Fiber-Reinforced Concrete Incorporating Recycled Concrete Fines

Wong Shi Yun

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
COLLEGE OF ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY
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ABSTRACT

Recycling of construction and demolition (C&D) has been one of the paramount topics in the field of exploring new construction material. Applications of recycling these old concrete, mainly the recycled coarse aggregates (RCA), have replaced the aggregates in the production of the concrete and witnessed in numerous structural and non-structural projects such as Samwoh Eco-green building in Singapore\(^1\) and Michigan State University\(^2\).

Recycled concrete fines (RCF) are the fine particles and aggregates also derived from the construction and demolition waste of old concrete. Unfortunately, the potential of RCF has not been totally unleashed due to the high surface area and attached old mortar on the surface of RCF as compared to RCA.

Hence, in this project, the author will explore the potential of RCF by replacing sand with RCF and determine the interfacial properties and the matrix toughness of Engineered Cementitious Composites (ECC) incorporating RCF of different contents and particle sizes. ECC is a class of ultra-ductile fiber reinforced cementitious composites. Through the results, the micromechanics model can be tailored for this new composition of material.


\(^2\) [http://news.msu.edu/story/10401/](http://news.msu.edu/story/10401/)
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CHAPTER 1: INTRODUCTION

1.1 MOTIVATION

First and foremost, it is crucial for us to understand the importance of using the recycled concrete. The reuse of the demolition waste helps to relieve the problems of land scarcity especially for countries like Japan and Singapore. Land will not be wasted for these wastes and instead, other developments such as commercial or residential could be carry out on the same piece of land to cope with the rising population.

Besides relieving the problems of land scarcity, reuse of the recycled concrete also helps to preserves the finite raw materials. Construction industry has accounted for 40% of the total flow of raw materials into the global economy every year – some 3 billion cubic tons. Not only will it cause the rapid depletion of the available raw materials, the materials used and their processing and production will also have a detrimental impact on biodiversity.

In the context of Singapore with no natural resources, recycling of concrete can reduce the dependency of importing raw materials such as the sand. After the case of Indonesia banning the exporting of sand to Singapore in 2007, it have been the ‘wake up’ call for Singapore to be more self-sustainable and less rely on other countries. This has set the atmosphere for research studies to explore new construction material or recycling the materials locally.

Secondly, in order to achieve a sustainable environment, government agencies around the world has established green construction rating systems such as the green mark system in Singapore, LEED in the United States and EEWH in Taiwan. One of the green mark criteria includes the use of recycling and the adoption of building designs, construction practices and materials that are environmentally friendly and sustainable. The use of recycling materials includes Green Cements with approved industrial by-product (such as Ground Granulated Blast furnace Slag (GGBS), silica fume, fly ash, RCA and Washed Copper Slag (WCS). However, this criterion only involved the use of the RCA but not the RCF. Furthermore, many research programs have been done involving the use of RCA only. Therefore, for this project, we will replace Recycled Concrete Fines (RCF) instead of using sand in the production of Engineered Cementitious Composites (ECC).

3 http://www.businessandbiodiversity.org/construction.html
1.2 PROJECT OBJECTIVES

This project aims to study the Micromechanical of RCF-ECC. This includes determining the interfacial properties and the matrix toughness properties of RCF- ECC. Specimens will be cast based on different compositions of the RCF adding into ECC and perform various tests like Matrix Toughness Test and Single Fiber Pull–Out Test. The results will be used to evaluate the effects of RCF content and particle size on ECC tensile properties based on the micromechanics model.

1.3 PROJECT SCOPE

The main scope of the project consists of:

- Determine the content of RCF in terms of the RCF to cement ratio for the specimens.
- Casting of the specimens according to different particle size of RCF.
- To develop and conduct the matrix toughness test.
- To develop and conduct the single fiber pull-out test.

1.4 REPORT ORGANIZATION

This report is organized in the following chapters:

- Chapter 1 provides an introduction to the project which covers the motivation, objectives and scope of the project.
- Chapter 2 reviews the theory involved such as the Micromechanical Model, RCF properties, slag, ECC and test methods.
- Chapter 3 discusses about the experiment program with different compositions of the RCF adding into ECC and the various tests to be conducted.
- Chapter 4 reviews and evaluates the results for the matrix toughness test and single fiber pull-out test.
- Chapter 5 summarizes the work done in the project and listed some recommendations for future work.
CHAPTER 2: LITERATURE REVIEW

2.1 ENGINEERED CEMENTITIOUS COMPOSITES (ECC)

As the traditional concrete’s lack of durability and failure under tension, both stemming from brittle behavior, have been a pushing factor in the development of ECC. ECC is defined as a class of ultra ductile fiber reinforced cementitious composites developed for structural and non-structural applications. Example of the structural application is the Mitaka dam near Hiroshima. The components of ECC are similar to that of fiber reinforced concrete, including cement, sand, water, fiber, and a few chemical additives. The enabling design for ECC is the micromechanics model which will be further elaborated in section 2.2.

2.1.1 PROPERTIES OF ECC

This section will review some of the properties of ECC which is related in this project for RCF-ECC.

As stated in [6], one of the unique features of ECC is its ultra high ductility. This means that the structural failure by fracture is significantly less likely to occur in comparison to normal concrete or fiber-reinforced concrete (FRC). In the experiments demonstrated by Ohno shear beam tests in [7], ECC has excellent shear capacity. When under shear, multiple cracking with cracks aligned normal to the principal tensile direction were developed. As mentioned previously that ECC is ultra high ductility, the shear response is correspondingly ductile. This results in less or no conventional steel shear reinforcements needed for R/ECC elements. This was further exhibited in [8] when concrete were replaced by ECC in the beams without shear reinforcement, and demonstrated superior performance to HSC beams with closely spaced steel stirrups.

Another property of ECC is the tight crack width control which leads to the advantageous applications on structural durability and the minimization of repair needs after serve loading of an ECC element. Inelastic deformation occurs when an ECC structural element is loaded to beyond the elastic range. The inelastic deformation is associated with micro-cracking with continued load carrying capacity across these cracks. The cracks width is dependent on the type of fiber and interface properties.
2.2 MICROMECHANICAL MODEL

Micromechanics model is a tool to link the material microstructures to ECC tensile ductility behavior and forms the core of materials design theory. It guides the composite and material optimization of ECC through properly tailored of the Fiber, Matrix and the Interface properties.

Table 2.1: ECC Constituents and Properties

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>Elastic modules, tensile strength, length, diameter, volume fraction</td>
</tr>
<tr>
<td>Matrix</td>
<td>Fracture Toughness, Elastic Modules, initial flaw size</td>
</tr>
<tr>
<td>Interface</td>
<td>Interfacial frictional bond, interfacial chemical bond, slip hardening coefficient, snubbing coefficient, strength reduction factor</td>
</tr>
</tbody>
</table>

The composite tensile strain-hardening behavior is controlled by the fiber bridging properties which is referred to the $\sigma-\delta$ curve in fig 2.1

![Figure 2.1: The $\sigma-\delta$ curve. Hatched area represents maximum complimentary energy $J_b$. Shaded area represents crack tip toughness $J_{tip}$.](image-url)
There are two fundamental requirements that governed the strain-hardening behaviors. First requirement is the steady-state flat crack extension that prevail under tension, which requires the crack tip toughness $J_{\text{tip}}$ to be less than the complementary energy $J_b'$ calculated from the bridging stress $\sigma$ versus crack opening $\delta$ curve, as illustrated in [10],

$$J_{\text{tip}} \leq \sigma_0 \delta_0 - \int_0^{\delta_0} \sigma(\delta) d\delta \equiv J_b' \quad (1)$$

$$J_{\text{tip}} = \frac{K_m^2}{E_m} \quad (2)$$

$\sigma_0$ is the maximum bridging stress corresponding to the opening $\delta_0$, $K_m$ is the matrix fracture toughness, and $E_m$ is the matrix Young’s modulus. The stress-crack opening relationship $\sigma-\delta$, is derived by using analytic tools of fracture mechanics, micromechanics, and probabilistic [15]. In particular, the energetic of tunnel crack propagation along fiber/matrix is used to quantify the debonding process and the bridging force of a fiber with given embedment length. To describe the randomness of fiber location and orientation with respect to a crack plane, probabilistic is introduced. The random orientation of fiber also needed to take into the account the mechanics of interaction between an inclined fiber and the matrix crack. As a result, the $\sigma-\delta$ curve is expressible as a function of micromechanics parameters, including interface chemical bond $G_d$, interface frictional bond $\sigma_0$, and slip-hardening coefficient $\beta$ which account for the slip-hardening behavior during fiber pull-out. $G_d$ is used to quantify the fracture energy required for interface debonding and $\sigma_0$ describes the friction force during sliding. Furthermore, snubbing coefficient $f$ and strength reduction factor $f$ are also introduced to account for the interaction between the fiber and matrix as well as the reduction of fiber strength when pulled at an inclined angle. In addition, the $\sigma-\delta$ curve is also governed by the matrix young modulus $E_m$, fiber content $V_f$, and fiber diameter $d_f$, length $L_f$, and Young’s modulus $E_f$.

Another requirement for the strain-hardening behavior is the matrix first cracking strength $\sigma_{fc}$ must not exceed the maximum fiber bridging strength $\sigma_0$.

$$\sigma_{fc} \leq \sigma_0 \quad (3)$$

where $\sigma_{fc}$ is determined by the matrix fracture toughness $K_m$, preexisting internal flaw size $a_0$, and the $\sigma-\delta$ curve. Eq. (1) governs the crack propagation mode, while Eq. (3) controls the initiation of cracks. In order to achieve ductile strain-hardening behavior, both Eq. (1) and (3) are needed to be satisfied else, normal tension-softening behavior will be resulted. More details are covered in [9].
For this project, experiments will be carried out to determine how the difference in the RCF particles size and content will change the matrix toughness and the fiber-matrix interfacial properties for RCF-ECC. The results will be used to evaluate the effects of RCF content and particle size on ECC tensile properties based on the micromechanics model.

### 2.3 RECYCLED CONCRETE FINES

Recycled Concrete Fines are fine aggregates and particle size from the construction and demolition waste of old concrete. Most of the applications and researches involved the usage of RCA and not RCF as mainly due to RCF’s larger water absorption which is attributed by high surface area and the old mortar attached to the particles and also prevent the proper bonding between the matrix and aggregate [2][3].

#### 2.3.1 PROPERTIES OF RECYCLED CONCRETE FINES

It was reported in [1] that the increase content of the RCF will cause the increase of shrinkage and a reduction of compressive strength. The reduction of the compressive strength also occurred in [5]. In [6], the experiments results showed that the reduction in the modulus of elasticity was reduced with the increasing RCF replacement ratio. Experiments were also conducted to demonstrate that with the increase of the RCF content, the water absorption of RCF was higher than normal fine aggregate [5].

This will give a basic understanding the water absorption rate for the RCF and facilitate the calculation of the content of RCF in terms of the RCF to cement ratio.

In addition, by adding RCF into ECC, it may become an advantage due to lower matrix toughness and a lower matrix tensile strength given by the weak bonding between RCF particles and matrix. Hence, it will help the composite to satisfy Eqns (1) and (3).

### 2.4 SLAG

In the construction industry today, the use of slag cement is growing rapidly due to its superior mechanical strength and durability than Portland cement. To further incorporate the sustainability consideration of this project, slag being the supplementary cementitious materials, is added to RCF-ECC as to compensate one of the disadvantages of ECC- high cement content, which is typically two to three times higher than conventional concrete. Due to the pozzolanic reaction and the filler effect, slag composite is selected to be 80% and keep constant in all the mixes. Since slag is available locally unlike coal fly ash, and thus, fulfilled the part of sustainability, it is hence selected for this project. The age of the specimens for this project is chosen to be 90days as with the addition of the slag, the rate of hydration is slower.
than normal concrete. Hence, the strength gain may still show significant change at the later ages. [20]

### 2.5 MATRIX TOUGHNESS TEST

To obtain the J_{IP} values, Matrix toughness test is conducted to assess the matrix properties that are part of the component to determine the strain-hardening behavior.

The matrix toughness test in this project will be carried out based on the method proposed in [11].

A typical load-CMOD curve is shown in Figure 2.2, from which we obtained critical CMOD (CMOD_{c}) and critical (peak) load P_{c}.

![Figure 2.2: typical load- CMOD curve](image)

The value of P_{c} and CMOD_{c} are substituted into Eq (4), to calculate the critical crack length \( c \) at the peak load. As suggested in [16], to obtain the fracture toughness of the matrix \( K_{ic} = K_{m} \), \( c \) and the peak load \( P_{c} \) are further substituted into Eq (5).

\[
\begin{align*}
\text{CMOD}_{c} &= \frac{P_{c}}{BE} \left[ 11.56 \left( 1 - \frac{ac}{D} \right) \right]^{2} - 9.397 \\
K_{ic} &= (K_{m}) = \frac{P_{c}}{B \sqrt{D}} F(\alpha) \\
F(\alpha) &= 29.6 \alpha^{0.5} - 185.5 \alpha^{1.5} + 665.7 \alpha^{2.5} - 1017.0 \alpha^{3.5} + 638.9 \alpha^{4.5} \\
\alpha &= \frac{ac}{D}
\end{align*}
\]

Where B is the thickness of the specimen; D is the depth of specimen; \( a_{c} \) is the effective crack length. However, \( a_{c} \) is used instead of \( c \) for this calculation. \( F(\alpha) \) is being derived in [17] for the conventional wedge splitting specimens (eg. L/D = 1.2).

In this project, by varying the particle content and size, it will affect the value of matrix fracture toughness. As mentioned in [18] & [19], the increase of the particle size will increase
the fracture toughness due to the increase in the resistance to the propagating crack. Hence, it is expected that by adding different size of the fines, it should also exhibit similar result. The Young’s modules values are treated as constant (20GPa) in this research for the calculation of eq (4).

2.6 SINGLE FIBER PULL-OUT TEST

To obtain the Jb’ values and formulate the $\sigma$-$\delta$ curve; single fiber pull-out test is used to directly assess the fiber/mortar interfacial bond properties by pulling a single fiber out of its surrounding matrix. The bond properties are mainly described by chemical debonding energy, Gd, of frictional bond strength at the onset of fiber slippage, $\delta_0$, and of slip-hardening / slip softening coefficient, $\beta$.

The general profile of a single fiber pullout curve can be decomposed into three major regimes shown in Fig 2.3 described in [14].

![Figure 2.3: General Profile of a Single Fiber Pullout Curve](image)

At the initial stage, a stable fiber debonding process occurs along the fiber/matrix interface shown in Fig 2.3a. The load resisted by the fiber is increased up to $P_a$. Note that the fiber embedded end, $e$, does not move. The debond length, $d$, increases towards $d = e$. This displacement corresponds only to the elastic stretching of the debonded fiber segment and of the fiber-free length.

If the load drop is significant and sudden, from $P_a$ to $P_b$, it indicates that the chemical bond between the fiber and the matrix was broken. Hence, the chemical debonding energy value, $G_{de}$, is calculated from the $Pa$ to $Pb$ difference, shown in (8).
\[ G_d = \frac{2(P_a - P_b)^2}{\pi^2 E_f d_f^2} \]  \hspace{1cm} (8)

Where \( P_a \) = peak load during the debonding process; \( E_f \) = fiber axial Young’s modulus; and \( d_f \) = fiber diameter.

At point \( P_b \), the embedded fiber end is just debonded shown in Fig 2.3.b. From the \( P_b \) value, the frictional bond strength \( \tau_0 \) at the onset of fiber slippage (\( S' = 0 \) at \( P_b \)) is calculated as follows;

\[ \tau_0 = \frac{P_b}{\pi d_f l_e} \]  \hspace{1cm} (9)

At the final regime, the fiber load is resisted by frictional forces shown in Fig 2.3.c, the fiber can undergo sliding with either slip hardening, constant friction or slip-softening effect, which is characterized by the coefficient \( \beta \). Slip-hardening occurs often with polymer fibers as they are damaged and caused a jamming effect inside the matrix. This is due to the fiber being less hard than the surrounding matrix. This will result in the increase load resisting fiber pullout. Alternatively, slip-softening occurs when the fiber hardness is higher than the surrounding matrix. Hence, the \( \beta \) value is then calculated from the initial (\( S' \) approaching 0) slope of the \( P \) versus \( S' \) curve and using

\[ \beta = \left( \frac{d_f}{l_e} \right) \left[ \frac{1}{\tau_0 \pi d_f} \left( \frac{\Delta P}{\Delta S'} \right) \right]_{S' \to 0} + 1 \]  \hspace{1cm} (10)

Which is under the assumption that it is a linear slip dependence of the friction , so that

\[ \tau = \tau_0 \left( 1 + \beta \frac{S'}{d_f} \right) \]  \hspace{1cm} (11)

Therefore, in this project, by vary the content of RCF and the size of the particles, the chemical debonding energy, \( G_d \), of frictional bond strength at the onset of fiber slippage, \( \tau_0 \), and of slip-hardening / slip softening coefficient, \( \beta \) will be affected and, hence the fiber bridging law \( \sigma-\delta \).
CHAPTER 3: EXPERIMENTAL PROGRAM

3.1 MATERIALS

A brand of green cement Lafarge Phoenix was used, which complies with the requirements specified in the British Standard EN 197-1: 2000 CEM II/B-M 32.5 R.

The recycled concrete fines (RCF) were supplied by Pan-United Concrete Ltd in Singapore. For the experiment, to achieve well-graded particles and ensure good mix, RCF are prepared based on fuller-curve shown in fig 3.1. Fuller’s curve is given by the following formula for single fiber pullout test:

$$P_i = \left(\frac{d_i}{D}\right)^n \times 100\%$$  (12)

Where D represents the maximum fine particle size; \(d_i\) represents a given particle size, and \(P_i\) denotes the percent of the particle that is finer than \(d_i\). A typical value for the exponent \(n\) is 0.50.

Table 3.1: Percentage Passing of Particle Size

<table>
<thead>
<tr>
<th>Particle size range</th>
<th>0.3</th>
<th>0.6</th>
<th>1.18</th>
<th>2.360</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.3mm</td>
<td>100%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0-0.6mm</td>
<td>70.7%</td>
<td>100%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0-1.18mm</td>
<td>50.4%</td>
<td>71.3%</td>
<td>100%</td>
<td>-</td>
</tr>
<tr>
<td>0-2.36mm</td>
<td>35.7%</td>
<td>50.4%</td>
<td>70.7%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 3.1: Particle size Distribution of RCF
To take into account of the difference in the absorption rate by different particle sizes, the absorption of a particle in SSD state is calculated by the following equation;

Water absorption rate = \( \frac{M_{\text{SSD}} - M_{\text{OD}}}{M_{\text{OD}}} \)  

(13)

Where \( M_{\text{SSD}} \) is the weight of water in the particle under the SSD condition and \( M_{\text{OD}} \) is the weight of the particle in the oven-dry state.

Table 3.2: Water Absorption Rate

<table>
<thead>
<tr>
<th>Mass</th>
<th>Air Dry(AD)</th>
<th>Oven Dry (OD)</th>
<th>Water</th>
<th>SSD</th>
<th>% of Water</th>
<th>Water Absorption Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-0.3mm</td>
<td>200</td>
<td>180</td>
<td>45</td>
<td>225</td>
<td>25</td>
<td>0.125</td>
</tr>
<tr>
<td>0.3-0.6mm</td>
<td>200</td>
<td>189</td>
<td>30</td>
<td>219</td>
<td>15.9</td>
<td>0.095</td>
</tr>
<tr>
<td>0.6-1.18mm</td>
<td>200</td>
<td>187</td>
<td>25</td>
<td>212</td>
<td>13.4</td>
<td>0.06</td>
</tr>
<tr>
<td>1.18-2.36mm</td>
<td>200</td>
<td>189</td>
<td>20</td>
<td>209</td>
<td>10.6</td>
<td>0.045</td>
</tr>
</tbody>
</table>

Short polyvinyl alcohol fiber (PVA) of 8mm long was used. Properties of the PVA fiber as listed in table 3.3.

Table 3.3: Properties of PVA Fiber

<table>
<thead>
<tr>
<th>Diameter ( d_f ) (mm)</th>
<th>Tensile strength ( \sigma_f ) (MPa)</th>
<th>Elongation ( \varepsilon_f ) (%)</th>
<th>Young’s modulus ( E_f ) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.044</td>
<td>1640</td>
<td>5.3</td>
<td>41.1</td>
</tr>
</tbody>
</table>

The chemical admixture used was a super plasticizer (W.R. Grace, ADVA 181) available commercially in Singapore.
The slag used in this project was from EnGro’s VCEM GGBS production, which complies with SS EN15167: 2008 (BS EN 15167: 2006).

Table 3.4: Physical properties and chemical compositions of slag

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MgO, %</td>
<td>10.9</td>
<td>Fineness (m²/kg)</td>
<td>436</td>
</tr>
<tr>
<td>SO₃, %</td>
<td>1.3</td>
<td>Initial Setting Time(Mins)</td>
<td>130</td>
</tr>
<tr>
<td>Cl⁻, %</td>
<td>0.01</td>
<td>Activity index(%) -7 days</td>
<td>80.2</td>
</tr>
<tr>
<td>S, %</td>
<td>1.0</td>
<td>Activity index(%) -28 days</td>
<td>98.2</td>
</tr>
<tr>
<td>CaO+MgO+SiO₂, %</td>
<td>83.5</td>
<td>Loss on Ignition, %</td>
<td>0.18</td>
</tr>
<tr>
<td>(CaO+MgO)/SiO₂, %</td>
<td>1.37</td>
<td>Moisture Content, %</td>
<td>0.13</td>
</tr>
</tbody>
</table>
3.2 MIX PROPORTION

The specimens will be cast based on the mix proportion in section 3.2.1 and 3.2.1 respectively. 3 specimens for each mix will be cast for matrix toughness test and 24 specimens for each mix for single pullout test.

3.2.1 MIX PROPORTION FOR MATRIX TOUGHNESS TEST

RCF particle size used: 0-0.6mm

Table 3.5: Mix Proportion for Matrix Toughness Test

<table>
<thead>
<tr>
<th>Group</th>
<th>Cement</th>
<th>Water</th>
<th>RCF</th>
<th>W/C</th>
<th>RCF/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>9.56</td>
<td>3.32</td>
<td>0.00</td>
<td>0.35</td>
<td>0.00</td>
</tr>
<tr>
<td>M2</td>
<td>8.52</td>
<td>2.76</td>
<td>1.89</td>
<td>0.32</td>
<td>0.22</td>
</tr>
<tr>
<td>M3</td>
<td>7.66</td>
<td>2.32</td>
<td>3.40</td>
<td>0.3</td>
<td>0.44</td>
</tr>
<tr>
<td>M4</td>
<td>6.97</td>
<td>1.96</td>
<td>4.64</td>
<td>0.28</td>
<td>0.67</td>
</tr>
<tr>
<td>M5</td>
<td>6.39</td>
<td>1.66</td>
<td>5.67</td>
<td>0.26</td>
<td>0.89</td>
</tr>
<tr>
<td>M6</td>
<td>5.90</td>
<td>1.39</td>
<td>6.55</td>
<td>0.24</td>
<td>1.11</td>
</tr>
</tbody>
</table>

3.2.2 MIX PROPORTION FOR SINGLE FIBER PULLOUT TEST

Table 3.6: Mix Proportion for Single Fiber Pullout Test

<table>
<thead>
<tr>
<th>Group</th>
<th>RCF size/mm</th>
<th>Cement</th>
<th>Slag</th>
<th>Water/B(^1)</th>
<th>RCF/B(^1)</th>
<th>SP(^2)/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-1</td>
<td>0-0.6</td>
<td>1</td>
<td>0.8</td>
<td>0.25</td>
<td>0</td>
<td>0.005</td>
</tr>
<tr>
<td>RS-2</td>
<td>0-0.6</td>
<td>1</td>
<td>0.8</td>
<td>0.25</td>
<td>0.2</td>
<td>0.008</td>
</tr>
<tr>
<td>RS-3</td>
<td>0-0.3</td>
<td>1</td>
<td>0.8</td>
<td>0.25</td>
<td>0.5</td>
<td>0.008</td>
</tr>
<tr>
<td>RS-7</td>
<td>0-0.3</td>
<td>1</td>
<td>0.8</td>
<td>0.25</td>
<td>0.2</td>
<td>0.008</td>
</tr>
<tr>
<td>RS-8</td>
<td>0-1.18</td>
<td>1</td>
<td>0.8</td>
<td>0.25</td>
<td>0.2</td>
<td>0.008</td>
</tr>
<tr>
<td>RS-9</td>
<td>0-2.36</td>
<td>1</td>
<td>0.8</td>
<td>0.25</td>
<td>0.2</td>
<td>0.008</td>
</tr>
</tbody>
</table>

1.B=cement+slag; 2. SP=superplasticizer

Table 3.7: Mix Composition for Single Fiber Pullout Test (Unit: kg/m\(^3\))

<table>
<thead>
<tr>
<th>Group</th>
<th>RCF size/mm</th>
<th>Cement</th>
<th>Slag</th>
<th>Water/B(^1)</th>
<th>RCF/B(^1)</th>
<th>SP(^2)/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-1</td>
<td>0-0.6</td>
<td>339.4</td>
<td>1357.5</td>
<td>424.2</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>RS-2</td>
<td>0-0.6</td>
<td>292.3</td>
<td>1169.4</td>
<td>365.4</td>
<td>292.3</td>
<td>12</td>
</tr>
<tr>
<td>RS-3</td>
<td>0-0.6</td>
<td>242</td>
<td>968.2</td>
<td>302.6</td>
<td>605.1</td>
<td>10</td>
</tr>
<tr>
<td>RS-7</td>
<td>0-0.3</td>
<td>292.3</td>
<td>1169.4</td>
<td>365.4</td>
<td>292.3</td>
<td>12</td>
</tr>
<tr>
<td>RS-8</td>
<td>0-1.18</td>
<td>292.3</td>
<td>1169.4</td>
<td>365.4</td>
<td>292.3</td>
<td>12</td>
</tr>
<tr>
<td>RS-9</td>
<td>0-2.36</td>
<td>292.3</td>
<td>1169.4</td>
<td>365.4</td>
<td>292.3</td>
<td>12</td>
</tr>
</tbody>
</table>

1.B=cement+slag; 2. SP=superplasticizer.
3.3 MIXING

A Hobart mixer with 20L capacity was used in preparing the ECC mixtures. Cement and slag were first mixed for five minutes. The superplasticizer was poured in the water first and stirred thoroughly before pouring into the dry mixture and allowed them to mix for another five minutes. The RCF are added with the calculated amount of water separately from the wet mixture. Thereafter, the RCF was then added into the mixture and mixed for another 10 minutes. The liquefied mortar matrix should be uniformly mixed and reached the required fluidity before pour into the respective moulds for both Matrix toughness and Single fiber pull-out test. Vibration of the mould after pouring is needed to remove the air bubbles trapped inside the mortar.

3.4 MATRIX TOUGHNESS TEST

3.4.1 PREPARATION OF SPECIMENS AND LOADING DEVICE

The geometry and size of the specimens are shown in Fig 3.2 below. The initial notch was made by inserting a 1mm steel plate inside the specimen during the casting and taking the plate out after two day. After which, all specimens were cured in water until one day prior to the testing. The specimens are then removed from water and left for air dry. To facilitate the crack propagation, a 20mm groove was made by inserting the trigonal prism at each outer side. Clip gauges and loading devices were prepared before the testing for each specimen.

![Figure 3.2: Dimension of Specimen: (a) Front View; (b) Top View; (c) Side View](image-url)
3.4.2 TESTING PROCEDURE

The specimen with loading devices is shown in figure 3.3a and 3.3b. The machine used in this project will be Instron 5569. In order to increase the accuracy of the test, a 200KN capacity load cell was used for this test.

The steps for this test are:

1. Attach the knife edges on the specimen by using gauge cement with acceptable stability to support the clip gauge.
2. Place the specimen in the machine and move the actuator of the machine until the wedge enters between the bearings.
3. Apply load. The specimens were preloaded up to 100KN and unloaded to zero point with a displacement rate of 0.05mm/min. This procedure was carried out twice and the average value will be used.
4. During a test, the load in the vertical direction, Fv, and the crack mouth opening displacement (CMOD) are observed and recorded in the load-CMOD diagram. Only when the load-CMOD response is stable, the result will then consist valid.

Figure 3.3a: Schematic View of the Test Set-up  Figure 3.3b: Actual Test set-up
3.5 SINGLE FIBER PULL-OUT TEST

3.5.1 CASTING OF SPECIMENS

The casting process and preparation for testing will be the main focus in this section. The mould is made to the dimension of 90 x 80 x 5 mm for the base plate and for the internal 40 x 30 x 5 mm as shown in Fig 3.4. More details about the mould are shown in [14].

![Setup of the Mould and Fibers](image.png)

Casting is done in the order shown in Fig 3.5.

![Cross Section of the Mould and the Working Flow](image.png)

Figure 3.4: Setup of the Mould and Fibers (Courtesy of Li JunXia NTU)

Figure 3.5: Cross Section of the Mould and the Working Flow
Demoulding is done simply unscrewing of the nails on $U_b$ and $U_f$.

For the preparation of testing, small specimens containing 1 fiber are sawn out of the demoulded specimen in Fig 3.6.b by using a precise diamond saw with the thickness of the small specimen, around $L \leq 1$mm to ensure full debonding.
3.4.2 TESTING PROCEDURE

A 10N load cell is used to measure the pullout force for the fiber in this test with a displacement rate of 0.06mm/min. The base of the specimen is glued onto the specimen mould. The fiber is also glued to the aluminum plate at the top before reinforced by a tape. This is to prevent bending of the fiber during testing or sudden break of the fiber while setting the machine and make sure the accuracy of the alignment of the fiber as mentioned in [14]. The fiber-free length was kept at a maximum of 1mm. In addition, the fiber free length is adjusted by the x-y table until it is approximately perpendicular to the specimen mount.

The results are then plotted in the displacement, S, or x-axis of the pullout curves where the displacement is recorded by the actuator. Note that as mentioned in [12], for determining $\theta$ and $G_d$, the accuracy of the load is of a main determiner rather than the displacement, whereas for $\beta$, it is vice versa. The influence of elastic stretching of the fiber on the accuracy of $\beta$ is expected to be minimal for the measurement of displacement for $\beta$ which are in the order of 0.1 to 1mm.
CHAPTER 4: RESULTS AND DISCUSSION

4.1 SINGLE FIBER PULLOUT TEST

4.1.1 EVALUATION ON THE EFFECTS ON RCF CONTENT ON THE INTERFACIAL PROPERTIES

The following shows the results of the interfacial properties by varying in RCF content, obtained experimentally.

Figure 4.1: Gd vs RCF content

Figure 4.2: \( \tau \) vs RCF content
Figure 4.3: $\beta$ vs RCF content

Table 4.1: Average value of Gd, $\beta$, and $Jb'$ (different RCF content)

<table>
<thead>
<tr>
<th>RCF Size (0-0.6mm)</th>
<th>Gd (J/m$^2$)</th>
<th>$\beta$ (Mpa)</th>
<th>$Jb'$ (J/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS1 RCF/B=0</td>
<td>1.0162</td>
<td>0.5196</td>
<td>10.14</td>
</tr>
<tr>
<td>RS2 RCF/B=0.2</td>
<td>0.5475</td>
<td>0.2504</td>
<td>11.25</td>
</tr>
<tr>
<td>RS3 RCF/B=0.5</td>
<td>0.2623</td>
<td>0.1956</td>
<td>11.47</td>
</tr>
</tbody>
</table>
In Fig 4.1 and Fig 4.3, both the Gd and the β show a decreasing trend for increasing amount of RCF content for the mix while Fig 4.2, it shows that the σ is independent of the RCF content as the average values are approximately the same. With Fig 4.1 to Fig 4.3, it formulates the σ-δ curve in Fig 4.4. As mentioned in [6], the larger the complementary energy is, the more conducive it is to achieve the strain-hardening behavior. In Fig 4.4, it exhibits that the area of the complementary energy increases from RS1 to RS3. In addition, in Fig 4.5, the J’b values increase as the RCF content increases. These results coincide with the aim to obtain larger J’b so that the tendency violating the inequality sign for eqn (1) will decrease in order to achieve the strain-hardening behavior.
4.1.2 EVALUATION ON THE EFFECT ON RCF SIZE ON THE INTERFACIAL PROPERTIES

The following shows the results of the interfacial properties by varying in RCF particle size, obtained experimentally.

Figure 4.6: Gd vs RCF Size

Figure 4.7: T vs RCF Size
Figure 4.8: $\beta$ vs RCF Size

<table>
<thead>
<tr>
<th>RCF Content (0.2)</th>
<th>Gd (J/m^2)</th>
<th>$\beta$ (Mpa)</th>
<th>$Jb'$ (J/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS7 (0-0.3mm)</td>
<td>1.4241</td>
<td>0.4582</td>
<td>9.75</td>
</tr>
<tr>
<td>RS2 (0-0.6mm)</td>
<td>0.5475</td>
<td>0.2504</td>
<td>11.25</td>
</tr>
<tr>
<td>RS8 (0-1.18mm)</td>
<td>0.5697</td>
<td>0.1760</td>
<td>12.72</td>
</tr>
<tr>
<td>RS9 (0-2.36mm)</td>
<td>0.2438</td>
<td>0.3180</td>
<td>13.37</td>
</tr>
</tbody>
</table>

Table 4.2: Average value of Gd, $\beta$ and $Jb'$ (different RCF size)
Similarly for the RCF particle size, both the Gd and the β also show a decreasing trend for increasing amount of RCF particle size for the mix as shown in Fig 4.6 and Fig 4.8. As for Fig 4.7, it also shows that the ... are approximately the same. In Fig 4.8, it exhibits that the area of the complementary energy increases from RS7 to RS9. In addition, in Fig 4.10, the J’b values increase as the RCF particle size increase. With these, it satisfied the aim to obtain larger J’b to achieve the strain-hardening behavior.
4.2 MATRIX TOUGHNESS TEST

The following shows the experimental results obtained from the test plotted CMOD against load. The $P_c$ and $CMOD_c$ of each mix are hence determined from the graph. The $P_c$ and $CMOD_c$ shown in table 4.3 tabulated are the average values in each mix.

![Figure 4.12: Experimental results for M1](image)
Figure 4.13: Experimental results for M2

Figure 4.14: Experimental results for M3
Figure 4.15: Experimental results for M4

Figure 4.16: Experimental results for M5
Table 4.3: Value of $P_c$, $CMOD_c$, $K_m$ and $J_{tip}$

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c$ Unit: N</td>
<td>333.46</td>
<td>743.72</td>
<td>872.58</td>
<td>818.95</td>
<td>1358.55</td>
<td>1522.54</td>
</tr>
<tr>
<td>$CMOD_c$ Unit: m</td>
<td>0.04</td>
<td>0.05</td>
<td>0.04</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>$K_m$ Unit: MPa.m$^{1/2}$</td>
<td>0.256</td>
<td>0.426</td>
<td>0.424</td>
<td>0.458</td>
<td>0.598</td>
<td>0.620</td>
</tr>
<tr>
<td>$J_{tip}$ (Eq2) Unit: J/m$^2$</td>
<td>3.28</td>
<td>9.07</td>
<td>8.99</td>
<td>10.4</td>
<td>17.88</td>
<td>19.22</td>
</tr>
</tbody>
</table>

$E = 20$ GPa
Figure 4.11 to 4.16 exhibits the experimental results for the $P_c$ and CMOD for the 6 mixes with different content of the recycled concrete fines and the average values $P_c$ and CMOD are tabulated in Table 4.3. As shown from Figure 4.11 to Figure 4.16, all the curves correspond to the general trend showed in Figure 2.2 for a typical load-CMOD curve. Hence, it proves the validity of the experimental results. The $P_c$ increases from M1 to M6 as the amount of the RCF content increases. This is due to the resistance for crack propagation as higher RCF increases the fracture resistance. This is coincide as illustrated in [23], which demonstrated influence of mortar, aggregate, and interfacial fracture properties on the performance of concrete composites.

Table 4.4: Value of $K_m$, W/C and RCF content

<table>
<thead>
<tr>
<th></th>
<th>$K_m$</th>
<th>W/C</th>
<th>RCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.256</td>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>M2</td>
<td>0.426</td>
<td>0.32</td>
<td>0.22</td>
</tr>
<tr>
<td>M3</td>
<td>0.424</td>
<td>0.3</td>
<td>0.44</td>
</tr>
<tr>
<td>M4</td>
<td>0.458</td>
<td>0.28</td>
<td>0.67</td>
</tr>
<tr>
<td>M5</td>
<td>0.598</td>
<td>0.26</td>
<td>0.89</td>
</tr>
<tr>
<td>M6</td>
<td>0.620</td>
<td>0.24</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Figure 4.18: Graph of RCF content against $K_m$
The $K_m$ and $J_{tip}$ values of 6 mixes with different content of the recycled concrete fines are summarized in table 4.4 and a graph plotted of RCF content against $K_m$ in figure 4.17 to demonstrate the trend. Due to the high water absorption rate of the RCF, the water content in the mix decreases with the increase of RCF used. Hence, the results obtained are due to both the water content and the RCF used. However, the effect of water content can be separated by using the values in [21] & [24] to estimate the water content effect. Therefore, this result in the two graphs in Fig 4.17.

In Figure 4.17, it shows that the increase in the $K_m$ values increases with the RCF content. In [6], it reported the results of theoretical calculations and experimental research based on the micromechanics to investigate the effect of the replacement with fine aggregate on the strain hardening behavior of fiber reinforced cementitious composites. With the addition of the fine aggregates content, it increases the matrix toughness. This trend is also exhibited in figure 4.17 and table 4.4 with the use of RCF into ECC.

### 4.3 MICROMECHANICS MODEL

#### 4.3.1 EVALUATION ON THE OVERALL EFFECT ON RCF CONTENT

<table>
<thead>
<tr>
<th>RCF content</th>
<th>$J'$ (J/m2)</th>
<th>$J_{tip}$ (J/m2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS1</td>
<td>0</td>
<td>10.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.14</td>
</tr>
<tr>
<td>RS2</td>
<td>0.2</td>
<td>11.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.10</td>
</tr>
<tr>
<td>RS3</td>
<td>0.5</td>
<td>11.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.75</td>
</tr>
</tbody>
</table>
In order to evaluate the overall effect on the RCF content in ECC, it depends on the amount of increment for both $J_b'$ and $J_{tip}$ values. In Fig 4.18, the gradient of $J_{tip}$ vs RCF content is steeper as compared to $J_b'$ vs RCF content. The overall results plotted in figure 4.19 showing a decreasing trend. The decreasing trend of the $J_b'/J_{tip}$ is not desirable to achieve the strain-hardening behavior.

### 4.3.2 EVALUATION ON THE OVERALL EFFECT ON RCF

#### PARTICLE SIZE

Table 4.6: Values for $J_b'$ and $J_{tip}$ (RCF Particle size)

<table>
<thead>
<tr>
<th>RCF size (mm)</th>
<th>$J_b'$ (J/m$^2$)</th>
<th>$J_{tip}$ (J/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS7</td>
<td>0.3</td>
<td>9.75</td>
</tr>
<tr>
<td>RS2</td>
<td>0.6</td>
<td>11.25</td>
</tr>
<tr>
<td>RS8</td>
<td>1.18</td>
<td>12.72</td>
</tr>
<tr>
<td>RS9</td>
<td>2.36</td>
<td>13.37</td>
</tr>
</tbody>
</table>
In order to evaluate the overall effect on the RCF particle size in ECC, it depends on the amount of increment for both $J_b'$ and $J_{tip}$ values. In Fig 4.20, the gradient of $J_{tip}$ vs RCF content is steeper as compared to the gradient of $J_b'$ vs RCF size. The overall results plotted in figure 4.21 showing a decreasing trend. The decreasing trend of the $J_b'/J_{tip}$ is not desirable to achieve the strain-hardening behavior.

Figure 4.20: $J_b'$ and $J_{tip}$ vs RCF size

Figure 4.21: $J_b'/J_{tip}$ vs RCF size
CHAPTER 5: SUMMARY AND CONCLUSION

5.1 CONCLUSION

To source for an alternative for sand, due to sky-rocketing price of sand after the ban from importing from Indonesia, and sustainability issues, RCF was incorporated into the ECC mixtures, replacing sand. Micromechanics model were used to tailor the design process for maximizing strain-hardening potential.

From the research, several conclusions can be drawn as follows:

1. $J_{\text{tip}}$ and $J_{\text{b'}}$ increases with both RCF content and size.

2. The increment for $J_{\text{tip}}$ is much faster than $J_{\text{b'}}$ which is not desirable to achieve the strain-hardening behavior.

3. RCF is not suitable material to replace sand in the ECC unless the optimal amount of RCF input is obtained which can achieve the tensile strain-hardening behavior.

5.2 RECOMMENDATIONS

In consideration of the current progress and the development potential of the RCF, the author would like to make the following recommendations.

1. To determine a more accurate experimental work, the Young modules for every mix should be determined as the RCF-ECC is different from the conventional concrete.

2. Further research could be done to determine the optimal amount of RCF content and size that achieve the maximum strain hardening effect which is beneficial to the construction industry.
REFERENCES


