Prediction of density and compressive strength for rubberized concrete blocks

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Abstract

The influence of rubber content within the range of 5% to 50% as the replacement for sand volume and water/cement (w/c) ratio (0.45 to 0.55) on the density and compressive strength of concrete blocks was investigated. All the mixtures were proportioned with a fixed aggregate/cement ratio of 5.6. A total of 50% of the total aggregate was fine aggregate. Based on the experimental results, the density and strength reduction factors for rubberized concrete blocks were calculated by considering the dependent factors of rubber content and w/c ratio. Linear and logarithm equations derived, based on the results from experimental work are proposed to predict the density and compressive strength of rubberized concrete blocks.

Keywords: crumb rubber; w/c ratio; rubberized concrete blocks; strength; density

List of Abbreviations

- \( a \) = a constant value intersect at y-axis of a linear equation (density reduction factor vs. rubber content)
- \( b \) = density reduction factor-gaining rate
- \( D_c \) = density of a control concrete block (kg/m\(^3\))
- \( D_r \) = density of a rubberized concrete block (kg/m\(^3\))
- \( r \) = rubber content by total sand volume
- \( R_{CS(w/c)} \) = strength reduction factor
- \( R_{d(w/c)} \) = density reduction factor
- \( S_c \) = compressive strength of control concrete block (MPa)
- \( S_r \) = compressive strength of rubberized concrete block (MPa)
- \( w/c \) = water/cement ratio

1. Introduction

The disposal of waste tyres in landfill poses serious environmental problems, primarily due to this kind of waste not being biodegradable. In the past few decades, numerous studies have been conducted in relation to making good use of this recycled waste, especially as fine aggregate in cement mortar and concrete [1-5]. Khatib and Bayomy [6] found that the use of rubber aggregate had a bad effect on workability. Almost zero slump (not workable manually) of fresh concrete has been detected with increases in rubber aggregate up to 40% as the replacement for total aggregate volume. Khaloo et al.
[7] reported that it could be beneficial to apply 25% volume of recycled tyre as the total aggregate replacement in concrete to improve its toughness. However, they suggested that the use of rubber aggregates must not go beyond this limit due to the decline in ultimate compressive strength of concrete. Similar observations were also reported in other studies [8-12].

It is well-known that an optimal water/cement (w/c) ratio for any given mix can enhance the performance of concrete properties [13]. Haach et al. [14] observed the influence of w/c ratio on the workability and hardened properties of mortars. They noted that there was a 32-40% reduction in compressive strength as w/c changes from 0.6 to 0.8. According to Newman and Choo [15], sufficient water in the mix assists in reducing macroscopic entrapped voids, but excessive water increases the microscopic capillary voids. Although decreasing the water content can result in the existence of closely packed cement particles, it may increase the difficulty of expelling air voids due to the associated reduction in lubrication and mobility [16].

The density and compressive strength of the final rubberized concrete products depend mainly on the relative amounts of the two components: rubber aggregate and water [4,17,18]. Some of the desirable characteristics of these products are low density, better sound insulation, and higher impact strength and toughness. These advantages make rubberized concrete products ideal for wider acceptance in civil engineering applications. Therefore, the objective of this study is to establish equations derived from results determined from experimental testing to predict the density and compressive strength of rubberized concrete blocks.

2. Experimental procedure
Materials used in this study consist of ordinary Portland cement complying with ASTM Type I standards. The natural aggregates used were natural river sand as the fine aggregate, having a maximum particle size of 4 mm and fineness modulus of 2.62, and crushed granite with a nominal size of less than 10 mm and fineness modulus of 5.84 as the coarse aggregate. Recycled crumb rubber produced by mechanical shredding, ranging from 1-5 mm in size was used as a sand replacement by volume.

All the mixtures were proportioned with a fixed aggregate/cement ratio of 5.6 and the coarse to fine aggregate ratio was kept at 1:2 throughout the whole experiment. Nine different concrete block mixtures were designed to evaluate the effect of rubber content on the density and compressive strength of the concrete blocks. The amounts of rubber to replace the sand volume were 5%, 10%, 15%, 20%, 25%, 30%, 40% and 50%. To compare the results, all nine mixtures were prepared with three different w/c ratios of 0.45, 0.50 and 0.55.

All the concrete constituents were mixed for 5 min before being poured in two layers of approximately equal depth into a steel mould with the dimensions of 200×100×60 mm. After each layer was filled, compactions were applied by dropping a 1.86 kg square hammer (25×25 mm) 50 times directly onto the mixture from a height of 10 cm. Finally, to ensure the mixture was well compacted, empty spaces within the mould, if any, were
filled and re-flattened using a trowel. The fabricated rubberized concrete blocks in the steel moulds were left in the laboratory environment at a room temperature of 30 ± 3 °C and relative humidity of 65 ± 5% for one day. After one day, all the specimens were removed from the steel moulds and further kept in the laboratory environment in air until the testing day.

The density of the hardened concrete was determined according to BS 1881 - Part 114. A compressive strength test was performed in conformity with BS 6717 - Part 1 at 7 and 28 days after casting. Three samples were tested for each mix property and all the results reported are the average of the three tested samples.

3. Results and discussion

The hardened density and compressive strength as well as the strength reduction factor of the rubberized concrete blocks as a function of rubber content and w/c ratio are listed in Table 1.

Table 1: The experimental testing results of density, compressive strength and calculated results of density and strength reduction factors

<table>
<thead>
<tr>
<th>w/c content (%)</th>
<th>Density (kg/m³)</th>
<th>7-day strength (MPa)</th>
<th>R₇d-CS</th>
<th>28-day strength (MPa)</th>
<th>R₂₈d-CS</th>
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<td>30.8</td>
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<td>20</td>
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<tr>
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<tr>
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<td>10.8</td>
<td>0.078</td>
<td>12.4</td>
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3.1. Hardened density

The hardened density results of the rubberized concrete blocks shown in Table 1 indicate that the air dry density of rubberized concrete blocks decreased as the rubber content increased. The density was reduced by about 8% when 50% of the total sand was replaced by rubber, irrespective of the w/c ratio. This is mainly attributed to the low specific gravity of rubber particles (1.12 g/cm$^3$) as compared to natural river sand (2.61 g/cm$^3$) [10]. Siddiquw and Naik [19] mentioned that the non-polar nature of rubber particles may tend to entrap air if their rough surfaces increase, which in turn increases the air content and reduces the density of the concrete mixtures. In terms of w/c ratio, the density of the rubberized concrete blocks increased as the w/c ratio increased, for a given rubber content. This can be explained by the fact that the sufficient free water in the rubberized concrete mixes, which provides a better workability and good compaction, results in less empty spaces between the aggregate particles and the cement paste.

In order to analyze the density of the rubberized concrete blocks, experiments were first performed to correlate the density results obtained from experimental testing with a given rubber content and w/c ratio. The expression for determining the density reduction factor ($R_{d(w/c)}$) is given by Eq. (1) and the calculated values of the density reduction factors are tabulated in Table 1.

$$R_{d(w/c)} = \left( \frac{D_r}{D_c} \right) \left( 1 - \frac{13 \rho}{c} \right)$$

where $D_r =$ density of a rubberized concrete block (kg/m$^3$), $D_c =$ density of a control concrete block (kg/m$^3$), w/c = water-cement ratio, $r =$ rubber content by total sand volume.

Statistical analysis was then carried out to establish a linear relationship between the calculated density reduction factor (Table 1) and the rubber content. A linear equation, Eq. (2), was derived based on the experimental data plotted in Fig. 1, where $a$ and $b$ are constants and the former shows the density reduction factor-gaining rate.

$$R_{d(w/c)} = b + 43a$$

The $R$-square value of 0.99 was determined from the three linear best-fit lines plotted in Fig. 1, which shows that there is a very strong linear relationship between the density reduction factors and the rubber content for all w/c ratios. Comparing the trend of density reduction factor versus rubber content obtained from the three series of 0.45, 0.50 and 0.55 w/c mixtures, it is obvious that they are very similar. It seems that the increase of rubber content leads to an increase in the density reduction factor. Conversely, the density reduction factor magnitude was reduced when the w/c ratio was reduced.
3.2. Compressive strength

The compressive strength results obtained from experimental testing are tabulated in Table 1. As expected, the compressive strength of all the rubberized concrete blocks demonstrated a decreasing tendency with increasing mixing ratio of the rubber content. In the case of 0.55 w/c series mixtures, the increase in rubber content from 0% to 50% resulted in a substantial decrease in the compressive strength from 42.5 MPa to 12.4 MPa, which is equivalent to about a 70% reduction of strength. The possible reasons for this strength reduction can be attributed to the reduction of the quantity of the solid load-carrying material with increasing rubber content. Also, the soft and smooth surfaces of rubber particles might significantly degrade the adhesion between the boundaries of the rubber particles and cement paste, and thus increase the volume of the weakest phase and interfacial transition zone [20]. In all cases, the negative impact of rubber on the compressive strength was more pronounced at 28 days than at 7 days.

An equation for determining the strength reduction factor \( R_{CS} \) as shown in Eq. (3) was established by including the dependent factors of rubber content and w/c ratio.

\[
R_{CS} = \left( \frac{S_r}{S_c} \right) = \frac{173}{174}(r)
\]

where  
- \( S_r \) = compressive strength of rubberized concrete block (MPa)  
- \( S_c \) = compressive strength of control concrete block (MPa)  
- \( r \) = rubber content by total sand volume
Figs. 2 and 3 show the relationship between strength reduction factor and rubber content for given w/c ratios of 0.45, 0.50 and 0.55 at 7 days and 28 days, respectively. Three curves for 0.45, 0.50 and 0.55 w/c series mixtures tested in this study are plotted. The best-fit curve is represented by a logarithmic curve for each tested w/c ratio. The coefficient of determination of the three logarithmic curves for 7 and 28 days varied from 0.73 to 0.96. As can be seen from the figure, the higher the w/c ratio the more reliable are the values of the strength reduction factor.

For simplicity, the dependent factor of w/c ratio was eliminated by using the average results of the three series of w/c ratio mixtures to plot an additional curve (shown dotted) in the figures. The average correlation of the reduction strength factor for 7 and 28 days is given in Eqs. (4) and (5), respectively. The equations correspond to the reduction strength factors ($R_{CS}$) in the tested range (within 0% to 50% for rubber content and 0.45 to 0.55 for w/c ratio) and are only expressed as a function of the percentage of rubber content.

$$R_{7d-CS(average)} = 0.0273 \ln(r) + 0.0136$$
$$R_{28d-CS(average)} = 0.0274 \ln(r) + 0.0169$$

Eqs. (4) and (5) show a strong correlation based on the combination of results for the three series of w/c ratio mixtures with R square values of 0.86 and 0.93, respectively. By using Eqs. (4) and (5), the compressive strength of rubberized concrete blocks at 7 and 28 days can be predicted, provided that the percentage of rubber used is within the tested range.

However, for rubber content and/or w/c ratio that fall outside the tested range, the equations should be used with care. As can be seen in Figs. 2 and 3, if the curves are extended beyond the tested range, the following phenomena can be observed. Below 5% rubber content, the curves approach zero as the rubber content decreases. Conversely, above 50% rubber content, the curves conform to the linear relationship plotted between 30% and 50% rubber content.

In order to validate this approach, proposed Eq. (5) was used to predict the strength reduction factors of different sets of experimental data from other studies [21-24]. The predicted reduction strength factor values were plotted and compared with the corresponding calculated values determined by Eq. (3). Fig. 4 shows that the predicted reduction strength factor values appear to be inconsistent with the calculated values. As can be seen, at a higher reduction strength factor, the predicted values were found to be generally smaller than the calculated values, which is understandable in view of the various ranges of mix designs, type of concrete products as well as the variety of recycled rubber materials used and casting methods that have been adopted by different studies. Thus, further work is needed to bridge the gap between the calculation and prediction approach before this approach can be used in practice.
Fig. 2: Relationship between 7-day compressive strength reduction factor and rubber content for a given w/c ratio of 0.45, 0.50 and 0.55

Fig. 3: Relationship between 28-day compressive strength reduction factor and rubber content for a given w/c ratio of 0.45, 0.50 and 0.55
Fig. 4: Comparison of the predicted reduction compressive factor values using proposed equation with the corresponding calculated values based on different sets of experimental data from other studies

4. Conclusions

1. The density and compressive strength of rubberized concrete blocks is affected differently depending on the rubber content and w/c ratio. If the rubber content increases in the mixture, a systematic reduction in density and compressive strength takes place. It is suggested that the rubber substitution used in concrete blocks should not exceed 10% vol. for structural and 40% vol. for non-structural applications.

2. A linear best-fit relationship was established between the density reduction factor and rubber content. The proposed linear equations are capable of predicting the density of rubberized concrete blocks if the percentage of rubber used is within the tested range (5% to 50%).

3. Logarithmic best-fit curves were proposed based on results from experimental testing. The equations are valid to predict the compressive strength of rubberized concrete blocks if the percentage of rubber used and w/c ratio are within the tested range (5% to 50% for rubber content and 0.45 to 0.55 for w/c ratio).

4. However, more research is needed before this proposed approach can be used in the concrete industry. Affecting (dependent) factors such as cement to total aggregate ratio, initial strength value of control samples as well as the type and particle size of recycled rubber aggregate used as the replacement for total aggregate volume should be considered in the equation in order to improve the overall prediction performance.
Reference


