Mechanical performance of engineered cementitious composite containing crumb rubber at elevated temperature

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Abstract. The growing amount of waste tires has raised ever-increasing environmental concern with the development of the automobile industries. Therefore, utilization of crumb rubber in Engineered Cementitious Composite (ECC) has attracted attention in the construction industry. During elevated temperature, the crumb rubber (CR) melts and creates escape routes for build-up pressure due to moisture in the matrix. This research reports the influence of crumb rubber on the residual compressive strength of ECC after exposure to elevated temperature up to 1000°C. The CR-ECC mixes were developed for utilizing crumb rubber in the percentage of 0%, 1%, 3% and 5%. The CR-ECC fresh mixtures were cast into 50 mm cube moulds and cured for 28 days. The samples were preconditioned and exposed to elevated temperature (23°C, 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, 900°C, 1000°C) for 1-hour duration. Afterward, the samples were evaluated for residual compressive strength. However, there was no explosive spalling recorded in all the specimens used for the experiment.

1. Introduction

Engineered cementitious composite (ECC) is a class of high-performance fibre reinforced cementitious composites (HPFRCC) which has been developed based on the principles of micromechanics to exhibit strain-hardening behaviour when subjected to uniaxial tensile testing [1]. It usually utilizes short-discontinued fibres not exceeding 2% volume fraction to ensure proper dispersion fibre and improved composite action between the fibre and the matrix [2]. Similarly, the coarse aggregate has been fully replaced with fine aggregate in micro-size to achieve better composite interaction between the matrix and fibres. The interaction between the fibre and matrix during the tensile tests encourages tight multiple cracking behaviours which enables the ECC to develop strain more than 5%. The ductility of the ECC is several hundred times that of the normal concrete and enhances the structural reliability during the extreme loading events by maintaining a portion of its tensile capacity [3].

However, achieving the multiple cracking behaviours is governed by the fracture behaviour of the matrix which has an indirect relationship with the energy absorption of the material. Recently, in order to improve the material performance of ECC, crumb rubber has been incorporated. Several studies have been conducted on the utilization of crumb rubber in cementitious composites. In the past
decade, crumb rubber has been utilized in ECC to improve the engineering performance of ECC in structural used and as well encourage the utilization of waste crumb rubber [4, 5].

There are estimated up to 1200 millions of discarded tires by the year of 2030 [6]. It is a significant environmental issue for the disposal of waste tire rubber, and it will also cause potential damages to human health. Introducing crumb rubber into the ECC mixtures can mitigate the environmental issues posed by waste crumb rubber.

The CR-ECC exhibits excellent energy absorbing ability [7]. The inclusion of crumb rubber may further improve the considerable risk of explosive spalling of ECC under elevated temperature. When the crumb rubber melts, the interconnected pore formed in the matrix will create pathways through which build-up pore water pressure can be safely expelled to the outside of the specimen. As a result, CR-ECC may further mitigate the elevated temperature explosive spalling potential in CR-ECC materials. The decrease in the pore pressure inside the ECC further reduces the possibility of an explosion spalling during fire accident.

This study aims to investigate the influence of elevated temperature on CR-ECC. The residual compressive strength and surface physical characteristic of the CR-ECC will be investigated after exposure to elevated temperatures.

2. Materials and methods

2.1. Materials
Ordinary Portland cement (OPC), Type I conforming to the requirement specification of ASTM C150, and Class F fly ash (FA) conforming to the requirement of ASTM C618 were used. Fine aggregate is commonly considered as filler that defines the ECC’s elastic and thermal properties and dimensional stability. Fine aggregate obtained from washed river fine with average size about 450 µm was utilized. Crumb rubber particles processed from waste tire rubber of average size ranging from 600µm to 2.36mm was utilized in the mixtures. High range water reducer superplasticizer termed as modified polycarboxylate-based manufactured by Sika ViscoCrete with a pH value of 6.2 and specific gravity of 1.08 and 0.1% of free chloride content. PVA fibre produced by Kuraray Japan coated with oiling agent 1.2% weight.

2.2. Mix design
In this study, four levels of crumb rubber addition (0%, 1%, 3%, and 5%) by volume of fine aggregate. The ECC was designed at a constant water-cement ratio of 0.32. A total of 132 samples were with different percentage of crumb rubber prepared and tested for the compressive strength after exposure to elevated temperature. The 132 samples were calculated from three samples for each replacement level of crumb rubber, and three samples for each exposure temperatures (i.e. 23°C, 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, 900°C, 1000°C). The mixture proportions are shown Table 1.

| ID | OPC (kg/m³) | FA (kg/m³) | Fine Aggregate (kg/m³) | PVA Fiber (%) | Superplasticizer (%) | Water (kg/m³) | CR (%) |
|----|-------------|------------|------------------------|---------------|----------------------|---------------|--------|
| 1  | 583         | 700        | 467                    | 2             | 0.99                 | 187           | 0      |
| 2  | 583         | 700        | 467                    | 2             | 0.99                 | 187           | 1      |
| 3  | 583         | 700        | 467                    | 2             | 0.99                 | 187           | 3      |
| 4  | 583         | 700        | 467                    | 2             | 0.99                 | 187           | 5      |

2.3. Experimental methods
To prepare the CR-ECC mixtures, the OPC, fly ash, fine aggregate, and crumb rubber were added in a dry state and mixed in Hobart mixer for at least 2 minutes to ensure thorough and uniform dispersion of the constituent materials. Afterward, a mixture of water and superplasticizer was added while the mixer was still rotating for another 3 to 5 minutes. Finally, while the mixer was still rotating, PVA
fibre was added and the mix allowed rotating until the PVA fibre was thoroughly dispersed in the mixture. This stage lasted for another 2 minutes. The fresh mixture was then cast into 50mm cube moulds. After 24 hours, the samples were remoulded, labelled and inserted in the water curing tank for 28 days before testing.

After 28 days of curing, the samples were preconditioned before exposure to various levels of elevated temperatures before testing in compression machine for residual compressive strength. Immediately after curing for 28 days, the samples were kept in an oven at 60℃ for 24 hours to expel the trapped moisture in the matrix. At least 3 samples were tested for each mix at each temperature levels (room temperature (23℃) and elevated temperature (100℃ - 1000℃) in a furnace with a maximum temperature capacity of 1200℃. The samples attained the various maximum temperatures at a rate of 15℃/min and allowed for 1-hour at the predetermined maximum temperature for thermal stability before cooling down naturally to room temperature. The samples were immediately tested for compressive strength in according to the requirement of BS EN 12390-3:2009 after attaining the room temperature.

3. Results and discussion

3.1. Compressive strength

The result of the compressive strengths of ECC at various temperatures is shown in Figure 1. The addition of crumb rubber to ECC causes the reduction of compressive strength which is attributed to the lesser stiffness of the crumb rubber material. When the percentage of the crumb rubber increases, the density of the ECC decreases. This is due to the specific gravity of the crumb rubber which is lower than the fine aggregate, and during the mixing process, the air bubbles may be trapped at the crumb rubber surfaces due to the non-polar property of the rubber. The voids lead to decrease in the density of the CR-ECC specimens.

![Figure 1. Compressive strength of ECC with varying CR and Elevated Temperatures.](image)

3.2. Surface analysis after compressive strength test

The mass of the ECC will be decreased with the increase of the heating temperature. The fine aggregate has a significant influence on mass loss in ECC beyond 500℃ and mass loss insignificant when the temperature above 500℃. As the heating temperature ranges between 500℃ ~ 1000℃, the compressive strength of the ECC decreases rapidly. When the heating temperature is lower than 400℃, it has little impact on the compressive strength of the ECC which still achieve the 80% of the ECC at normal temperature. The result of the compressive strengths of ECC at various temperatures is shown in Figure 1. The addition of crumb rubber to ECC causes the reduction of compressive strength which is attributed to the lesser stiffness of the crumb rubber material. When the percentage of the
crumb rubber increases, the density of the ECC decreases. This is due to the specific gravity of the crumb rubber which is lower than the fine aggregate, and during the mixing process, the air bubbles may be trapped at the crumb rubber surfaces due to the non-polar property of the rubber. The voids lead to decrease in the density of the CR-ECC specimens. In order to investigate the influence of CR on ECC after exposing to the elevated temperature, the figures of the CR-ECC samples at the various temperatures in Figure 2.

**Figure 2.** Compressive failure of the samples with different % of crumb rubber at varying temperatures.
Figure 2 shows the effect of the different heating temperature and different percentage of the crumb rubber on the compressive strength of ECC. From Figure 2, the compressive strength of the ECC decreases with the increase of temperature.

Throughout the experiments, there were no explosive spalling of the samples took place. This is because the crumb rubber melted when subjected to high temperature and the free water in the ECC can escape through the channel.

However, numeral multiple-cracks were developed. The coarse aggregate was completely replaced by the fine aggregate and part of the stress was eliminated. The fine aggregate can improve the fiber bridging because the matrix is more uniform which may lead to a better fiber distribution [8]. Therefore, the multiple cracking performances of the ECC can be enhanced.

3.3. Surface analysis of samples after the heating test
Crack is an incomplete separation into one or more parts with or without space between. The cracks can be classified by width, direction, and depth in term of transverse, longitudinal, vertical, random or diagonal. The cracking in this research is caused by thermal contraction.

![Image 1](image1.png)

a) 0% crumb rubber at 900°C  

b) 5% crumb rubber at 900°C

![Image 2](image2.png)

c) 0% crumb rubber at 700°C  
d) 5% crumb rubber at 00°C

**Figure 3.** Compressive failure of the samples with different % of crumb rubber at varying temperatures.

The crack pattern, crack width and the number of cracks were observed to demonstrate the typical characteristic of ECC materials with the elevated temperature. From Figure 3a and Figure 3b, Figure 3c and Figure 3d, the multiple of cracks is developed in the samples with 0% of crumb rubber compare to the sample with 5% of crumb rubber at 900°C. This is because during the elevating temperature, the crumb rubber can help in the alleviation of the initiation and development of the
cracks in concrete. The crumb rubber will melt approximately 400°C and it can create the channel for the evaporated water in the ECC to escape. Thus, the pore pressure caused by the water pressure can be reduced by adding the crumb rubber to the ECC under higher temperature. Besides, after the exposure to elevated temperature, the ECC with crumb rubber can improve its energy absorption capacity. From the Figure 3 after heating the ECC at 700°C with 0%, 1%, 3% and 5% of crumb rubber, there are some cracking appear on the surface of the samples. The cracks in the 3% and 5% of crumb rubber are not very obvious compared to the 0% and 1% of the ECC with crumb rubber.

Throughout the observation, the more the crumb rubber added the number of cracks and the cracks width will be decreased. The addition of crumb rubber to ECC can further improve the network of the channel which makes the pressure easily to release. The risk of spalling or explosion caused by the elevated temperatures can be reduced by adding the crumb rubber into the ECC.

4. Conclusion
The following conclusions were drawn

1. At all level incorporation of crumb rubber, the compressive strength decreases due to the physical properties of the crumb rubber which will entrap the air on the surface of the crumb rubber and repel the water during the mixing process.
2. At 0% crumb rubber and expose temperature at 100°C, there was increased in compressive strength due to the pozzolanic reaction and the hydration process of the materials.
3. At all crumb rubber level, the failure mood of compressive strength in compression shown ductile behaviour due to the crumb rubber energy absorption.
4. At all crumb rubber level after exposing to the samples, it did not show the explosive spalling due to the melting of crumb rubber provide escape routes for the build of pressure.

References
[1] Li V C, Mishra D K, Naaman A E, Wight J K, LaFave J M and Wu H C 1994 Cem. Based Materials 1
[2] Shah D U, Schubel P J, Licence P, and Clifford M J 2012 Composites Sci & Tech 72
[3] Li M and Li V 2012 High Performance Fiber Reinforced Cement Composites 108
[4] Issa C A and Salem G 2013 Constr & Building Materials 42
[5] Atahan A O and Yücel A Ö 2012 Constr & Building Materials 36
[6] Thomas B S and Gupta R C A 2016 comprehensive review on the applications of waste tire rubber in cement concrete Renewable & Sustainable Energy Reviews, 54
[7] Mohammed B S and Adamu M 2018 Mechanical performance of roller compacted concrete containing crumb rubber and nano silica, Constr & Building Materials, 159
[8] Yu J, Lin J, Zhang Z and Li V C 2015 Constr & Building Materials 99