Effects of different crumb rubber sizes on the flowability and compressive strength of hybrid fibre reinforced ECC

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Abstract. The different sizes of crumb rubber have been used to investigate the effects on flowability and the compressive strength of the hybrid fibre reinforced engineered cementitious composite. Two sizes of crumb rubber 30 mesh and 1 to 3mm were used in partial replacement with the fine aggregate up to 60%. The experimental study was carried out through mathematical and statistical analysis by response surface methodology (RSM) using the Design Expert software. The response models have been developed and the results were validated by analysis of variance (ANOVA). It was found that finer sized crumb rubber inclusion had produced better workability and higher compressive strength when compared to the larger size and it was concluded that crumb rubber has negative effect on compressive strength and positive effect on workability. The optimization results are found to an approximately good agreement with the experimental results.

1. Introduction
Crumb rubber (CR) is recycled rubber produced from automotive and truck scrap tires. During the recycling process, steel and tire cord (fluff) are removed, leaving tire rubber with a granular consistency. Every year the plenty of scrap tyres are being discarded to the environment. It has been reported that every year about 1000 millions of used tyres were produced by the passenger vehicles [1]. Thus, disposal of crumb rubber has become a major environmental problem in most of the countries due to its non-biodegradable property, risk of fire, breeding locality for harmful insects and rodents [2]. In contrast, there a major quantity of natural resources are required for the production of concrete. Usage of these natural fine and coarse aggregates induces the huge environmental problem. By using the crumb rubber in partial replacement with the fine aggregate solves the problem of environmental causes and also bring the economic benefits [3]. Engineered cementitious composite (ECC) is a unique kind of fibre reinforced high-performance cementitious composites based on the theory of micromechanics. ECC has strain hardening behaviour after the first crack and develops a high tensile ductility of about 3 to 7% when compared to the 0.01% tensile strain of conventional concrete [4].

Crumb rubber in ECC improved the flexural deflection capacity, reduces the crack width [5] increased the tensile ductility, deformation durability, and reduced unit weight [6]. Previously in many studies, the crumb rubber was used in the conventional concrete in partial replacement with the fine aggregate which reported that there has been an improvement in various fresh and hardened properties of rubberized concrete. Fresh rubberized concrete contains a greater percentage of entrained air which facilitates to have better freeze and thaw protection [7] in addition to higher workability and lower unit weight [8]. In terms of hardened properties rubberized concrete exhibits good seismic resistivity in the
form of energy dissipation capacity and damping ratio [9], better ductility [10], improved impact resistance [11, 12], low thermal conductivity [13], higher electric resistivity [14], good sound absorbent [15, 16], resistant to chloride ion penetration and acid attack [17] and performed better against the fatigue loads [18]. Apart from these advantages, rubberized concrete has negativity in the form of reduction in strengths because of crumb rubber’s physical properties and the compatibility for the fine aggregate. Attributable to the hydrophobic behavior of crumb rubber particles makes the water to repel and air entraps on the surface.

ECC with hybrid fibre includes steel and PVA exhibited an improved compressive strength, ultimate flexural strength, Young's modulus [19]. Crumb rubber aggregates are produced by treating (by shredding, chipping, etc.) waste tires into a variety of classified particle size distributions or fibers processing is mechanical and normally occurs either at an ambient or cryogenic temperature. The rubber particles and the tirewire can be separated by grinding mechanically with ambient temperature and by cryogenic process. The tires from trucks and cars are required different processes for the separation because these influence the properties of concrete[20]. To stimulate the concrete industries to utilize the crumb rubber in partial replacement with fine aggregates [21], and many studies have used it as a partial replacement for natural sand. The different types of rubber particles are shown in Figure 1.

a. The rubber particles which are passing through No. 40 sieve are referred as grounded tire rubber particles. Many researchers had used in SCRC and asphalt concrete.[21]

b. Fiber rubber particles. A few studies had included the tire particles which are in the form of fibers. [22].

![Figure 1. Different types rubber particles](image)

In this study, two different sizes of crumb rubber in partial replacement with the fine aggregate are used as variables along with optimum ratios of tirewire and PVA as hybrid fibres in ECC, to study the flowability and compression strength.

2. Experimental program
Type I Portland cement according to the ASTM C150 (Standard Specification for Portland cement) was used for the production of ECC mixtures. The cement has the surface area and the specific gravity of 295 m\(^2\)/kg and 3.15 respectively. Class F fly ash with an overall content of oxides 88.5% i.e. Iron (Fe\(_2\)O\(_3\)), aluminium (Al\(_2\)O\(_3\)) and silicon (SiO\(_2\)). With a loss on ignition of less than 6% confirming to the ASTM C 618 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete). The compositions of chemicals from cement and fly ash are given in Table 1. The river sand of maximum particle size of 300 µm with a specific gravity of 2.65. Crumb rubber of size 30 mesh, 30 mesh and 1 to 3 mm were used. The particle size distributions using the sieve analysis of river sand and all the two sizes of crumb rubber are shown in Figure 2. Clean water for mixing was used according to ASTM C1602 with polycarboxylic based superplasticizer “Sika Viscocrete 2044”. The ECC mixture was reinforced with hybrid fibres, which are 1.5% PVA and 0.5 % tirewires (wires from the waste tyres). The mechanical properties of fibres are depicted in Table 2.
Table 1. Chemical configuration of the cementitious and pozzolanic materials.

| Chemical composition | Cement (%) | Fly ash (%) |
|----------------------|------------|-------------|
| SiO₂                 | 25.21      | 64.69       |
| Al₂O₃                | 4.59       | 18.89       |
| Fe₂O₃                | 2.99       | 4.9         |
| CaO                  | 62.85      | 5.98        |
| MgO                  | 1.7        | 1.99        |
| Na₂O                 | 0.98       | 2.41        |
| Specific gravity     | 3.15       | 2.3         |
| Loss on ignition     | 2.02       | 1.87        |

Table 2. Mechanical properties of fibres.

| Type  | Specific gravity | Length of fibre (mm) | Diameter of fibre (µm) | Aspect ratio (l/d) | Tensile strength (MPa) | Modulus of Elasticity (GPa) |
|-------|------------------|----------------------|------------------------|--------------------|------------------------|----------------------------|
| PVA   | 1.3              | 12                   | 40                     | 462                | 1600                   | 41                         |
| Tirewire | 7.85             | 10 to 35             | 11 to 43               | 600(Average)       | >1200                  | 200                        |

Figure 2. Particle size distributions.

2.1. Mix proportion, procedure, curing

Thirteen mixtures were prepared for the rubberized ECC using Design expert software for RSM (Response surface methodology). The ingredients cement, fly ash, sand was mixed together with the two variables as different sizes of crumb rubber in partial replacement with the fine aggregate up to the 60%. The superplasticizer which is the weight percentage of cementitious material was mixed with the water in order to get the required flow ability according to EFNARC 2002. The rubberized ECC after mixing, 6 cubes of size 100x100x100 were cast and then cured for 7 days and 28 days. Then cubes were tested in the compression machine. The mix proportions for rubberized hybrid fibre reinforced ECC are shown in Table 3.
Table 3. Mix proportions.

| Mixtures | Cement kg/m³ | Sand kg/m³ | Fly ash kg/m³ | Water kg/m³ | Crumb rubber 30 mesh % | Crumb rubber 1 to 3mm % | CR 1-3mm kg/m³ | CR 3-5mm kg/m³ | PVA fibres in % | Tirewire fibres in % |
|----------|--------------|------------|---------------|-------------|------------------------|------------------------|----------------|----------------|----------------|-------------------|
| M1       | 583          | 227.83     | 700           | 187         | 36.21                  | 15                     | 60.63          | 25.11          | 1.5            | 0.5               |
| M2       | 583          | 326.9      | 700           | 187         | 15                     | 15                     | 25.11          | 25.11          | 1.5            | 0.5               |
| M3       | 583          | 326.9      | 700           | 187         | 15                     | 15                     | 25.11          | 25.11          | 1.5            | 0.5               |
| M4       | 583          | 326.9      | 700           | 187         | 15                     | 15                     | 25.11          | 25.11          | 1.5            | 0.5               |
| M5       | 583          | 326.9      | 700           | 187         | 0                      | 30                     | 0              | 50.22          | 0              | 1.5               |
| M6       | 583          | 326.9      | 700           | 187         | 30                     | 0                      | 50.22          | 50.22          | 1.5            | 0.5               |
| M7       | 583          | 186.8      | 700           | 187         | 30                     | 30                     | 50.22          | 50.22          | 1.5            | 0.5               |
| M8       | 583          | 326.9      | 700           | 187         | 15                     | 15                     | 25.11          | 25.11          | 1.5            | 0.5               |
| M9       | 583          | 326.9      | 700           | 187         | 15                     | 15                     | 25.11          | 25.11          | 1.5            | 0.5               |
| M10      | 583          | 227.83     | 700           | 187         | 36.21                  | 15                     | 60.63          | 25.11          | 1.5            | 0.5               |
| M11      | 583          | 396.95     | 700           | 187         | 15                     | 15                     | 25.11          | 0              | 1.5            | 0.5               |
| M12      | 583          | 467        | 700           | 187         | 0                      | 0                      | 0              | 0              | 1.5            | 0.5               |
| M13      | 583          | 396.95     | 700           | 187         | 15                     | 15                     | 25.11          | 1.5            | 0.5            | 0.5               |

2.2. Experimental design using RSM

Response surface methodology (RSM) is an optimization process for the experiments and is being used in various fields. RSM is a method used to optimize the responses influenced by the number of variables by modelling the set of data by means of mathematical and statistical techniques. Statistical models were validated for concrete using wood chipping [23]. This analysis of variables is named as the design of experiment (DOE). The better performance can be obtained using RSM analysis [24]. The primary step in RSM is to get an appropriate functional relationship between the variables and responses. The most common method used in RSM to find the relationship between variables and responses is central composite design (CCD), which has been used in this study. The CCD should be rotatable with second-order response surfaces as suggested by BOX and Hunter in 1957. CCD can be made rotatable by choosing the axial run α from design center model. The characterization of CCD is shown in Figure 3.

![Figure 3. CCD Design Model.](image)

In this work, the response models were selected for flowability and compressive strength of rubberized ECC with the factors as different crumb rubber sizes in partial replacement with the fine aggregate. The optimum conditions were determined by selecting an appropriate model which explains the response surface [25]. Thus, in this case, the quadratic equation models were selected, which is as shown in the equation (1).

\[ y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{j=2}^{k} \sum_{i=1}^{j-1} \beta_{ij} x_i x_j + \epsilon \]  
………..(1)
Where, \( y \) is the response which are fresh and hardened properties, \( x_i, x_j \) are the coded values for the variables w/c ratio and crumb rubber, \( i \) is the linear co-efficient, \( j \) is the quadratic co-efficient, \( \beta \) represents regression co-efficient, \( k \) represents number of factors and \( \varepsilon \) indicates random error. A suitable model has been selected, so that the response surface can be well described. The individual responses were analysed thus, a fitting model (linear, quadratic or cubic) was selected.

3. Results and Discussion
The compressive strength test was carried in accordance with the BS 1881: Part 116:1983. The compression strength results for 7 days, 28 days and Superplasticizer required for the flowability as per EFNARC [26] for the different mixtures of rubberized hybrid fibre reinforced ECC are tabulated in Table 4. The superplasticizer requirement decreased as the crumb rubber quantity increases. It is due to the water repelling nature of crumb rubber. Smaller sized crumb rubber produced more workable composite than the higher sized crumb rubber. In order to quantify the significance of the RSM model, the analysis of variance (ANOVA) is considered, which indicated that 95% of significance level.

Table 4. Compressive strength and SP required for flowability.

| Mixtures | SP for \( T_{500} \) (kg/m\(^3\)) | 7 day Compressive strength (MPa) | 28 day Compressive strength (MPa) |
|----------|-----------------------------------|---------------------------------|----------------------------------|
| M1       | 10.44                             | 47.58                           | 58.52                            |
| M2       | 12.53                             | 59.33                           | 74.76                            |
| M3       | 12.53                             | 57.65                           | 70.33                            |
| M4       | 12.53                             | 58.76                           | 77.56                            |
| M5       | 12.11                             | 58.55                           | 72.6                             |
| M6       | 12.95                             | 60.46                           | 72.55                            |
| M7       | 10.03                             | 42.24                           | 52.8                             |
| M8       | 12.53                             | 58.24                           | 73.96                            |
| M9       | 12.53                             | 57.42                           | 74.07                            |
| M10      | 10.86                             | 45.84                           | 55.51                            |
| M11      | 13.78                             | 67.85                           | 85.49                            |
| M12      | 15.04                             | 76.56                           | 94.17                            |
| M13      | 13.37                             | 65.78                           | 83.54                            |

The equations (1) and (2) were developed by ANOVA in which the 7 days and 28 days compressive strength can be predicted respectively by substituting the values for two different crumb rubbers in percentages.

7 days Compressive strength (MPa) = \(+76.289777 - 0.58183 * (30 mesh) - 0.68706 * (1 to 3mm) - 0.00023333 * (30 mesh) * (1 to 3mm) + 0.00181178 * (30 mesh)\(^2\) + 0.0025696 * (1 to 3mm)\(^2\)\) (1)

28 days Compressive strength (MPa) = \(+94.57442 - 0.65871 * (30 mesh) - 0.63437 * (1 to 3mm) + 0.00202222 * (30 mesh) * (1 to 3mm) - 0.0019547 * (30 mesh)\(^2\) - 0.00438723 * (1 to 3mm)\(^2\)\) (2)

Figure 4, shows the 3D contour diagrams for 7 days and 28 days compressive strength for the two variable 30 mesh and 1 to 3mm crumb rubber sizes. It can be noticed that as the crumb rubber in partial replacement with fine aggregate increases the compressive strength decreases. It is due to the hydrophobic property of the crumb rubber which in turn creates the voids in the composite. From figures,
it can also be observed that the finer crumb rubber which is 30 mesh has more effect in increasing the compressive strength than the 1 to 3mm crumb rubber. Figure 5 shows 2D contour plots, from which it can be observed that variation of compressive strength for the different intervals of 30 mesh and 1 to 3mm sized crumb rubber.

![Figure 4. 3D Response Surface Diagrams](image)

![Figure 5. D Contour Diagrams](image)

4. Model validation
The response surface models were validated using the ANOVA method of analysis for the two responses of compressive strength with the variables as two sizes of crumb rubber. The analysed values have been shown in Table 5. It can be observed that for both 7 days and 28 days compressive strength the model and the variable terms are significant with the probability value of more than 95% which is also the confidence level. Thus, the developed models can provide excellent results in terms of responses.

| Response            | Source     | Sum of squares | df  | Mean Square | F Value | p-value | Significance |
|---------------------|------------|----------------|-----|-------------|---------|---------|-------------|
| 7 days compression test | Model      | 1011.79        | 5   | 202.36      | 365.58  | < 0.0001 | Yes         |
|                     | A-30 mesh  | 410.69         | 1   | 410.69      | 741.95  | < 0.0001 | Yes         |
|                     | B-1 to 3mm | 548.23         | 1   | 548.23      | 990.43  | < 0.0001 | Yes         |
|                     | AB         | 0.011          | 1   | 0.011       | 0.02    | 0.8917   | NO          |
|                     | A²         | 0.8            | 1   | 0.8         | 1.45    | 0.2676   | NO          |
|                     | B²         | 1.61           | 1   | 1.61        | 2.92    | 0.1314   | NO          |
| 28 days compression test | Model      | 1639.54        | 5   | 327.91      | 71.67   | < 0.0001 | Yes         |
|                     | A-30 mesh  | 687.55         | 1   | 687.55      | 150.28  | < 0.0001 | Yes         |
|                     | B-1 to 3mm | 788.34         | 1   | 788.34      | 172.31  | < 0.0001 | Yes         |
|                     | AB         | 0.83           | 1   | 0.83        | 0.18    | 0.6833   | NO          |
|                     | A²         | 0.93           | 1   | 0.93        | 0.2     | 0.665    | NO          |
|                     | B²         | 4.71           | 1   | 4.71        | 1.03    | 0.3442   | NO          |
From Table 6, the model terms it can be observed that the difference between the predicted and adjustable R squared values are less than 0.2 and, they are more than 95% probability. Thus the predicted R squared values are in good agreement with the adjustable R squared values. The models can also be validated from the normality plots shown in Figure 6. The points approximately falling on the normality line thus it can be said that the predicted values give more accurate results as expected.

| Response/Model Terms          | 7 Days compressive strength | 28 Days compressive strength |
|------------------------------|-----------------------------|------------------------------|
| Std. Dev.                    | 0.74                        | 2.14                         |
| Mean                         | 58.17                       | 72.76                        |
| C.V. %                       | 1.28                        | 2.94                         |
| PRESS                        | 14.99                       | 85.73                        |
| -2 Log Likelihood            | 21.16                       | 48.61                        |
| R-Squared                    | 0.9962                      | 0.9808                       |
| Adj R-Squared                | 0.9935                      | 0.9672                       |
| Pred R-Squared               | 0.9852                      | 0.9487                       |

5. Experimental validation
The RSM optimization results were validated by conducting the experiments in the laboratory. The test was performed for two optimized outputs with the variable 30 mesh crumb rubber 10% and 1 to 3mm crumb rubber 30% and vice versa with a desirability of 100%. The results between the two methods were compared and it was found that a less than 4% variation as shown in Table 7.

| Type          | Validation | 30 mesh CR in % | 1 to 3mm CR in % | Compressive strength 7 days (MPa) | Compressive strength 28 days (MPa) |
|---------------|------------|-----------------|------------------|-----------------------------------|-----------------------------------|
| Rubberized ECC| Optimization| 10              | 30               | 52.28                             | 65.42                             |
|               | Experimental|                 |                  | 51.06                             | 66.17                             |
|               | Variation % |                 |                  | 2.39%                             | 1.15%                             |
|               | Optimization| 30              | 10               | 53.78                             | 66.87                             |
|               | Experimental|                 |                  | 55.24                             | 69.12                             |
|               | Variation % |                 |                  | 2.71%                             | 3.36%                             |

Figure 6. Normality plots for residuals
6. Conclusions
The following conclusions can be drawn from this paper.

- The higher compressive strength can be achieved by using the finer crumb rubber partially replaced with sand for the rubberized hybrid fibre reinforced engineered cementitious composite. The finer crumb rubber produced better workability than the larger sized crumb rubber.
- RSM models to predict 7 days and 28 days compressive strength of rubberized hybrid reinforced ECC based on the amount of two different sizes of crumb rubber have been developed with ANOVA of more than 95% significance level. The difference between Adjusted R$^2$ and Predicted R$^2$ is less than 0.2.
- From models validation, the difference between findings in the optimized RSM and the experimental results is less than 4% with desirability function 1

References
[1] Thomas B S, Gupta R C., Kalla P., and Cseteneyi L 2014 Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates," Construction and Building Materials 59 204-212
[2] Youssf O, Mills J E, and Hassanli R 2016 Assessment of the mechanical performance of crumb rubber concrete Construction and Building Materials 125 175-183
[3] Mohammed B S, Awang A B, San Wong S, and Nhavene C P 2016 Properties of nano silica modified rubbercrete Journal of Cleaner Production 119 66-75
[4] Mohammed B S, Syed Z I, Khed V and Qasim M S 2017 Evaluation of Nano-Silica Modified ECC Based on Ultrasonic Pulse Velocity and Rebound Hammer The Open Civil Engineering Journal 11(1)
[5] Zhang Z, Ma H and Qian S 2015 Investigation on properties of ECC incorporating crumb rubber of different sizes Journal of Advanced Concrete Technology 13(5) 241-251
[6] Huang X, Ranade R, Ni W and Li V C 2013 On the use of recycled tire rubber to develop low E-modulus ECC for durable concrete repairs Construction and Building Materials 46 134-141,
[7] Richardson A, Coventry K, Edmondson V and Dias E 2016 Crumb rubber used in concrete to provide freeze–thaw protection (optimal particle size) Journal of Cleaner Production 112 599-606,
[8] Kardos A J and Durham S A 2015 Strength, durability, and environmental properties of concrete utilizing recycled tire particles for pavement applications Construction and Building Materials 98 832-845
[9] Youssf O, ElGawady M A and Mills J E 2015 Experimental investigation of crumb rubber concrete columns under seismic loading Structures 3 13-27
[10] Mohammed B S 2010 Structural behavior and m–k value of composite slab utilizing concrete containing crumb rubber Construction and Building Materials 24(7) 1214-1221
[11] Al-Tayeb M M, Bakar B A, Ismail H and Akil H M 2013 Effect of partial replacement of sand by fine crumb rubber on impact load behavior of concrete beam: experiment and nonlinear dynamic analysis Materials and structures (2014) 1221-1231
[12] Vadivel T S, Thenmozhi R and Doddurani M 2014 Experimental Behaviour of Waste Tyre Rubber Aggregate Concrete Under Impact Loading Iranian Journal of Science and Technology Transactions of Civil Engineering 38 251-259
[13] Hall M R, Najim K B and Hopfe C J 2012 Transient thermal behaviour of crumb rubber-modified concrete and implications for thermal response and energy efficiency in buildings," Applied thermal engineering 33 77-85
[14] Mohammed B S, Hossain K M A, Swee J T E., Wong G and Abdullahi M 2012 Properties of crumb rubber hollow concrete block Journal of Cleaner Production 23(1) 57-67
[15] Ghizdăveţ B, Ştefan M, Nastac D, Vasile O and Bratu M 2016 Sound absorbing materials made by embedding crumb rubber waste in a concrete matrix Construction and Building Materials,
124 755-763

[16] Holmes N, Browne A and Montague C 2014 Acoustic properties of concrete panels with crumb rubber as a fine aggregate replacement Construction and Building Materials 73 195-204

[17] Thomas B S and Gupta R C 2016 A comprehensive review on the applications of waste tire rubber in cement concrete Renewable and Sustainable Energy Reviews 54 1323-1333

[18] Liu F, Meng L.-y, Ning G-F and Li L-J 2015 Fatigue performance of rubber-modified recycled aggregate concrete (RRAC) for pavement Construction and Building Materials 95 207-217,

[19] Soe K T, Zhang Y and Zhang L 2013 Material properties of a new hybrid fibre-reinforced engineered cementitious composite Construction and Building Materials 43 399-407

[20] Sherwood P 1995 The use of waste and recycled materials in roads International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 7(32) 341A.

[21] Ganjian E, Khorami M and Maghsoudi A A 2009 Scrap tyre-rubber replacement for aggregate and filler in concrete Construction and Building Materials 23(5) 1828-1836

[22] Emiroglu M, Kelestemur M H and Yildiz S 7-9 November 2007 An investigation on ITZ microstructure of the concrete containing waste vehicle tire 8th International fracture conference, Istanbul 453-459

[23] Mohammed B S, Abdullahi M and Hoong C 2014 Statistical models for concrete containing wood chipping as partial replacement to fine aggregate Construction and Building Materials. 55 13-19

[24] Mohammed B S, Fang O C, Hossain K M A and Lachemi M 2012 Mix proportioning of concrete containing paper mill residuals using response surface methodology Construction and Building Materials 35 63-68

[25] Mohammed B S, Achara B E, Nuruddin M F, Yaw M and Zulkefli M Z 2017 Properties of nano-silica-modified self-compacting engineered cementitious composites Journal of Cleaner Production 162 1225-1238

[26] EFNARC, Guidelines for Self-compacting Concrete. The European Federation of Specialist Construction Chemicals and Concrete Systems. May 2005 www.efnarc.org