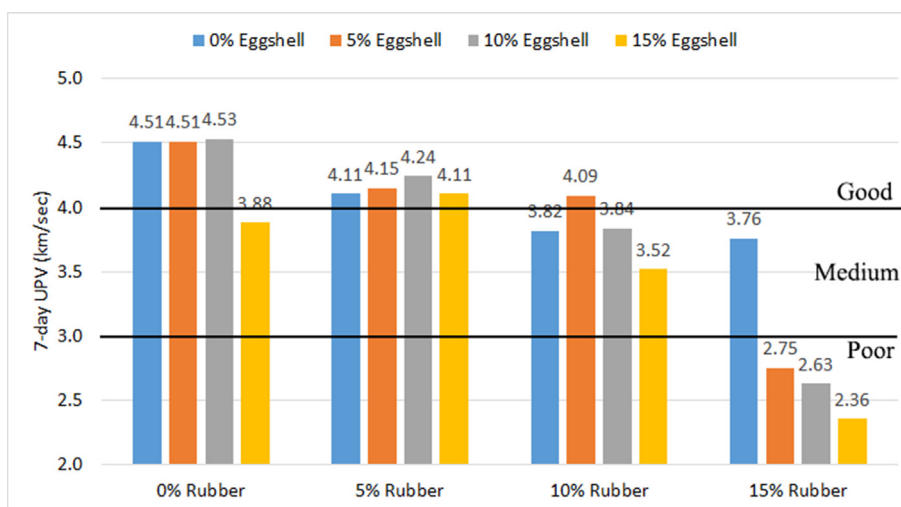


Fig. 2 – 7-day UPV of concrete.

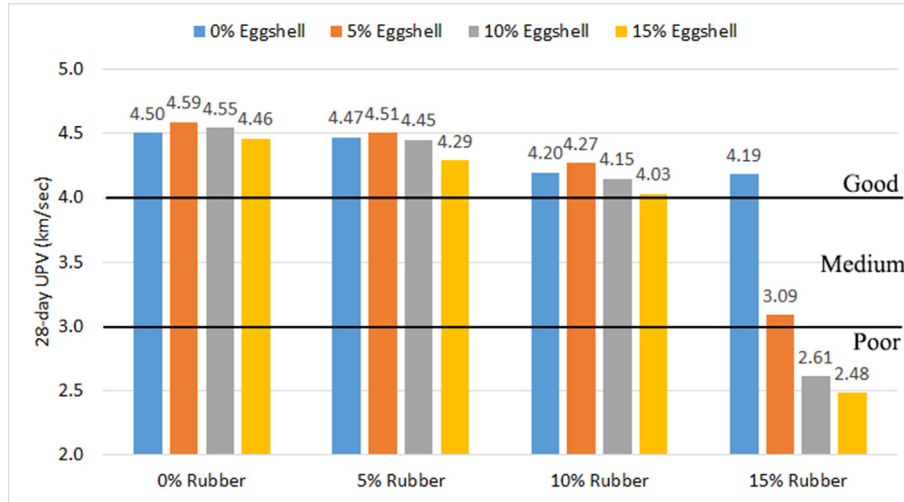


Fig. 3 – 28-day UPV of concrete.

4.3. Ultrasonic pulse velocity test

The result for 7-day and 28-day UPV test were presented on Figs. 2 and 3. For concrete with the same percentage of rubber replacement, varying percentages of eggshell replacement did not cause significant variation to the pulse velocity of concrete. For example, at 28 days, the pulse velocity of control specimen was 4.50 km/s. A small increase of 2% was observed at 5% eggshell concrete, which had pulse velocity of 4.59 km/s. The exception was specimens with 15% rubber replacement where huge drop in pulse velocity was observed when eggshell replacement was introduced. This may be explained by insufficient hydration of concrete. The quality of concrete dropped significantly with large number of voids and pores in the internal structure [52]. According to Marie [53], pulse velocity was an indication of the compressive strength of rubberised concrete, and a drop in pulse velocity happened because of internal voids and cracks affecting the structural integrity of the concrete. In other studies of rubberised concrete [23,54], it was concluded that the amount of rubber replacement caused the pulse velocity of concrete to drop. In

the case of percentage replacement, the pulse velocity of rubberised concrete can be correlated with compressive strength and percentage of rubber replacement [55].

From Abutaha et al. [56], the quality of concrete specimen is considered to be very high when the pulse velocity reading is above 4.0 km/s, while specimen with pulse velocity lower than 3.0 km/s has a low quality. Hence, all specimens with 0% and 5% rubber replacement except for 15% eggshell concrete achieved high quality in just 7 days. After 28 days curing, most concrete specimen achieves excellent quality. However, the quality of concrete with 15% rubber replacement remained mostly poor. This may indicate that at 15% tire rubber replacement, the negative impact to concrete quality is too adverse.

4.4. Compressive strength

The charts for 7-day, 28-day, 56-day and 90-day compressive strength are plotted on Figs. 4-7 respectively. From the table, the control specimen achieved compressive strength of 62.57 MPa at 28 days after curing. Then, concrete with 10% eggshell replacement had the highest compressive strength at

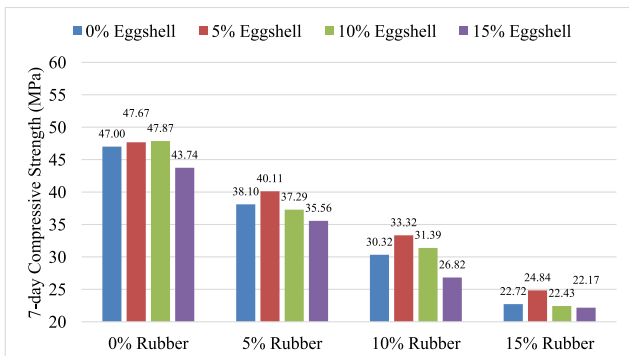


Fig. 4 – 7-day compressive strength of concrete.

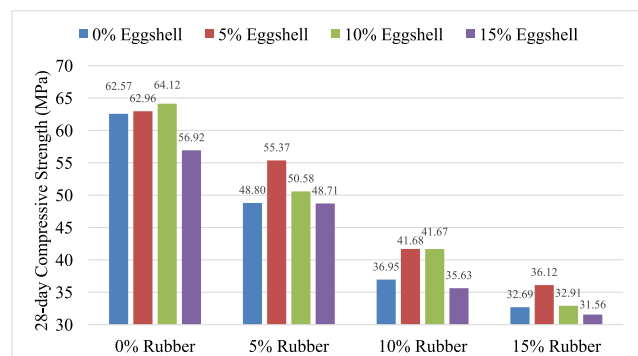


Fig. 5 – 14-day compressive strength of concrete.

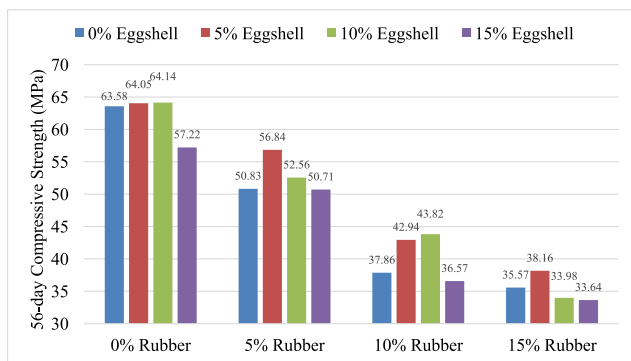


Fig. 6 – 28-day compressive strength of concrete.

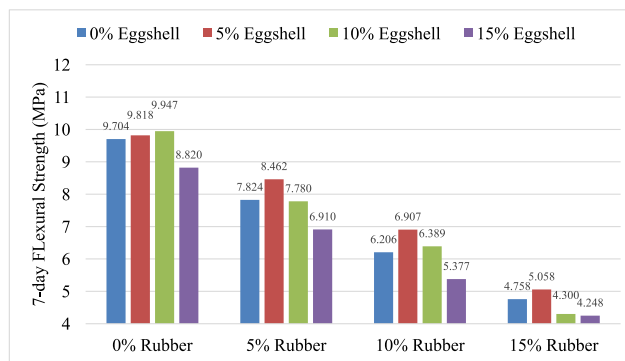


Fig. 8 – 7-day flexural strength of concrete.

all age, which was 64.12 MPa at 28 days and 68.29 MPa at 90 days. Based on Fig. 4, for the same percentage of rubber replacement, concrete specimen with 5% eggshell replacement had the highest compressive strength within the group. However, in certain cases, concrete with 10% eggshell replacement had the highest strength, followed by that with 5% eggshell replacement with both specimens having higher strength than the control and 20% eggshell specimen. This is shown in 0% rubber specimens, where in Figure 5.2, 10% eggshell concrete had the highest 28-day compressive strength of 64.12 MPa, followed by 5% eggshell concrete which had 64.05 MPa. In general, concrete with 5% or 10% eggshell replacement always shows higher compressive strength in the group with same percentage of rubber replacement. The effect is even more clear in Fig. 7 whereby at the age of 90-day all concrete specimen with 5% and 10% eggshell replacement has higher compressive strength than the control specimen and 20% eggshell specimen.

Incorporation of eggshell powder is beneficial to concrete compressive strength at all age due to the contribution of high CaCO₃ content in eggshell [14] which promotes the hydration process of cement paste [57]. During hydration, CaCO₃ reacts with C₃A from the cement and provides nucleation site for accelerated hydration process [58]. This results in a more complete hydration and the formation of more C–H–S gel which enhances the internal microstructure of concrete and minimises voids and porosity [59]. Past research of eggshell as

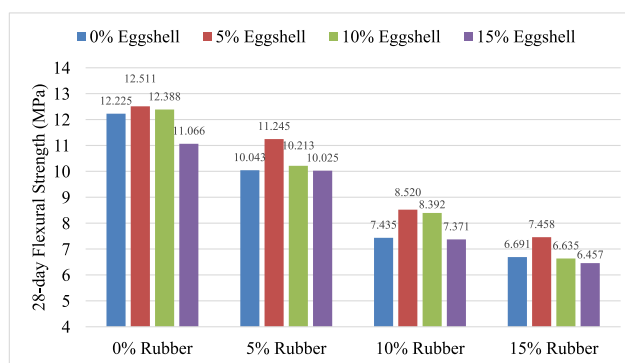


Fig. 9 – 28-day flexural strength of concrete.

cement replacement had generally agreed the optimum percentage of replacement to be around 10% [47,60], with more extensive studies and reviews [61,62] concluded that the improvement of concrete strength and durability are highest at 5% and 10% replacement. Beyond the optimum replacement proportion, a decrease in strength has been observed due to the water absorbing capability of eggshell powder which causes an increased water demand and a dry mix [63].

It was also observed that there was significant strength decrease between specimens with different percentages of tire rubber as sand replacement. For instance, the compressive strength of 10% eggshell concrete at 28 days after curing is 64.12 MPa. At 5% rubber replacement, the strength of concrete

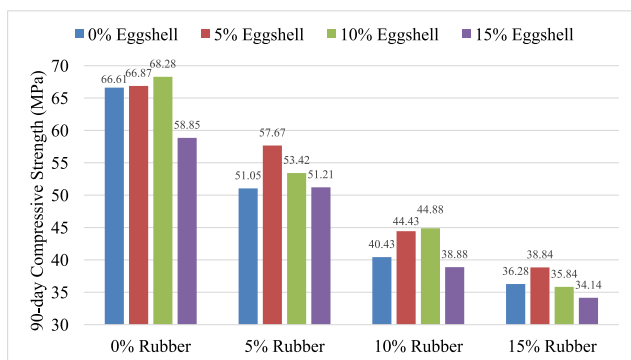


Fig. 7 – 90-day compressive strength of concrete.

Table 4 – RSM output for concrete slump.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	6556.3	2185.42	135.35	0.000
Linear	2	6331.3	3165.63	196.06	0.000
%TR	1	551.3	551.25	34.14	0.000
%ES	1	5780.0	5780.00	357.99	0.000
Square	1	225.0	225.00	13.94	0.003
%TR*%TR	1	225.0	225.00	13.94	0.003
Error	12	193.8	16.15		
Total	15	2052.90			
RMSE		3.482			
R ²		0.9713			
R ² adj		0.9641			

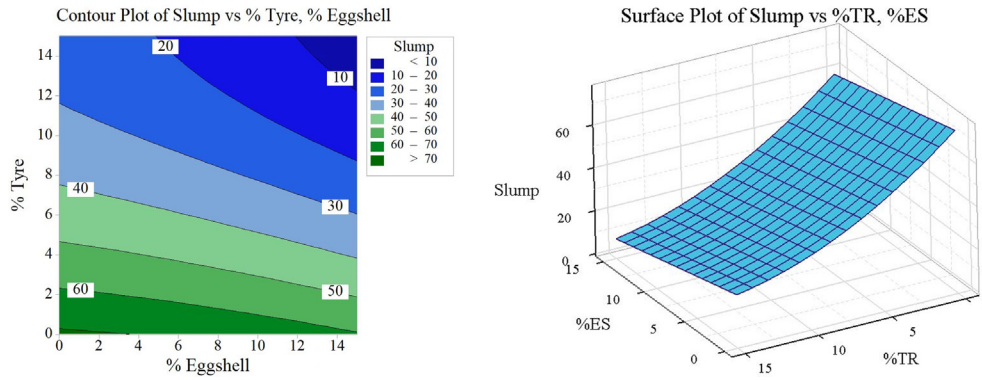


Fig. 10 – Contour and surface plot of concrete slump.

Table 5 – RSM output for concrete compressive strength.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	1986.18	331.030	104.78	0.000
Linear	4	1671.79	417.947	132.29	0.000
RH	1	2.34	2.343	0.74	0.412
UPV	1	2.15	2.147	0.68	0.431
%ES	1	0.19	0.188	0.06	0.813
%TR	1	49.00	48.999	15.51	0.003
Square	1	41.87	41.865	13.25	0.005
%ES*%ES	1	41.87	41.865	13.25	0.005
2-Way Interaction	1	20.69	20.686	6.55	0.031
RH*%TR	1	20.69	20.686	6.55	0.031
Error	9	28.43	3.159		
Total	15	2014.62			
RMSE		1.332			
R ²		0.9859			
R ² adj		0.9765			

dropped to 50.58 MPa, and at 10% rubber replacement, the strength dropped further to 41.67 MPa. This is a common challenge faced by studies of rubber replacement as rubber particles are naturally incompatible with cement paste and other aggregate [64]. The bonding between rubber particles and cement paste is significantly weaker compared to that of conventional aggregate and it leads to microcracking at the

interfacial transition zone (ITZ) and more porous internal structure [65]. In addition, rubber particle is softer and lighter than aggregate, causing a reduction in load-taking capacity [19]. However, proper handling and treatment of rubber helps to offset the strength loss [17]. In addition, eggshell as cement replacement can recover more strength in concrete. In this experiment, concrete with 5% rubber replacement achieved 28-day compressive strength of 48.80 MPa. With an additional 5% eggshell powder as cement replacement, the strength of concrete increased by 13.46%–55.37 MPa, which achieved the standard for M55 concrete. Hence, the combination of eggshell powder and tire rubber is feasible option for producing green HPC.

4.5. Flexural strength

The 7-day flexural strength of concrete specimen was plotted on Fig. 8. In that age, the highest flexural strength is exhibited by 10% eggshell concrete which was 9.946 MPa. Next, 5% eggshell concrete achieved flexural strength of 9.818 MPa, followed by the control specimen with 9.704 MPa. However, 15% eggshell concrete had significantly lower flexural strength which was 8.820 MPa. For 5% rubber replacement group, 5% eggshell incorporation produced concrete with the highest flexural strength of 8.462 MPa. The 28-day flexural strength was indicated by Fig. 9. At 5% and 10% replacement, concrete

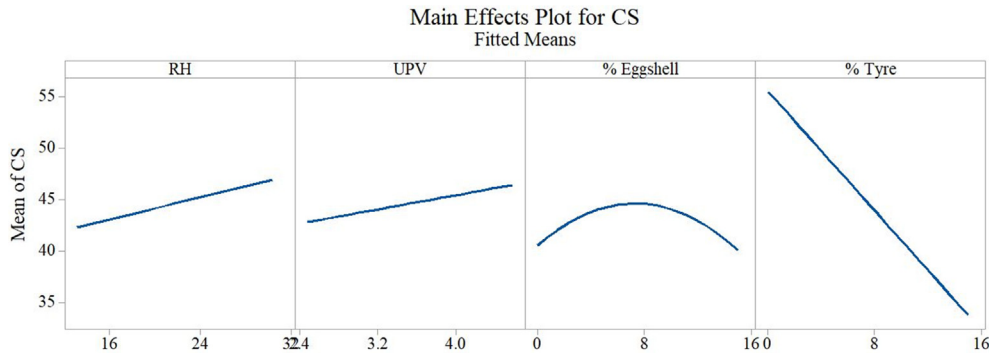


Fig. 11 – Main effect plot of concrete strength.

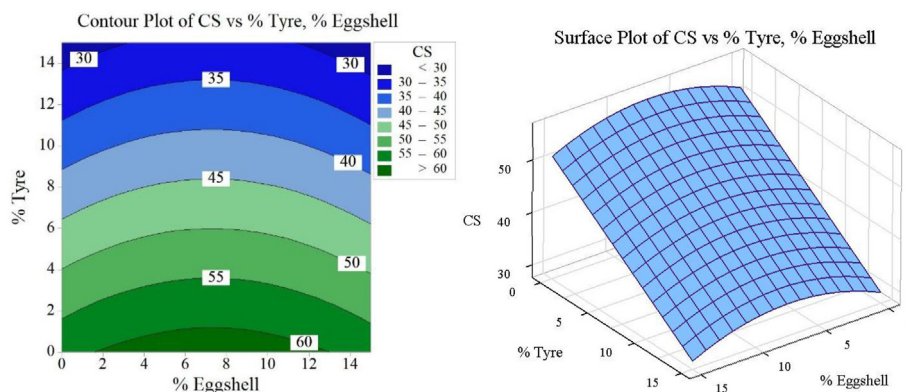


Fig. 12 – Contour and surface plot of concrete compressive strength.

specimens gained strength higher than that of the control specimen. However, at 15% replacement, concrete specimens became weaker than the control. The highest flexural strength is 5% eggshell concrete, which was 12.511 MPa, followed by 10% eggshell concrete and then the control specimen, which are 12.388 MPa and 12.225 MPa respectively.

At the same percentage of tire rubber replacement, concrete specimens with 5% eggshell replacement demonstrated the highest 28-day flexural strength within their groups. This showed the impact of eggshell replacement on flexural strength was similar to that of compressive strength [46,66]. In this experiment, the optimum eggshell replacement for maximum flexural strength is 5%. The number is similar to several studies of eggshell concrete which obtain an optimum percentages of 6% [46] at 6% interval and 7.5% [67] at 2.5% interval. Other studies on normal strength concrete with eggshell replacement obtain an optimum percentages of 10% [66,68]. The difference may be due to the different behaviour of HPC. However, the difference is not significant as 10% eggshell specimens in this experience also have superior strength at 7-day and comparable strength with control at 28-day.

Replacement of sand with tire rubber reduced flexural strength of concrete specimens even though it improved the ductility of concrete. This was depicted in other studies involving self-compacting concrete [69], high-strength concrete [20,70] and normal-strength concrete [71]. Regardless, the HPC design with 5% eggshell and tire powder showed satisfactory performance under flexural load.

4.6. Workability RSM model

In the selection of regression model, forward selection was favoured when a large number of variables were studied. On the other hand, backward elimination was preferred when collinearity was a concern [72]. Since concrete workability was modelled with two variables and compressive strength was

modelled with four variables, the backward elimination model was selected for RSM analysis with a confidence level of 95% ($\alpha = 0.05$). In backward elimination, the full quadratic terms of all variables were included into the initial model. The least significant variables were then removed one-by-one until threshold established by confidence level was achieved.

The output of concrete workability RSM analysis is shown on Table 4. The resulting model has coefficient of determination (R^2) value of 0.9713 and adjusted R^2 of 0.9641, which indicates that a huge proportion of the variation of concrete slump can be explained by eggshell and tire rubber replacement proportion. The RMSE of the model is 3.482 which is minimal. There is also no unusual observation expect for concrete with 15% replacement of both materials which is an extreme condition of the experiment. The p-value of every term in the analysis is also satisfactory, with the linear terms having negligible p-value while the quadratic term has a low p-value of 0.003. The equation for concrete slump based on percentages of eggshell and tire rubber replacement is given as:

$$\text{Slump} = 74.63 - 5.650 \%TR - 1.050 \%ES + 0.1500 \%TR\%TR \quad (1)$$

Figure 10 presents the contour plot for the RSM model. There are a few deductions that can be made from the analysis. First, the usage of eggshell powder and rubber powder in concrete both reduces the workability of concrete specimen. Then, the reduction in workability occurs in a linear function for percentage of eggshell powder as only the linear term (%ES) is significant. However, the reduction for percentage of rubber powder happens in a polynomial function as the both the linear (%TR) and quadratic (%TR*%TR) term has been included in the model. The constant of the model is 74.63, which is very close to the slump value of control specimen which is 75 mm. From the coefficient of the other terms, every percent incorporation of eggshell powder reduces concrete slump by about 1 mm, but every percent of tire rubber reduces concrete slump by about 5.650 mm.

Hence, tire rubber reduces the workability of concrete more heavily than eggshell powder and the replacement rubber must be done sparingly.

4.7. Compressive strength RSM model

RSM was applied to model the 28-day compressive strength of concrete. Four factors, namely the percentage of eggshell (%ES), the percentage of tire rubber (%TR), ultrasonic pulse velocity (UPV), and rebound hammer number (RH) were selected as the independent variables of the analysis. Since the model was meant to predict the compressive strength of concrete, all variables were information which could be obtained without performing any destructive testing. The percentage of both replacement materials were known at the design stage, while UPV and rebound number were obtained through non-destructive test. Table 5 shows the output of RSM analysis. The model has R^2 and adjusted R^2 value of 0.9858 and 0.9765, respectively. RMSE of the model is 1.332, indicating that the model can predict compressive strength of concrete with minimal deviation. The output equation is given as:

$$CS_{28} = 24.1 + 0.979 RH + 1.72 UPV + 1.117 \%ES + 0.62 \%TR - 0.0766 \%ES*\%ES - 0.0949 RH*\%TR \quad (2)$$

Fig. 11 shows the main effect plot of the model. The main effect plot showcases the general relation or influence of each independent variable on the dependent variable. Rebound number and UPV result has a minor correlation with compressive strength [73]. Fig. 12 presents the contour and surface plot of eggshell and tire rubber replacement with respect to compressive strength. The relationship between strength and eggshell replacement is an upward curve, and the peak of the curve happens at about 8% eggshell. The curvilinear relation agrees with the review on eggshell concrete which estimated the optimum eggshell replacement to be between 5% and 10% [74]. Lastly, replacement of sand with waste tire rubber results in a steep loss of strength.

5. Conclusion

In the study, the rheological and mechanical properties of concrete with eggshell powder and waste tire rubber powder are tested experimentally and modelled using RSM. Based on the experiment conducted, the following conclusions can be drawn:

- Incorporation of both eggshell powder and waste tire rubber reduces concrete workability. The minor reduction due to eggshell powder is caused by water absorption of eggshell powder, while waste tire rubber reduces workability more significantly due to its rough and elastic morphology.
- Non-destructive tests show linear correlation with the strength of concrete. Assessment of concrete quality shows that concrete has excellent quality at 28 days when rubber replacement is controlled at 10%.

- Mechanical strength of concrete increases when 5%–10% eggshell powder is incorporated due to the calcium carbonate content and filling effect of eggshell powder. In contrary, waste tire rubber forms weaker bond with cement paste and hence reduces concrete strength. However, eggshell incorporation can recover sufficient strength to reach compressive strength of 55 MPa at the age of 28 days after curing.
- The relationship between eggshell powder replacement and concrete strength is curvilinear. RSM model provides accurate information and prediction of concrete workability and strength. The models achieve R^2 value of 0.9713 and 0.9859 which is highly satisfactory (close to 1.0). RMSE of both models are also minimal and prediction of data does not result in significant unusual observation.

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.

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