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PREDICTION OF CRUMB RUBBER CONCRETE STRENGTH

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ABSTRACT

In recent years, a very important environmental issue all over the world is the disposal of waste tyres. Rubber from waste tyres can be used to replace part of the natural aggregates in conventional concrete, resulting in a product called crumb rubber concrete (CRC). CRC can improve ductility, damping ratio, and energy dissipation, which are the most important parameters in concrete structures resisting earthquakes. However, CRC can have lower compressive strength when compared with conventional concrete. This paper presents an empirical model able to predict CRC compressive strength. The proposed model is verified using 148 different CRC mixes and compared to two previous models. The proposed model resulted in CRC strength predictions with only 10.7% mean error. The proposed model reduced the mean error in the predictions by 24.6% compared to the nearest predictions by previous models. This paper can aid structural designers who are considering using CRC as a promising alternative to conventional concrete in seismic zones.

KEYWORDS

Crumb rubber concrete, rubberized concrete, strength losses, strength prediction.

INTRODUCTION

The rubber from used tyres that is currently dumped to landfill is a significant problem in Australia and the rest of the world. Due to the low density and poor degradation of tyres they cannot be buried in landfills (Segre and Joekes, 2000). Furthermore, tyres are not desired at landfills, due to their large volume. Across the world, one billion tyres reach the end of their useful lives every year and 0.5 billion more are expected to be discarded each year by 2030 (Torgal et al., 2012). In Australia, forty eight million tyres are disposed of each year. Only sixteen percent are recycled with the majority going into landfill, stockpiles, or being exported or dumped (Media-Release, 2014). This rapid increase provides added motivation to find different ways to re-use this waste rubber. One possibility being explored is to use crumbed rubber from waste tyres to replace part of the natural aggregates in conventional concrete resulting in a new product called crumb rubber concrete (CRC). Compared to conventional concrete, CRC has higher ductility, durability, viscous damping, impact resistance, and toughness (Fattuhi and Clark, 1996, Zheng et al., 2008a, Zheng et al., 2008b, Youssf and ElGawady, 2012, Youssf et al., 2014). These issues encourage researchers to use CRC in construction, particularly for structures subject to seismic loads. However, CRC has lower compressive strength than conventional concrete.

Determination of CRC strength is of great interest in designing of CRC structures. In this paper, an empirical model is proposed for predicting CRC strength (f'_{CRC}). The proposed model prediction was verified and compared to previous model predictions using a large experimental results database of 148 data sets.

OVERVIEW OF CRC STRENGTH

Concrete compressive strength is the main mechanical property that would be affected by using rubber aggregates in concrete. Through reviewing of 23 previous studies on CRC, a large database of 148 CRC mixes is collected. In these mixes, the control compressive strength of the conventional concrete (f'_c) was ranged between 23 and 90 MPa, the cement content was ranged between 280 kg/m^3 and 513 kg m^3, the water to cement ratio was ranged between 0.25 and 0.75. Since it has been suggested that rubber content should not exceed 20% of the total aggregate volume because of the negative effect on its strength (Khatib and Bayomy, 1999), the collected data was limited to concrete with a maximum of Rt = 25% to cover the recommended range; where Rt is the percentage of rubber content in the total volume of aggregates. The fine aggregates' replacement percentage in the data base was ranged between 0% and 60% and the coarse aggregates replacement percentage ranged between 0% and 50%. All these studies have used graded rubber particles, but Youssf et al., (2014) considered the effect of using graded rubber particles compared with non-graded rubber particles on f'_{CRC} and reported an improvement in f'_{CRC} by using non-graded rubber compared to using graded rubber. At the same Rt, using big rubber particles improved the f'_{CRC} compared to using smaller rubber particles (Youssf et al., 2014).

The data set used in this study was collected at 28-days concrete age from the following references: (Li et al., 2011, Ganjian et al., 2009, Balaha et al., 2007, Skripkiūnas et al., 2007, Topcu, 1995, Hernández-Olivares and Barluenga, 2004, Tian et al., 2011, Turatsinze and Garros, 2008, Khatib and Bayomy, 1999, Valadares et al., 2012, Güneyisi et al., 2004, Youssf et al., 2014, Azevedo et al., 2012, Issa and Salem, 2013, Karahan et al., 2012, Liu et al., 2012, Bowland, 2011, Aiello and Leuzzi, 2010, Son et al., 2011, Najim and Hall, 2012, Eldin and Senouci, 1993, Grinys et al., 2012, Dong et al., 2013). Figure 1 shows the effect of increasing rubber content in concrete on its compressive strength based on these data. As shown in the figure, there is a strong correlation between increasing rubber content and compressive strength reduction. The reduction in compressive strength reached 70% at 25% rubber content. This reduction is attributed to several reasons which can be summarized in the following points:

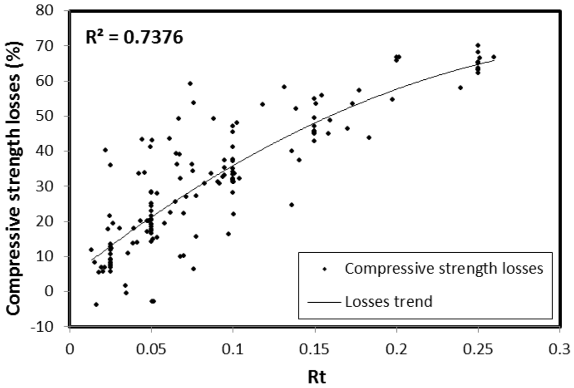

Figure 1. Effect of rubber content on concrete compressive strength losses.

(1) The Poisson's ratio of rubber is twice that of concrete and the Young's modulus of rubber is about 1/3 that of concrete. Thus, significantly large relative deformations between rubber and concrete occur which lead to early cracking (Youssf and ElGawady, 2012).
(2) High internal tensile stresses perpendicular to the direction of the applied compression load are produced because of the low modulus of elasticity of rubber particles. These tensile stresses cause early failure in cement mortar (Topcu, 1995).
(3) Rubber particles act as air voids for crack initiation followed by crack propagation, and then, strength reduction (Youssf and ElGawady, 2012).
(4) The low permeability of rubber particles might significantly degrade the interaction between the boundaries of the rubber particles and the cement paste, thus increasing the volume of the weakest phase and the interfacial transition zone (Youssf et al., 2014).
(5) Rubber has a specific gravity lower than concrete. Hence, due to the vibration process during concrete mixing and placement, the rubber migrates to the top surface of the concrete resulting in a non-homogeneous mix and reduction in concrete strength (Najim and Hall, 2010).

In Figure 1, it can also be observed that in some cases at low rubber content (up to 5%) the losses were negative values (compressive strength increased). This is attributed to the filling mechanism, in which the rubber particles can reduce the porosity of concrete mixtures resulting in compressive strength increasing. However, when rubber content is larger, the deformability mechanism was more predominant than the filling mechanism, resulting in higher stress concentrations around the rubber particles. Ganjian et al. (2009) related the increase in compressive strength of concrete having small rubber contents to the improvement of the coarse and fine aggregate grading.

ESTIMATION OF CRC STRENGTH

The collected 148 CRC mixes were used to develop the present model and to compare the present model predictions to the previous models' predictions (Model-1(Khatib and Bayomy, 1999) and Model-2 (Khaloo et al., 2008)). The error percentages for each model's predictions were calculated using Eq. 1.

$$\text{Error}\ \% = \frac{|\text{Experimental results} - \text{Model results}|}{\text{Experimental results}} \qquad (1)$$

The compressive strength model was proposed in an exponential form, which was selected among several forms (e.g. linear, polynomial, logarithmic, exponential, power). The exponential form has an advantage compared to the others that when the rubber content Rt equals zero (no rubber), the concrete compressive strength is not affected ($e^0 = 1.0$). Thus, the initial model formula was proposed as $[f'_{CRC} = f'_c\ [e^{\alpha\, Rt}]]$, where f'_{CRC} is the compressive strength of the crumb rubber concrete, f'_c is the compressive strength of the control concrete (without rubber), Rt is the rubber content by volume of the total aggregates and α is a constant. Since the value of $e^{\alpha\, Rt}$ term in this formula has to decrease as Rt increases, the value of constant "α" was calibrated using a wide range of negative values ranging from -0.1 to -30.0 to select the appropriate value that resulted in the least root mean square error in the model predictions. A value of -4.2 was found to be the appropriate one, as shown in Figure 2. Thus, the final form of the proposed model is presented in Eq. 2.

$$f'_{CRC} = f'_c\ [e^{-4.2\, Rt}] \qquad (2)$$

VERIFICATION AND COMPARISON

Figures 3-5 show comparisons between the predictions of all models. As shown in the figures (left sides), compared to other models, the proposed model has the least scattering in its predictions. The proposed model's error decreased with increasing Rt compared to a continuous error increase using the previous models as shown in the figures (right sides).

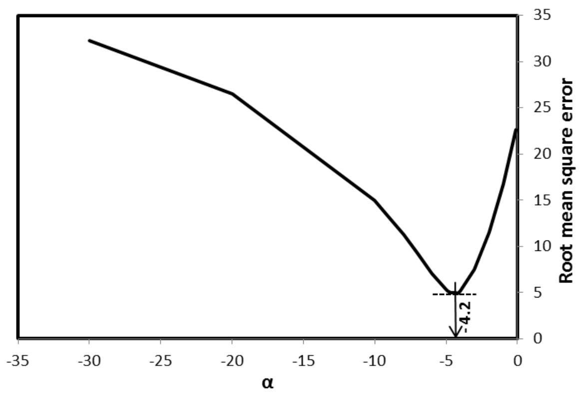

Figure 2. Effect of “α” value on the root mean square error in the model predictions.

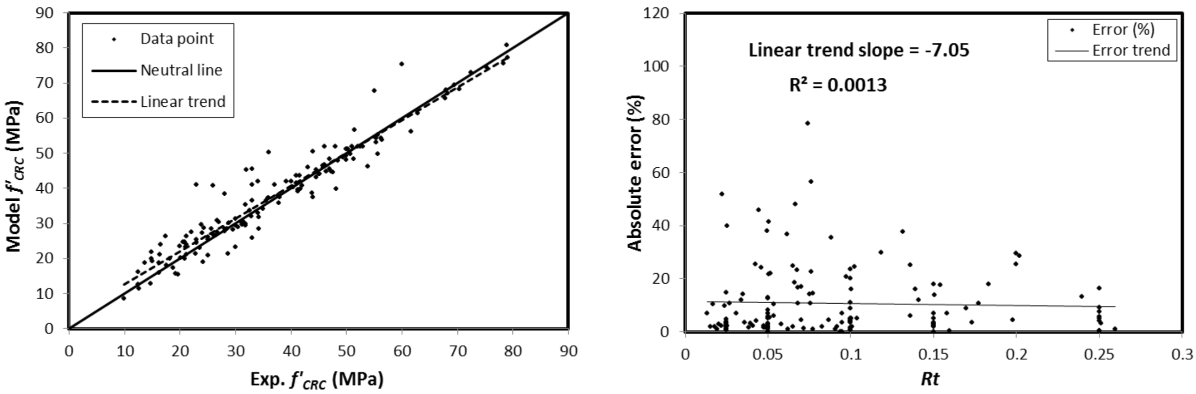

Figure 3. Proposed model predictions.

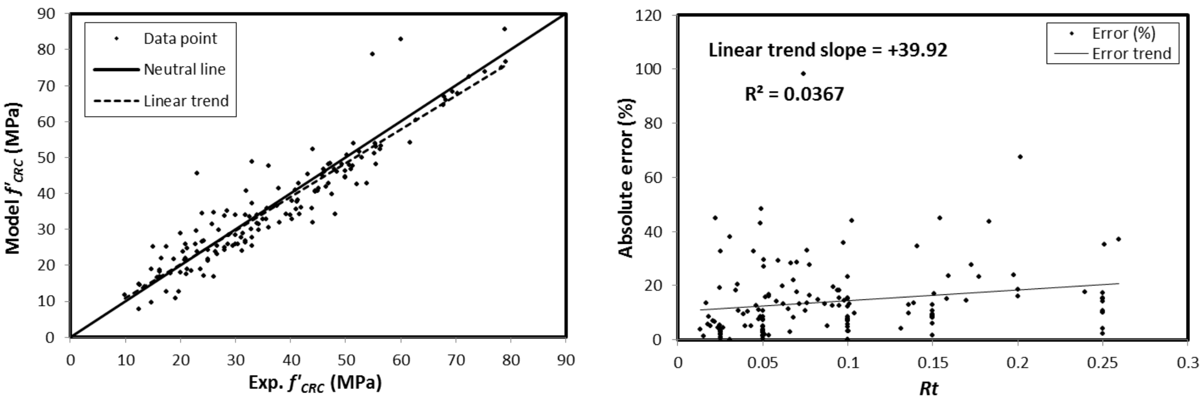

Figure 4. Model-1 predictions.

Table 1 shows the statistical parameters for all comparable models in this study. For this comparison, the absolute mean error (M), the error standard deviation (SD), maximum error %, error linear trend slope, and the ability of the model to predict experimental results within 20% error were calculated for the predictions of each of the three models. The proposed model reduced M, SD, and max. error % by 24.6%, 5.8%, and 20.2%, respectively, compared to Model-1 predictions, and by 75.5%, 46.4%, and 9.3% compared to Model-2 predictions. When considering the limits of 20% error, the proposed model was able to predict 83.1% of the experimental data to be within 20% error compared to 80.4% and 21.6% for Model-1 and Model-2, respectively.

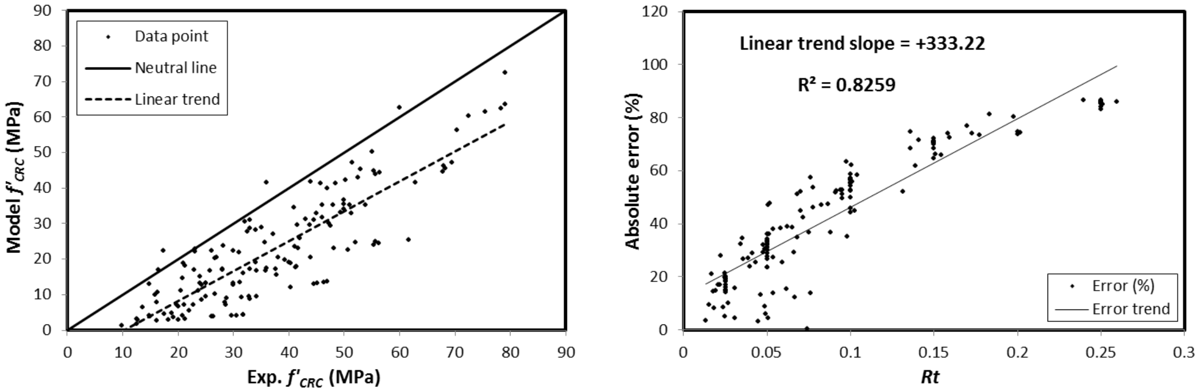

Figure 5. Model-2 predictions.

Table 1. Statistical results of the errors for each model.

Model	Proposed model	Model-1	Model-2
M (%)	10.7	14.2	43.7
SD (%)	12.9	13.7	24.1
Max. error (%)	78.4	98.3	86.5
Linear trend slope	-7.05	+39.92	+333.22
Predictions less than 20% error (%)	83.1	80.4	21.6

SUMMARY AND CONCLUSIONS

This paper presented an empirical model able to predict the compressive strength of CRC. A set of 148 data results for CRC compressive strength was used to verify the proposed model. The proposed model had the least scattering in its predictions compared to similar previous models. This model reduced M, SD, and max. error % by 24.6%, 5.8%, and 20.2%, respectively, compared to the Khatib and Bayomy (1999) model predictions, and by 75.5%, 46.4%, and 9.3% compared to the Khaloo et al. (2008) model predictions. Within error range of 20%, the model was able to predict 83.1% of the experimental data compared to 80.4% and 21.6% for Khatib and Bayomy (1999) model and Khaloo et al. (2008) model, respectively. The proposed model can aid structural designers who are considering using CRC as a promising alternative to conventional concrete in seismic zones.

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