Predicting the Compressive Strength of Rubberized Concrete Using Artificial Intelligence Methods

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Abstract: In this study, support vector machine (SVM) and Gaussian process regression (GPR) models were employed to analyse different rubbercrete compressive strength data collected from the literature. The compressive strength data at 28 days ranged from 4 to 65 MPa in reference to rubbercrete mixtures, where the fine aggregates (sand fraction) were substituted with rubber aggregates in a range from 0% to 100% of the volume. It was observed that the GPR model yielded good results compared to the SVM model in rubbercrete strength prediction. Two strength reduction factor (SRF) equations were developed based on the GPR model results. These SRF equations can be used to estimate the compressive strength reduction in rubbercrete mixtures; the equations are provided. A sensitivity analysis was also performed to evaluate the influence of the w/c ratio on the compressive strength of the rubbercrete mixtures.

Keywords: rubbercrete; strength reduction factor (SRF); artificial intelligence methods; Gaussian process regression (GPR); support vector machine (SVM)

1. Introduction

Waste tyre disposal represents a growing environmental problem, not to be overlooked. Globally, more than 500 million units of waste tyres are discarded every year without any treatment [1] and their increasing number has raised concerns worldwide due to the threat they pose directly and indirectly to human health and the environment. For this reason, recycling of waste tyres has been implemented in many countries.

The possibility of recycling scrap tyres as aggregates in concrete gained acceptance worldwide in the engineering sector, and positive results have already been achieved, preserving natural resources and helping to maintain ecological balance.

Scrap tyres undergo several processes to separate the steel wires from the rubber and to reduce the rubber to smaller crumbs. This crumb rubber can then be added into concrete mixture as partial replacement of the natural aggregates [2], modifying the concrete properties [3–11].

In some cases, cleaned, shredded rubber can be used. For example, the textile components are removed, steel fibres are pulled out, and the rubber surface is sometimes subjected to pre-treatments to consolidate the adhesion with the cement paste, improving the final properties of the modified concrete. The size, shape, and level of cleanliness of the fragments of rubber are essential factors in defining the final characteristics of the material.

The resulting material is called rubbercrete, a lightweight concrete with specific mechanical, thermal, acoustic, and rheological characteristics. Rubbercrete exhibits numerous benefits compared to conventional concrete, such as lower density [12], increased ductility [13], enhanced plastic capacity [14], higher toughness [15], higher impact resistance [16], better resistance to chloride penetration [17], lower thermal conductivity [2], higher noise reduction [18], and better electrical resistivity [19].
Rubbercrete is also known to have better energy dissipation, durability, and damping ratios compared to normal concrete \([20,21]\). Such features enable rubbercrete to be used in impact resistance structures, such as road bumpers and sound barriers \([22]\). Despite such advantages, a reduction in the compressive strength is observed throughout the literature. This reduction in strength is caused by the weak bond between the cement matrix and the crumb rubber due to the hydrophobic properties of rubber \([23]\). Rubber repels water and traps air, causing the formation of micro air pockets between the rubber and the cement, which thicken the interfacial transition zone \([13]\). This weak chain within concrete leads to micro-cracks due to stress concentration and induces structural failure \([18]\). Furthermore, aggregate properties have a strong effect on concrete compressive strength \([24]\); when aggregates of higher density and strength are replaced with less dense rubber aggregates, the compressive strength decreases.

In different studies, authors noticed that the size, proportion in concrete, and different surface textures of the rubber particles have a significant effect on concrete strength properties. Generally, the reduction in compressive strength is observed to be larger when coarse aggregates are replaced with crumb rubber compared to fine aggregates \([6,12,13,25–27]\). Concrete containing coarse rubber aggregates exhibits a reduction in strength but also significant energy absorption \([28]\).

It was found that replacing less than 5% in volume of the natural aggregates with waste tyre rubber does not induce any particular change in the performance of the material \([5]\). Compared to bending and tensile strength, compressive strength decreases more \([3,29–31]\).

To enhance the compressive strength of rubbercrete, the adhesion between the rubber particles and the cement matrix can be increased by operating natural or chemical pre-treatments on the rubber particles \([3,5,8,13,18,30,31]\). Certain studies \([18,29]\) reported that rubber particles washed in water exhibited a 16% increase in compressive strength compared to untreated rubber, and a further improvement (higher than 57%) when rubber particles were treated with carbon tetrachloride.

Although this material has been used for a wide variety of construction applications, clear design guidelines for rubbercrete mixtures have not been developed. Especially for structural applications, in which the use of rubber particles is allowed as replacement of fine aggregates in small percentages (up to a maximum of 10%), and only under severe quality control processes \([32,33]\), specific studies are required to better understand the phenomenon of strength reduction compared to the obvious reduction that occurs when coarse aggregates are replaced.

The main purpose of this study is to develop a simple model that can predict the compressive strength reduction of concrete containing crumb rubber as a partial replacement for fine aggregates (sand fraction). For this purpose, advanced modelling techniques were employed on various rubbercrete compressive strength data gathered from the literature; experimental campaigns and predictive equations of the strength reduction factor (SRF) are provided.

2. Methodology of the Study

In this study, the reduction in compressive strength in rubbercrete mixtures is investigated, concerning the following mix design parameters: percentage of rubber, size of crumb rubber, cement content, water content, additions, pre-treatments on crumb rubber, fine aggregate content, and coarse aggregate content.

In Appendix A, experimental data from different literature studies concerning rubbercrete mixtures, where natural fine aggregates (sand fraction) were substituted with rubber of the same size \([28,32,34–42]\), are reported.

For each mixture considered, the mix design parameters are indicated, and the respective compressive strength values are reported in relation to the amount of aggregates substituted. The percentages of substitution refer to the type of aggregate considered (fine).

To better understand the global trend, the compressive strength values are reported in the form of the strength reduction factor (SRF) and are plotted in Figure 1, where the
percentages of rubber reference the total volume of aggregates in the mixture. The strength reduction factor is defined as the ratio between the compressive strength of the concrete with a certain percentage of rubber and the compressive strength of the concrete without rubber: \( SRF = \frac{f_c}{f_{c0}} \).

The values in Figure 1 show a decrease in the compressive strength. This reduction is higher when the amount of rubber particles replacing the natural sand increases.

An accurate study of the mix design procedures is useful to better understand the rubbercrete behaviour under load and to set conditions for the starting concrete mix design to obtain the required performance from the rubbercrete.

**Artificial Intelligence Modelling Techniques**

In this study, two different artificial intelligence (AI) models were employed to conduct a sensitivity analysis and to create a uniform platform for analysis of the collected literature data (provided in Appendix A). The AI models used were support vector machine (SVM) and Gaussian process regression (GPR). The rubbercrete strength models were developed using MATLAB software and their performances were compared using test data. The best-performing model was used for the evaluation of the influence factors in rubbercrete strength prediction.

SVMs are based on the structural risk minimization principle [43], which can find a hypothesis with the lowest true error. This learning method performs non-linear classification, regression, and outlier detection with an intuitive model that can be approximately represented by Figure 2, which is adapted from Meyer’s work [44]. Figure 2 shows the optimal separating hyperplane between two classes, which is obtained by maximizing the margin between the classes’ closest points. The points lying on the boundaries are called support vectors and the middle of the margin is the optimal separating hyperplane [44]. SVM is the statistical learning theory that can rather precisely identify the factors that must be taken into account to learn successfully [45].
GPRs capture a wide variety of relations between inputs and outputs by utilizing a theoretically infinite number of parameters and letting the data determine the level of complexity through the means of Bayesian inference [46,47]. GPR models are nonparametric kernel-based probabilistic models. Consider the training set \( \{(x_i, y_i); i = 1, 2, ..., n\} \), where \( x_i \in \mathbb{R}^d \) and \( y_i \in \mathbb{R} \), drawn from an unknown distribution. A GPR model addresses the question of predicting the value of a response variable \( y_{\text{new}} \) given the new input vector \( x_{\text{new}} \) and the training data. A linear regression model is in the form \( y = x^T \beta + \epsilon \), where \( \epsilon \sim N(0, \sigma^2) \). The error variance \( \sigma^2 \) and the coefficients \( \beta \) are estimated from the data. A GPR model explains the response by introducing latent variables \( f(x_i), i = 1, 2, ..., n \), from a Gaussian process (GP) and explicit basis functions \( h \). The covariance function of the latent variables captures the smoothness of the response, and basic functions project the inputs \( x \) into a \( p \)-dimensional feature space [48].

In this study, 89 different mixtures were used as a test set. The training data were developed based on experimental data in the literature, as shown in Appendix A. The input parameters included cement content (v1), fine aggregate content (v2), coarse aggregate content (v3), aggregate pre-treatment condition (v4) (1 for soaked and 0 for non-soaked), water-to-cement ratio (v5), fine aggregate replacement percentage (v6), and coarse aggregate replacement percentage (v7). The corresponding output was set as the compressive strength of the concrete.

Based on artificial intelligence models literature and our experience, a typical data division between testing and training data is identified in a range of 10–20% for testing and 90–80% for training. In this study, the developed SVM and GPR models’ performances were evaluated using 15 testing data (about 17%) and 74 training data (about 83%). Figure 3 shows the models’ performance based on original compressive strength values. A comparison of these two models, based on the strength reduction factor (SRF), was performed; this is discussed in the next section.

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Figure 2. Linear classification using support vector machine (SVM).

Figure 3. Models’ performance based on testing data.
3. Results and Discussion

3.1. Comparing GPR and SVM Model Performance

To test the performance of GPR and SVM models, simulations of mix design procedures were carried out, starting from a reference mixture with cement 400 kg/m$^3$, sand 800 kg/m$^3$, and gravel 1100 kg/m$^3$. While keeping these three parameters constant, the w/c ratio was considered, ranging from 0.25 to 0.65, in both treated and non-treated rubber particles (treated rubber particles were soaked in water before their use in the mixture). Substitutions of sand aggregates were then operated with percentages of rubber ranging from 0% to 100%, as summarised in Table 1.

Table 1. Mix design proportions for GPR and SVM models’ predictions.

| $v_1$ Cement Content kg/m$^3$ | $v_2$ Fine Aggregate Content kg/m$^3$ | $v_3$ Coarse Aggregate Content kg/m$^3$ | $v_4$ Aggregate Pre-Treatment | $v_5$ Water/Cement Ratio | $v_6$ Replacement of Fine Aggregate % | $v_7$ Replacement of Coarse Aggregate % |
|---|---|---|---|---|---|---|
| 400 | 800 | 1100 | 1 or 0 | 0.25–0.65 | 0–100 | 0 |

Hence, 98 mixtures were generated, and data were analysed with GPR and SVM models to predict the compressive strength and respective SRF values. The results are graphed in Figures 4–7, where the two models (GPR and SVM) are distinguished, and the rubber pre-treatments operated (soaked and non-soaked).

Figure 4. SRF values of different rubbercrete mixtures predicted with the GPR model at different w/c ratios and soaked rubber particles.

Comparing Figures 5 and 7 with the trends in the experimental data from the literature in Figure 1, we observed that, in this study, the SVM model predictions were not representative of the compressive strength behaviour in rubbercrete mixtures. Experimental data in the literature state a reduction in the compressive strength when the rubber content increases (Figure 1). In Figure 5, the SRF values, which correspond to substitutions greater than a 50%, increase instead of decreasing further. This is not physically significant because when the amount of rubber particles in the mixture increases, the compressive strength must decrease [27,49–52].

For non-soaked rubber mixtures (Figure 7), a greater reduction in compressive strength is expected compared to soaked rubber mixtures. No negative values of the SRF are physically admitted, as the greatest reduction that can be obtained is reporting a zero
value for the compressive strength, not a negative value. In this case, the SVM model is not representative of the rubbercrete mixture’s behaviour under compressive strength for this reason.

Figure 5. SRF values of different rubbercrete mixtures predicted with the SVM model at different \( w/c \) ratios and soaked rubber particles.

The GPR model, instead, well-represented the behaviour of these rubbercrete mixtures, both for the soaked rubber mixtures and the non-soaked rubber mixtures. Following previous studies [35,38,40], rubber particles that were pre-treated (soaked in water) presented a lower reduction in the compressive strength (Figure 4) compared to the rubber particles without pre-treatments (Figure 6). This was demonstrated for each \( w/c \) ratio considered. In this study, the percentage of rubber, the \( w/c \) ratio, and the condition of rubber (soaked or non-soaked) were the most influential parameters in the models. Among these, we observed that the \( w/c \) ratio was the predominant factor influencing the model performance, so, for this reason, it was deeply investigative, as described in Section 3.2.
Comparing Figures 5 and 7 with the trends in the experimental data from the literature in Figure 1, we observed that, in this study, the SVM model predictions were not representative of the compressive strength behaviour in rubbercrete mixtures. Experimental data in the literature state a reduction in the compressive strength when the rubber content increases (Figure 1). In Figure 5, the SRF values, which correspond to substitutions greater than a 50%, increase instead of decreasing further. This is not physically significant because when the amount of rubber particles in the mixture increases, the compressive strength must decrease [27,49–52].

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3.2. Influence of w/c Ratio on the Compressive Strength: Calibration Laws

As graphed in Figures 4 and 6, different values of the SRF were obtained, varying the w/c ratio in the range of 0.25–0.65. Regressions were operated to fit the SRF values obtained at different percentages of substitution for each w/c ratio considered, both in the case of soaked and non-soaked rubber particles. The equation of the regression curves is expressed in the exponential and polynomial form:

\[ SRF = \exp^{-kx} \]  
(1)

where \( x \) represents the amount of rubber in volume expressed in %, and \( k \) is the parameter depending on the w/c ratio.

\[ SRF = a + b \cdot (1 - x)^m \]  
(2)

where \( x \) represents the amount of rubber in volume; \( a, b, \) and \( m \) are the parameters depending on the w/c ratio; and \( a + b = 1 \).

For each w/c ratio considered, the parameter \( k \) and the parameters \( a, b, \) and \( m \), together with the respective \( R^2 \) coefficients, were summarised and are reported in Table 2.

Table 2. Parameters of Equations (1) and (2) obtained for the GPR model, with soaked and non-soaked rubber particles included in the mixture.

| Pre-Treatment | w/c   | a      | b      | m      | \( R^2 \) | k      | \( R^2 \) |
|---------------|-------|--------|--------|--------|-----------|--------|-----------|
| Soaked        | 0.25  | 0.546  | 0.454  | 1.261  | 0.965     | 0.006  | 0.997     |
|               | 0.35  | 0.451  | 0.549  | 1.439  | 0.965     | 0.008  | 0.994     |
|               | 0.45  | 0.418  | 0.582  | 1.435  | 0.969     | 0.009  | 0.995     |
|               | 0.50  | 0.426  | 0.574  | 1.383  | 0.971     | 0.009  | 0.996     |
|               | 0.55  | 0.477  | 0.523  | 1.311  | 0.971     | 0.008  | 0.997     |
|               | 0.60  | 0.448  | 0.552  | 1.334  | 0.972     | 0.008  | 0.997     |
|               | 0.65  | 0.512  | 0.488  | 1.310  | 0.976     | 0.007  | 0.997     |
| Non-soaked    | 0.25  | 0.495  | 0.505  | 1.133  | 0.959     | 0.007  | 0.995     |
|               | 0.35  | 0.342  | 0.658  | 1.163  | 0.943     | 0.010  | 0.989     |
|               | 0.45  | 0.180  | 0.82   | 1.248  | 0.921     | 0.016  | 0.979     |
|               | 0.50  | 0.139  | 0.861  | 1.304  | 0.923     | 0.018  | 0.978     |
|               | 0.55  | 0.152  | 0.848  | 1.350  | 0.930     | 0.017  | 0.983     |
|               | 0.60  | 0.178  | 0.822  | 1.450  | 0.944     | 0.017  | 0.987     |
|               | 0.65  | 0.224  | 0.776  | 1.555  | 0.956     | 0.015  | 0.990     |
As noticed from Table 2, both polynomial and exponential laws fit well with the SRF values obtained from the GPR model, both with an $R^2$ value-approximating unit.

To better understand how the w/c ratio influences the rubbercrete mechanical behaviour, procedures were adopted to calibrate the parameter $k$ and parameters $a$, $b$, and $m$. In the graph in Figure 8, the values of parameter $k$ are reported in relation to the corresponding w/c ratio.

Regression analyses were conducted to obtain the equations of the parameter $k$:

- for soaked rubber particles in the mixture

$$k = -0.0592x^2 + 0.0556x - 0.0042 \quad (3)$$

- for non-soaked rubber particles in the mixture

$$k = -0.5588x^3 + 0.6368x^2 - 0.1916x + 0.0237 \quad (4)$$

where $x$ represents the value of the w/c ratio considered in the mixture.

For the mixtures with soaked rubber particles, it can be noted that for very low or very high w/c ratio values, the decrease in the compressive strength is lower than for middle values of 0.45–0.50. In contrast, for mixtures with non-soaked rubber particles, a general greater decrease in compressive strength was observed for w/c ratio values higher than 0.45.

For the parameters $a$, $b$, and $m$, a calibration procedure was also carried out, considering the cases of soaked and non-soaked rubber particles. The results are plotted in Figures 9 and 10.

Regression analyses were then operated to obtain the equations of the parameters $a$, $b$, and $m$:

- for soaked rubber particles in the mixture

$$a = -3.4442x^3 + 7.1842x^2 - 4.3403x + 1.236 \quad (5)$$
$$b = 3.4442x^3 - 7.1842x^2 + 4.3403x - 0.236 \quad (6)$$
$$m = 22.351x^3 - 33.572x^2 + 15.883x - 0.9615 \quad (7)$$

- for non-soaked rubber particles in the mixture

$$a = 4.4419x^2 - 4.7362x + 1.4179 \quad (8)$$
$$b = -4.4419x^2 + 4.7362x - 0.4179 \quad (9)$$
$$m = 2.5408x^2 - 1.2552x + 1.2902 \quad (10)$$
where \( x \) represents the value of the w/c ratio considered in the mixture.

Polynomial and exponential prediction laws for SRF values of rubbercrete mixtures with different w/c ratios were obtained, both for soaked rubber particles and non-soaked rubber particles.

Regression analyses were then operated to obtain the equations of the parameters \( a, b, \) and \( m \):

- for soaked rubber particles in the mixture
  \[
  a = -3.4442x^3 + 7.1842x^2 - 4.3403x + 1.236 \\
  b = 3.4442x^3 - 7.1842x^2 + 4.3403x - 0.236 \\
  m = 22.351x^3 - 33.572x^2 + 15.883x - 0.9615
  \]

3.3. Validation of the Predicted Results

The obtained mathematical laws were validated by comparing SRF values obtained from the GPR model predictions with the experimental results obtained by Eldin and Senouci [35] and Khatib and Bayomy [40], who used mix design proportions of the mixtures similar to those adopted in this study for model prediction. The results are presented in Table 3.

The final predicted SRF values are very close to those found by the authors in their experimental campaigns, thus confirming the validity of GPR model predictions and that the calibration laws obtained are suitable for mix design procedures of the rubbercrete mixtures.
Table 3. Validation of calibration laws for the w/c ratio and the SRF of the rubbercrete mixtures.

| Mixtures                      | Cement kg/m³ | Sand kg/m³ | Gravel kg/m³ | Water kg/m³ | Pre-Treatments of Rubber | w/c | Total Volume of Aggregates /m³ | % Fine Aggregates /Total Volume of Aggregates | % Substitution of Fine Aggregates (Referred to the Volume of Fine Aggregates) | Compressive Strength MPa | SRF (Experimental) | a   | b   | m   | SRF (Polynomial) | k   | SRF (Exponential) |
|------------------------------|--------------|------------|--------------|-------------|---------------------------|-----|-------------------------------|-----------------------------------------------|--------------------------------------------------------------------------------|--------------------------|-------------------|-----|-----|-----|------------------|-----|------------------|
| Eldin and Senouci [35]       | 447          | 629        | 1116         | 214         | Soaked in water           | 0.48| 0.72                          | 36.11                                         | 0                                                                           | 35                        | 1.00              | 0.427| 0.573| 1.399| 1.00            | 0.009| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 25                                                                          | 23.4                      | 0.67              | 0.81 | 0.64 | 0.64 | 1.00            | 0.009| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 50                                                                          | 19.2                      | 0.55              | 0.64 | 0.51 | 0.51 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 75                                                                          | 14.7                      | 0.42              | 0.51 | 0.51 | 0.51 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 100                                                                         | 12.4                      | 0.35              | 0.43 | 0.43 | 0.41 | 1.00            | 0.017| 1.00             |
| Khatib and Bayomy [40]       | 388          | 786        | 1024         | 186         | non-soaked                | 0.48| 0.68                          | 42.65                                         | 0                                                                           | 37.5                      | 1.00              | 0.168| 0.832| 1.273| 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 5                                                                           | 35                        | 0.93              | 0.95 | 0.92 | 0.92 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 10                                                                          | 30.5                      | 0.81              | 0.90 | 0.85 | 0.85 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 15                                                                          | 29                        | 0.77              | 0.84 | 0.78 | 0.78 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 20                                                                          | 25.7                      | 0.69              | 0.79 | 0.72 | 0.72 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 40                                                                          | 18                        | 0.48              | 0.60 | 0.51 | 0.51 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 60                                                                          | 9                         | 0.24              | 0.43 | 0.37 | 0.37 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 80                                                                          | 4.8                       | 0.13              | 0.28 | 0.26 | 0.26 | 1.00            | 0.017| 1.00             |
|                              |              |            |              |             |                           |     |                               |                                 | 100                                                                         | 3                         | 0.08              | 0.17 | 0.19 | 0.19 | 1.00            | 0.017| 1.00             |
4. Conclusions

In this paper, a comprehensive study was performed on different mix design parameters that influence rubbercrete compressive strength: cement content ($v_1$), fine aggregate content ($v_2$), coarse aggregate content ($v_3$), aggregate pre-treatment condition ($v_4$) (one for soaked and zero for non-soaked), water-to-cement ratio ($v_5$), fine aggregate replacement percentage ($v_6$), and coarse aggregate replacement percentage ($v_7$). Advanced modelling techniques, i.e., SVM and GRP models, were employed to predict rubbercrete compressive strength behaviour. In this study data, we observed that the GPR model performed better compared to the SVM model. Simple equations were proposed to calculate the strength reduction factor. Calibration of the parameters of these equations was carried out considering the influence of the water/cement ratio. The accuracy of the developed equations and the predicted results was verified using experimental data in the literature. This study can aid in the study of rubbercrete and assist in promoting its usage among professionals without needing to perform preliminary experimental tests on the material.

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## Appendix A

| Mixtures       | Cement kg/m³ | Sand kg/m³ | Gravel kg/m³ | Water kg/m³ | Type of Additions | Pre-Treatments of Rubber | w/c | Total Volume of Aggregates m³ | % Fine Aggregates (Total Volume of Aggregates) | % Coarse Aggregates (Total Volume of Aggregates) | % Substitution of Fine Aggregates (Referred to the Volume of Fine Aggregates) | Compressive Strength MPa | SRF |
|----------------|--------------|------------|--------------|-------------|-------------------|--------------------------|-----|-----------------------------|---------------------------------|---------------------------------|-------------------------------------|------------------------|-----|
| Eldin and Senouci [35] | 447          | 629        | 1116         | 214         | Soaked in water   | 0.48                     | 0.72 | 36.11                       | 63.89                           | 0                               | 0.48                                 | 35          | 1.00|
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
| Topcu [41]    | 357.5        | 609        | 1148.1       | 222.4       |                   | 0.62                     | 0.66 | 34.85                       | 65.15                           | 0                               | 23.48                               | 0.99        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
| Khatib and Bayomy [40] | 388          | 786        | 1024         | 186         |                   | 0.48                     | 0.68 | 42.65                       | 57.35                           | 0                               | 37.5                                 | 1.00        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
| Batayneh et al. [34] | 446          | 585        | 961          |             |                   | 0.56                     | 0.69 | 37.68                       | 62.32                           | 0                               | 25.33                                | 1.00        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
| Aiello and Leuzzi’[28] | 335          | 279 + 1116 | 465          | 200         | superplasticizer  | 0.60                     | 0.79 | 74.68                       | 25.32                           | 0                               | 27.11                                | 1.00        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
| El-Gammal et al. [36] | 350          | 588        | 980          |             |                   | 0.35                     | 0.77 | 37.66                       | 62.34                           | 0                               | 26.9                                 | 1.00        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
|                |              |            |              |             |                   |                          |      |                             |                                 |                                 |                                      |                        |     |
Table A1. Cont.

| Mixtures                     | Cement kg/m³ | Sand kg/m³ | Gravel kg/m³ | Water kg/m³ | Type of Additions       | Pre-Treatments of Rubber | w/c  | Total Volume of Aggregates /m³ | % Fine Aggregates (Total Volume of Aggregates) | % Coarse Aggregates (Total Volume of Aggregates) | % Substitution of Fine Aggregates (Referred to the Volume of Fine Aggregates) | Compressive Strength MPa | SRF  |
|------------------------------|--------------|------------|--------------|-------------|-------------------------|--------------------------|------|------------------------------|-----------------------------------------------|-------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|--------------------------|------|
| Godfrey [38]                 | 475          | 775        | 950          |             | Soaked in water         |                          | 0.38 | 0.73                         | 44.52                                                        | 55.48                                                                  | 0                                             | 58.39                    | 1.00 |
| Grinys et al. [39]           | 451          | 873        | 949          |             | superplasticizer        |                          | 0.35 | 0.75                         | 48                                                          | 52                                                      | 0                                             | 64                         | 1.00 |
| Tung-Chai Ling [42]          | 328          | 1246.4     | 590.4        |             | superplasticizer        |                          | 0.45 | 0.82                         | 56.7                                                        | 43.3                                                                  | 0                                             | 31.1                      | 1.00 |
| Mohammed and Azmi [32]       | 556.1        | 803.58     | 697.32       | 228         |                          |                          | 0.41 | 0.66                         | 53.03                                                      | 46.97                                                                 | 0                                             | 35.5                      | 1.00 |
| Mohammed and Azmi [32]       | 400          | 887.16     | 769.84       | 228         |                          |                          | 0.57 | 0.73                         | 53.42                                                      | 46.58                                                                 | 0                                             | 29.56                     | 1.00 |
| Mohammed and Azmi [32]       | 335.29       | 921.8      | 799.9        | 228         |                          |                          | 0.68 | 0.75                         | 53.33                                                      | 46.67                                                                 | 0                                             | 23.4                      | 1.00 |
| Mohammed and Azmi [32]       | 592.68       | 775.96     | 673.35       | 243         |                          |                          | 0.41 | 0.63                         | 53.54                                                      | 46.46                                                                 | 0                                             | 44.3                      | 1.00 |
| Mohammed and Azmi [32]       | 10           | 34.21       | 15           | 24.56        | 55                       | 20                        | 22.19 | 0.50                         | 18.56                                                    | 0.42                                                                 | 0                                             | 10                         | 0.77 |
| Mohammed and Azmi [32]       | 15           | 24.56       | 20           | 22.19        | 55                       | 30                        | 18.56 | 0.42                         | 18.56                                                    | 0.42                                                                 | 0                                             | 10                         | 0.77 |
| Mohammed and Azmi [32]       | 20           | 22.19       | 30           | 18.56        | 55                       | 0                         | 18.56 | 0.42                         | 18.56                                                    | 0.42                                                                 | 0                                             | 10                         | 0.77 |
| Mohammed and Azmi [32]       | 30           | 18.56       |              |              | 55                       | 0                         | 18.56 | 0.42                         | 18.56                                                    | 0.42                                                                 | 0                                             | 10                         | 0.77 |
Table A1. Cont.

| Mixtures               | Cement kg/m³ | Sand kg/m³ | Gravel kg/m³ | Water kg/m³ | Type of Additions | Pre-Treatments of Rubber | w/c | Total Volume of Aggregates /m³ | % Fine Aggregates (Total Volume of Aggregates) | % Coarse Aggregates (Total Volume of Aggregates) | % Substitution of Fine Aggregates (Referred to the Volume of Fine Aggregates) | Compressive Strength MPa | SRF |
|------------------------|--------------|------------|--------------|-------------|-------------------|--------------------------|-----|-------------------------------|----------------------------------|-----------------------------------------------|-------------------------------------------------|------------------------|-----|
| Mohammed and Azmi [32] | 426.32       | 865.03     | 750.65       | 243         |                   |                          | 0.57| 0.71                          | 53.54                             | 46.46                                          | 0                                  | 36.5                   | 1.00|
|                        |              |            |              |             |                   |                          | 10  | 26.2                          | 0.72                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 15  | 21.74                         | 0.60                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 20  | 18.45                         | 0.51                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 30  | 12.3                          | 0.34                              |                                                |                                                  |                        |     |
| Mohammed and Azmi [32] | 357.35       | 901.96     | 782.69       | 243         |                   |                          | 0.68| 0.74                          | 53.54                             | 46.46                                          | 0                                  | 30.12                  | 1.00|
|                        |              |            |              |             |                   |                          | 10  | 19.39                         | 0.64                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 15  | 17.24                         | 0.57                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 20  | 15.5                          | 0.51                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 30  | 11.1                          | 0.37                              |                                                |                                                  |                        |     |
| Mohammed and Azmi [32] | 629.27       | 748.35     | 649.39       | 258         |                   |                          | 0.41| 0.61                          | 53.54                             | 46.46                                          | 0                                  | 48.1                   | 1.00|
|                        |              |            |              |             |                   |                          | 10  | 37.2                          | 0.77                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 15  | 27.1                          | 0.56                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 20  | 24.5                          | 0.51                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 30  | 20.1                          | 0.42                              |                                                |                                                  |                        |     |
| Mohammed and Azmi [32] | 452.63       | 842.92     | 731.45       | 258         |                   |                          | 0.57| 0.69                          | 53.54                             | 46.46                                          | 0                                  | 40.1                   | 1.00|
|                        |              |            |              |             |                   |                          | 10  | 28.8                          | 0.72                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 15  | 23.2                          | 0.58                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 20  | 20.1                          | 0.50                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 30  | 14.3                          | 0.36                              |                                                |                                                  |                        |     |
| Mohammed and Azmi [32] | 379.41       | 882.12     | 765.47       | 258         |                   |                          | 0.68| 0.72                          | 53.54                             | 46.46                                          | 0                                  | 34.2                   | 1.00|
|                        |              |            |              |             |                   |                          | 10  | 22.5                          | 0.66                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 15  | 19.6                          | 0.57                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 20  | 17.1                          | 0.50                              |                                                |                                                  |                        |     |
|                        |              |            |              |             |                   |                          | 30  | 13.4                          | 0.39                              |                                                |                                                  |                        |     |
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